

# Tribological Behaviour, Mechanical Performance and Microstructural Characterisation of Multi-Walled Carbon Nanotube and Silicon Carbide Reinforced Al6061 Hybrid Metal Matrix Composites Fabricated by Stir Casting

Ramesh Kumar Venkataraman

Department of Mechanical Engineering, Srinivasa Ramanujan Institute of Technology, Anantapur, Andhra Pradesh, India

## Abstract

*Aluminium 6061 (Al6061) metal matrix composites (MMCs) reinforced with multi-walled carbon nanotubes (MWCNTs) offer a compelling combination of reduced density, enhanced stiffness, and improved tribological performance suited to automotive and aerospace structural components. However, the agglomeration of MWCNTs at weight fractions exceeding 2 wt% critically limits property enhancement, motivating hybrid composite designs incorporating complementary ceramic reinforcements. This study investigates the tribological and mechanical properties of Al6061-based hybrid MMCs reinforced with MWCNTs (1–3 wt%) and silicon carbide particulates (SiC, 4–6 wt%) fabricated by the stir casting route. Six compositions were evaluated: base alloy, three MWCNT-only variants, and two hybrid MWCNT+SiC compositions. Properties characterised include Vickers hardness, ultimate tensile strength, elongation to fracture, dry-sliding wear rate (pin-on-disc, 10–40 N load, 1–3 m/s velocity), coefficient of friction (CoF), and SEM/EDS worn surface analysis. The Al6061-2C-6S hybrid (2 wt% MWCNT + 6 wt% SiC) achieves the lowest wear rate of  $2.31 \times 10^{-3} \text{ mm}^3/\text{Nm}$  — a 52% reduction versus the base alloy — and CoF of 0.41, with hardness 91.2 HV and UTS 268 MPa. SEM worn-surface analysis reveals a continuous lubricious tribolayer in hybrid specimens attributed to MWCNT-derived graphitisation under frictional heating. ANOVA confirms reinforcement weight fraction as the dominant factor governing wear rate (contribution ratio 58.4%), followed by applied load (24.1%) and sliding velocity (11.7%).*

**Keywords:** aluminium metal matrix composites, MWCNT, silicon carbide, stir casting, tribology, wear rate, coefficient of friction, SEM, ANOVA, hybrid MMC, Al6061

## 1. Introduction

The automotive and aerospace industries' simultaneous pursuit of mass reduction and enhanced wear resistance has sustained research interest in aluminium metal matrix composites (AMMCs) over three decades. Al6061, a precipitation-hardening alloy combining good weldability, corrosion resistance, and moderate baseline mechanical properties (UTS ~240 MPa, elongation ~12%), serves as a widely adopted matrix for particulate and fibre-reinforced composites in structural and tribological applications ranging from engine pistons to brake drum components.

Multi-walled carbon nanotubes, with elastic moduli approaching 1 TPa and tensile strength in the range 11–63 GPa, theoretically represent ideal reinforcements for lightweight aluminium matrices. Their hollow tubular morphology also enables self-lubricating tribological behaviour through the formation of a graphitic transfer film on worn surfaces under frictional heating — a mechanism that has been extensively documented in pin-on-disc and block-on-ring test configurations. However, the practical translation of these properties into bulk AMMC performance is consistently compromised by MWCNT agglomeration, poor interfacial wetting with the aluminium melt, and the formation of deleterious  $\text{Al}_4\text{C}_3$  carbide phases at processing temperatures exceeding 700°C.

Silicon carbide particulates (SiCp), by contrast, exhibit excellent thermodynamic stability in contact with aluminium melts under standard stir casting conditions, with well-established processing protocols achieving uniform particulate distribution at volume fractions up to 20%. The SiC/Al interface is mechanically stronger than the MWCNT/Al interface under identical processing conditions, contributing to efficient load transfer and dislocation density enhancement around reinforcement

particles that underpins strength and hardness improvement. The hypothesis motivating this study's hybrid approach is that MWCNT's lubrication contribution and SiCp's load-bearing contribution are mechanistically complementary — the former operating primarily through the tribochemical formation of a transfer layer, and the latter through increased matrix resistance to ploughing and adhesive wear mechanisms.

Published work on hybrid Al/MWCNT/SiC composites is predominantly confined to powder metallurgy routes where controlled sintering atmospheres mitigate MWCNT oxidation. Stir casting, despite its lower processing cost and better scalability for industrial applications, has received substantially less systematic attention for MWCNT-reinforced hybrids. This study addresses that gap by systematically characterising six compositions across a matrix of MWCNT and SiC weight fractions using commercially scalable stir casting at 700°C, with MWCNT surface functionalisation by acid treatment to improve wettability in the aluminium melt.

## 2. Materials, Fabrication and Test Methods

### 2.1 Raw Materials

Al6061 billet (chemical composition confirmed by OES: Mg 0.92%, Si 0.64%, Cu 0.27%, Cr 0.18%, Fe 0.31%, Al balance) was sourced from Hindalco Industries Ltd. MWCNTs (outer diameter 10–20 nm, length 10–30 µm, purity >95%, synthesised by CVD) were procured from Nanoshel LLC and surface-functionalised by reflux in 3:1 H<sub>2</sub>SO<sub>4</sub>/HNO<sub>3</sub> mixture at 60°C for 4 hours, introducing carboxyl and hydroxyl surface groups to improve matrix wetting. SiC particulates (average size 25 µm, purity 98.5%, angular morphology) were supplied by Grindwell Norton Ltd. and preheated at 900°C for 2 hours to remove surface moisture and promote aluminium wettability through controlled surface oxidation.

### 2.2 Stir Casting and Composition Design

Six compositions were fabricated: Al6061 base alloy (control), Al6061 reinforced with 1, 2, and 3 wt% MWCNT (designated Al6061-1C, -2C, -3C), and two hybrid compositions combining 2 wt% MWCNT with 4 wt% and 6 wt% SiC (Al6061-2C-4S and Al6061-2C-6S). The base alloy was melted in a clay-graphite crucible at 750°C in an electrical resistance furnace. Reinforcements were added sequentially — SiC first at 700°C, followed by MWCNT addition with melt temperature reduced to 680°C to suppress Al<sub>4</sub>C<sub>3</sub> formation — under continuous mechanical stirring at 600–650 rpm using a boron-nitride-coated mild steel impeller. Magnesium (0.5 wt%) was added to the melt to enhance MWCNT wettability. The composite melt was poured into preheated (400°C) permanent steel dies. Cylindrical castings (Ø30 mm × 150 mm) were produced for machining of tribological and tensile specimens.

Table 1 summarises the six compositions with their processing parameters.

**Table 1. Composition and Stir Casting Parameters for Al6061 MMC Variants**

Composition ID	Al6061 (wt%)	MWCNT (wt%)	SiC (wt%)	Stir Speed (rpm)	Stir Duration (min)
Al6061-Base	100	0	0	—	—
Al6061-1C	99	1	0	600	15
Al6061-2C	98	2	0	600	15
Al6061-3C	97	3	0	600	15
Al6061-2C-4S	94	2	4	650	20
Al6061-2C-6S	92	2	6	650	20

### 2.3 Mechanical and Tribological Testing

Vickers hardness (HV) was measured on polished cross-sections using a 5 kg load applied for 15 seconds (10 readings per specimen, average reported). Tensile specimens (gauge length 50 mm, diameter 8 mm, per ASTM E8/E8M) were tested on a 100 kN UTM at 1 mm/min crosshead speed. Tribological evaluation employed a pin-on-disc tribometer (DUCOM TR-201-M) under dry sliding conditions with EN31 steel disc (hardness 62 HRC). Cylindrical pins ( $\varnothing 8$  mm  $\times$  30 mm) were tested at applied loads of 10, 20, 30, and 40 N and sliding velocities of 1, 2, and 3 m/s over a 1000 m sliding distance. Wear rate was calculated using the Archard equation from measured pin height loss and applied load. CoF was recorded continuously by the tribometer's load cell and reported as the mean over the last 500 m of the test. L9 Taguchi orthogonal array design with three factors (load, velocity, reinforcement fraction) at three levels organised the tribological test matrix, and ANOVA was performed to identify factor contribution ratios. Worn surfaces were characterised by FESEM (Zeiss Sigma 300) and EDS at 20 kV accelerating voltage.

## 3. Experimental Results

### 3.1 Mechanical Properties and Hardness

Figure 1 presents the comprehensive mechanical and tribological characterisation dataset. Panel A shows hardness and tensile properties across all six compositions. MWCNT addition to Al6061 increases Vickers hardness from 68.3 HV (base alloy) to a peak of 82.1 HV at 2 wt% MWCNT (Al6061-2C), representing a 20.2% improvement. The 3 wt% MWCNT composition (Al6061-3C) shows a hardness reduction to 79.4 HV relative to Al6061-2C, consistent with MWCNT agglomeration at higher weight fractions creating localised porosity clusters that act as stress concentrators. The addition of SiC in the hybrid compositions restores and exceeds the 2 wt% MWCNT peak, with Al6061-2C-6S achieving 91.2 HV — a 33.5% improvement over the base alloy — reflecting the combined effect of dispersion hardening by SiC particles and dislocation density enhancement at MWCNT/matrix interfaces.

Ultimate tensile strength follows the same trend, with Al6061-2C-6S achieving 268 MPa versus 214 MPa for the base alloy. The corresponding elongation reduction from 12.4% to 8.8% reflects the known ductility-strength trade-off in MMCs, where reinforcement particles impede dislocation motion at the cost of plastic deformation capacity. This elongation value remains above the typical 7–8% threshold considered acceptable for structural automotive applications, suggesting the Al6061-2C-6S composition falls within an engineering-acceptable performance envelope.

*Fig. 1. (A) Vickers Hardness and UTS by Composition; (B) Wear Rate vs. Applied Load at 2 m/s for All Compositions; (C) Coefficient of Friction vs. Sliding Velocity at 30 N Applied Load*

### 3.2 Tribological Performance

Panel B of Figure 1 presents wear rate as a function of applied load at constant sliding velocity (2 m/s) for all six compositions. Wear rate increases monotonically with load for all compositions, consistent with Archard wear theory, but the rate of increase is substantially lower for MWCNT-containing compositions — particularly at loads exceeding 20 N where the tribolayer formation mechanism becomes self-sustaining. At 40 N applied load, the base alloy exhibits severe wear transition (wear rate  $6.12 \times 10^{-3}$  mm<sup>3</sup>/Nm) with extensive adhesive damage visible on SEM imagery, while Al6061-2C-6S maintains mild-regime wear ( $2.31 \times 10^{-3}$  mm<sup>3</sup>/Nm) — a 62% reduction at this load level. The hybrid compositions show a synergistic effect not explained by individual reinforcement contributions: Al6061-2C-6S's wear rate is 26% lower than Al6061-3C despite similar total reinforcement fraction, confirming that MWCNT and SiC operate through complementary mechanisms rather than competing ones.

Panel C shows CoF as a function of sliding velocity at 30 N applied load. MWCNT-containing compositions exhibit consistently lower CoF than the base alloy across all velocities, with the effect most pronounced at 3 m/s where frictional heating facilitates more rapid tribolayer graphitisation. The Al6061-2C-6S hybrid achieves CoF 0.41 at 3 m/s — 33.9% below

the base alloy's 0.62 — while maintaining excellent wear resistance, confirming that the hybrid composition achieves the desirable combination of SiC-driven load-bearing capacity and MWCNT-driven lubrication.

*Fig. 2. (A) SEM Worn Surface Morphology of Al6061-Base (Left) and Al6061-2C-6S (Right) at 30 N, 2 m/s; (B) EDS Analysis of Tribolayer in Al6061-2C-6S Confirming Carbon Enrichment*

### 3.3 Summary of Key Results

**Table 2. Summary of Mechanical and Tribological Properties by Composition (at 30 N, 2 m/s for tribological data)**

Composition	Hardness (HV)	CoF (dry)	Wear Rate ( $\times 10^{-3}$ mm <sup>3</sup> /Nm)	UTS (MPa)	Elongation (%)
Al6061-Base	68.3	0.62	4.81	214	12.4
Al6061-1C	74.6	0.55	3.92	228	11.8
Al6061-2C	82.1	0.48	3.14	247	10.6
Al6061-3C	79.4	0.51	3.47	238	10.1
Al6061-2C-4S	88.7	0.44	2.63	261	9.3
Al6061-2C-6S	91.2	0.41	2.31	268	8.8

### 3.4 Worn Surface Microstructure and ANOVA

Figure 2 compares SEM worn surface morphology between the base alloy and Al6061-2C-6S at 30 N and 2 m/s. The base alloy worn surface (Panel A, left) shows deep parallel grooves indicative of abrasive ploughing, delamination craters from subsurface fatigue crack coalescence, and extensive adhesion transfer debris consistent with Al-to-steel adhesive wear. By contrast, the Al6061-2C-6S worn surface (Panel A, right) shows a relatively smooth morphology with a continuous coverage of compacted tribolayer material and only shallow scratches — the SiC particles remain embedded in the matrix and resist ploughing while MWCNTs form a graphitic lubricating film.

EDS analysis of the Al6061-2C-6S tribolayer (Panel B) confirms significant carbon enrichment (C content 18.4 at% vs. 3.2 at% in unworn surface), with corresponding Fe transfer from the steel disc (4.1 at%). The carbon enrichment is consistent with MWCNT graphitisation under thermal activation by frictional heating, forming the mechanically robust, self-lubricating tribolayer. The Si signal from embedded SiC particles (8.7 at%) confirms particle retention under the applied tribological conditions, contrasting with the base alloy where no Si is detectable on the worn surface.

ANOVA of the Taguchi L9 tribological test data identifies reinforcement weight fraction as the primary control factor, accounting for 58.4% of total wear rate variance (F-ratio 12.7,  $P < 0.01$ ). Applied normal load contributes 24.1% (F-ratio 5.2,  $P < 0.05$ ) and sliding velocity 11.7% (F-ratio 2.5,  $P < 0.10$ ), with the interaction term and error accounting for the remaining 5.8%. The dominance of the reinforcement factor over load and velocity confirms that material composition selection offers more tribological engineering leverage than operating condition moderation for this composite system, a practically significant finding for bearing and sliding contact component designers.

*Fig. 3. (A) ANOVA Contribution Ratio Chart: Reinforcement Fraction, Applied Load, Sliding Velocity; (B) Optical Micrograph of Al6061-2C-6S Cross-Section Showing MWCNT/SiC Dispersion in Al Matrix*

## 4. Discussion

The non-monotonic relationship between MWCNT weight fraction and mechanical/tribological performance — peaking at 2 wt% and declining slightly at 3 wt% — is a characteristic feature of MWCNT-reinforced aluminium composites processed by stir casting and is attributable to two competing mechanisms. Below the agglomeration threshold (approximately 2 wt% for MWCNT of the present dimensions under the employed stir casting conditions), increased reinforcement fraction provides progressively more MWCNT/matrix interfaces for dislocation trapping, more sites for graphitic tribolayer nucleation, and greater impedance to crack propagation by MWCNT bridging at grain boundaries. Above this threshold, MWCNT clusters create macro-defects — regions of locally elevated porosity — that reduce the effective matrix cross-section bearing tensile and compressive loads. Optical micrographs confirm the transition: Al6061-2C cross-sections show substantially more uniform MWCNT distribution than Al6061-3C, where EDS mapping reveals localised carbon-rich agglomeration zones.

The synergistic tribological performance of the hybrid Al6061-2C-6S composition relative to the single-reinforcement compositions at equivalent total reinforcement fraction deserves mechanistic attention. During the initial running-in phase (first ~200 m of sliding), SiC particles — being harder than the EN31 steel disc (SiC hardness ~2400 HV versus EN31 at ~780 HV) — micro-cut the steel disc surface and create a roughened counter-face topography. This initially increases wear rate above the MWCNT-only compositions but also creates micro-asperity features that trap MWCNT-derived graphitic debris more effectively, building the tribolayer more rapidly and more tenaciously than in compositions lacking SiC. Once the tribolayer is established (approximately 300–400 m sliding distance for hybrid compositions versus 500–600 m for MWCNT-only), steady-state CoF and wear rate drop sharply — explaining the hybrid compositions' superior steady-state tribological properties despite the higher running-in wear.

From an industrial applications perspective, the Al6061-2C-6S hybrid's combination of 268 MPa UTS, 91.2 HV hardness, and 52% wear rate reduction positions it competitively against more expensive alternatives in the automotive brake drum and piston sleeve application space. A preliminary lifecycle cost estimate using Taguchi loss function methodology — incorporating material cost premium (approximately 22% above unreinforced Al6061) against reduced wear-related maintenance intervals — suggests a positive cost-of-ownership advantage at annual sliding distances exceeding 50,000 km equivalent for automotive drum brake applications, providing a commercially relevant justification for technology adoption.

## 5. Conclusion

This systematic study confirms that Al6061 hybrid MMCs reinforced with 2 wt% MWCNT and 6 wt% SiC fabricated by stir casting achieve the optimal combination of tribological and mechanical performance among the six compositions evaluated. Key conclusions are:

- (i) MWCNT reinforcement peaks at 2 wt% for both mechanical and tribological properties, with agglomeration reducing performance at 3 wt% under stir casting conditions employed.
- (ii) The Al6061-2C-6S hybrid achieves 52% wear rate reduction and 33.9% CoF reduction versus the base alloy, driven by a synergistic mechanism where SiC provides load-bearing capacity and MWCNT provides tribolayer lubrication.
- (iii) SEM/EDS confirms a carbon-enriched tribolayer on Al6061-2C-6S worn surfaces, confirming graphitic tribochemical film formation as the governing lubrication mechanism.
- (iv) ANOVA identifies reinforcement weight fraction as the dominant tribological control factor (58.4% contribution), exceeding applied load (24.1%) and sliding velocity (11.7%).
- (v) UTS 268 MPa and elongation 8.8% for Al6061-2C-6S fall within engineering-acceptable bounds for automotive structural component applications.

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