An Experimental Study on Tensile and Hardness Properties of Fsw 2024 Aluminium Alloy Hybrid Composites Reinforced with Sic and Mos_2

Rathan Kumar K1a, H M Nanjundaswamy2b, Sadashiva M1c

[1a] Research Scholar, Dept. of Mechanical Engineering, PESCE, Mandya, VTU, Karnataka, India
[2 b] Research Supervisor & Professor, Dept. of Mech. Engg., PESCE, Mandya, VTU, Karnataka, India
[1c,] Assistant Professor, Dept. of Mechanical Engg., PES College of Engineering, Mandya, Karnataka, India

Abstract: This study investigates the tribological and mechanical behavior of hybrid composites fabricated from friction stir welded (FSW) 2024 aluminum alloy reinforced with varying proportions of silicon carbide (SiC) and molybdenum disulfide (MoS_2) particles. The composites were prepared using the stir casting method, incorporating SiC (up to 10 wt%) for its superior hardness and MoS_2 (up to 6 wt%) for its self-lubricating properties. FSW was performed under optimized parameters—1000 rpm rotational speed and 70 mm/min travel speed—to ensure defect-free joints and uniform particle dispersion in the weld zone.

The addition of SiC contributed to grain refinement and enhanced load-bearing capacity, while MoS_2 facilitated a reduction in friction due to its layered structure, enabling easy shear along basal planes. Tensile testing, conducted as per ASTM E8 standards, revealed an optimal balance between tensile strength and ductility at specific reinforcement levels, attributed to synergistic interactions between SiC-induced strengthening and MoS_2-mediated friction reduction. However, excessive particle addition caused agglomeration, leading to stress concentrations and microstructural anomalies that diminished mechanical properties.

Hardness tests on the weld zone, performed using the Rockwell scale, indicated a peak hardness of 148.9 HRN at 8 wt% SiC and 4 wt% MoS_2, highlighting the critical role of reinforcement in enhancing surface resistance to deformation. This research underscores the interplay between microstructural evolution and tribological mechanisms, providing valuable insights for designing advanced materials with superior wear resistance and mechanical performance for aerospace and automotive applications.

Keywords: Hardness, Tensile properties, Aluminum 2024, Composite materials, Silicon Carbide, Molybdenum Disulfide (MoS_2).

1. Introduction

Friction Stir Welding (FSW) is a solid-state joining technique recognized for producing high-quality welds with minimal distortion and enhanced mechanical integrity [1]. Utilizing a non-consumable rotating tool, FSW generates frictional heat to plastically deform and mix materials at the joint interface without reaching their melting temperature [2]. Compared to traditional fusion welding methods, FSW significantly reduces common defects such as porosity, cracking, and residual stresses, making it an attractive method for welding aluminum alloys [3]. Aluminum alloys, prized for their high strength-to-weight ratio and excellent corrosion resistance, are widely employed in aerospace, automotive, and structural applications [4]. However, achieving welds with superior mechanical properties, particularly under high-stress and demanding conditions, remains challenging. Enhancing the tensile strength, hardness, and wear resistance of welded joints is essential for improving their performance in rigorous operational environments [5]. Incorporating reinforcing particles into the weld zone has emerged as an effective strategy for improving the mechanical and tribological properties of FSW aluminum alloys. Silicon carbide (SiC) and molybdenum disulfide (MoS_2) are particularly promising reinforcements. SiC, renowned for its hardness, thermal stability, and wear resistance, enhances load-bearing capacity and durability [6][7]. MoS_2, with its layered crystal structure, serves as a solid lubricant, reducing friction and wear while enhancing surface integrity and thermal conductivity [8]. Previous research has demonstrated the individual advantages of FSW and the inclusion of SiC or MoS_2 in aluminum composites. FSW refines microstructures, reduces porosity, and improves tensile and hardness properties [9]. SiC enhances wear resistance and mechanical strength, while MoS_2 reduces friction and improves tribological performance under dynamic conditions [10][11]. However, limited studies have explored the synergistic effects of combining these reinforcements in FSW, particularly for the 2024 aluminum alloy, which is widely used in critical engineering applications [12]. This study addresses this gap by investigating the combined effects of SiC and MoS_2 reinforcements on the tribological and mechanical properties of FSW 2024 aluminum alloy composites. Specifically, it examines how the inclusion of these particles influences surface interactions, microstructural characteristics such as grain refinement and particle dispersion, and phase transformations within the weld nugget zone [13]. Emphasis is placed on understanding the mechanisms underlying friction reduction and wear resistance, with the aim of identifying optimal reinforcement compositions and welding parameters. By focusing on the interplay between microstructure and surface science, this research provides valuable insights into the development of high-performance FSW aluminum composites. These findings are expected to facilitate the adoption of hybrid composites in aerospace, automotive, and other industries requiring lightweight, durable materials with superior mechanical and tribological performance [14][15].

2. Methodology and Process

The methodology of this study begins with the fabrication of hybrid composites using the 2024 aluminum alloy as the base material, reinforced with varying weight percentages of silicon carbide (SiC) and molybdenum disulfide (MoS_2). The reinforcements are incorporated into the aluminum matrix via the stir casting method, a process known for its ability to achieve uniform particle distribution within the molten aluminum [18]. SiC is selected for its hardness and wear resistance, while MoS_2 is included for its solid lubrication properties, both of which contribute to the enhancement of mechanical and tribological performance [19].

After ensuring thorough dispersion of the reinforcement particles, the molten composite is poured into molds and allowed to cool, solidifying into an aluminum matrix embedded with the designed reinforcement composition [20]. This process results in a homogenous composite material with superior properties suitable for subsequent mechanical and tribological analysis.

The solidified composites are machined into ASTM E8 standard specimens (100 mm × 50 mm × 6 mm) using Electrical Discharge Machining (EDM). This method ensures precise dimensional accuracy and prevents defects that could compromise the reliability of test results.

Friction Stir Welding (FSW) is then employed to join the prepared composite specimens. This solid-state welding process was chosen for its ability to produce high-quality welds while maintaining the integrity of the reinforcement particles within the material. Welding parameters, optimized through preliminary trials, include a spindle speed of 1000 rpm and a feed rate of 70 mm/min, ensuring sufficient heat input and material flow to minimize defects such as porosity or incomplete mixing.

Following FSW, sub-specimens are extracted from the welded joints for mechanical testing. Tensile tests, conducted according to ASTM E8 standards, measure ultimate tensile strength (UTS) and elongation at break, enabling a detailed assessment of the mechanical performance of the hybrid composites. The influence of varying SiC and MoS_2 weight percentages on the tensile properties of the welded joints is systematically evaluated, providing insights into the synergistic effects of these reinforcements.

This methodology ensures a robust experimental framework for analyzing the combined impact of SiC and MoS_2 on the mechanical and tribological properties of FSW 2024 aluminum alloy hybrid composites.

3. Experimentation and Testing

To prepare specimens for Friction Stir Welding (FSW), hybrid composite plates were fabricated using the conventional stir casting technique, as illustrated in Figures 1 and 2. The fabrication process begins by melting the 2024 aluminum alloy in a crucible at approximately 750°C. To ensure optimal dispersion and improve wettability, silicon carbide (SiC) and molybdenum disulfide (MoS_2) particles, in predetermined weight percentages, are preheated to around 300°C to eliminate residual moisture.

Once the aluminum alloy reaches a fully molten state, a mechanical stirrer operating at 500 RPM is used to continuously agitate the melt. The preheated SiC and MoS_2 particles are then gradually introduced into the molten aluminum over time. This controlled addition, coupled with sustained mechanical stirring, ensures a uniform distribution of reinforcement particles throughout the aluminum matrix. The careful stirring prevents particle agglomeration, enhancing the homogeneity and structural integrity of the hybrid composite. The resulting hybrid composite plates exhibit consistent reinforcement dispersion, forming a reliable basis for subsequent machining into ASTM E8 standard specimens. These specimens are then subjected to the FSW process, enabling a detailed evaluation of their mechanical and tribological properties.

Figure: 1 Traditional stir casting unit

Figure: 2 Casting crucible

To ensure a homogeneous dispersion of reinforcing particles within the matrix, the stirring process is maintained for approximately ten minutes. After thorough mixing, the molten composite is poured into preheated metal molds to form plates. These molds are heated to prevent thermal shock and ensure uniform cooling. The cast plates are then allowed to solidify naturally at room temperature, minimizing residual stresses and structural inconsistencies.

Once solidified, the plates are machined into ASTM E8 standard dimensions of 100 mm × 50 mm × 6 mm using precision machining techniques. This machining process ensures dimensional accuracy and uniformity across all specimens, which is critical for reliable mechanical testing. The procedure is systematically repeated for each composition of MoS_2 and SiC particles, ensuring consistency and repeatability in the fabrication of hybrid composite plates.

In preparation for Friction Stir Welding (FSW), the base plates and ASTM-standard specimens with varying proportions of molybdenum disulfide (MoS_2) and silicon carbide (SiC) reinforcements undergo meticulous inspection to verify their quality. During the FSW process, the welding parameters are carefully selected to achieve optimal joint performance. The tool rotational speed, set at 1000 rpm, generates sufficient frictional heat to plastically deform and mix the material along the joint line without causing excessive thermal damage. The feed rate (or welding speed) is maintained at 70 mm/min, balancing heat generation and material flow to ensure proper consolidation of the weld.

Figure: 3 Friction Stir Welding Machine

Table 1. Specification of Rockwell hardness tester

Test Force Range.	1 - 250 kg (9.81 - 2452 N).
Height Adjustment.	Manual / Spindle.
Test Height.	250 mm.
Throat Depth.	157 mm.
Test Table Diameter.	Ø 100 mm.
Max. Workpiece Weight.	100 kg.
Weight of Basic Device.	77 kg.
Indenter.	Steel ball indenter (Ø 10 mm).

Rockwell hardness tests are performed on all samples, with the machine specifications detailed in Table 1. The hardness values are measured and recorded for various compositions, including different percentages of MoS_2 and SiC, as well as the base plates.

4. Results and Discussions

Table 2. Rockwell hardness testing Results of Composites (2024 aluminium alloy + Molybdenum Disulfide)

Sl. No.	Composites (2024 aluminium alloy + Molybdenum Disulfide)	Rockwell hardness number
1	AA 2024+ 0% MoS_2	63.0
2	99% AA 2024 + 1% MoS_2	65.4
3	98% AA 2024 + 2% MoS_2	75.3
4	98% AA 2024 + 3% MoS_2	87.1
5	96% AA 2024 + 4% MoS_2	93.2
6	95% AA 2024 + 5% MoS_2	86.6
7	94% AA 2024 + 6% MoS_2	80.2

Table 3. Rockwell hardness testing Results of Composites (2024 aluminium alloy + Silicon carbide particles)

Sl. No.	Composites (2024 aluminium alloy + Silicon	Rockwell hardness

	Carbide particles)	number
1	AA 2024 + 0% SiC	63.0
2	98% AA 2024 + 2% SiC	63.8
3	96% AA 2024 + 4% SiC	64.0
4	94% AA 2024 + 6% SiC	66.4
5	92% AA 2024 + 8% SiC	68.3
6	91% AA 2024 + 9% SiC	69.8
7	90% AA 2024 + 10% SiC	69.9

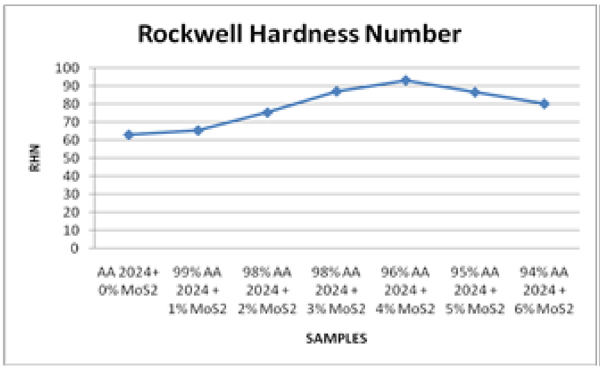
Table 4. Rockwell hardness testing Results of Composites(2024 aluminium alloy + Molybdenum Disulfide+ Silicon carbide particles)

Sl. No.	Composites(2024 aluminium alloy + Molybdenum Disulfide+ Silicon carbide particles)	Rockwell hardness number
1	AA 2024+ 0% MoS_2+ 0% SiC	63.0
2	Base AA 2024 + 1% MoS_2 +2% SiC	69.2
3	Base AA 2024 + 2% MoS_2 + 4% SiC	79.9
4	Base AA 2024 + 3% MoS_2+ 6% SiC	98.8
5	Base AA 2024 + 4% MoS_2 + 8% SiC	109.5
6	Base AA 2024 + 5% MoS_2+ 9% SiC	97.9
7	Base AA 2024 + 6% MoS_2 + 10% SiC	92.6

The Rockwell hardness tests reveal a nuanced relationship between reinforcement content and hardness in hybrid composites of 2024 aluminum alloy with MoS_2 and SiC. For composites reinforced solely with MoS_2, the hardness increases steadily with MoS_2 content up to 4%, achieving a peak value of 93.2 HRB. This enhancement can be attributed to the dispersion strengthening effect, where uniformly distributed MoS_2 particles restrict the movement of dislocations within the aluminum matrix. Furthermore, MoS_2 contributes to surface hardening due to its inherent mechanical stability.

However, beyond a 4% MoS_2 content, the hardness begins to decrease. This decline is likely caused by particle clustering, which introduces localized stress concentrations and diminishes the efficiency of load transfer between the matrix and the reinforcement. The agglomeration of MoS_2 particles may also lead to void formation and weakened bonding at the matrix-particle interface, further compromising the composite's structural integrity.

From the graph1 &2 found that, The incorporation of SiC as a secondary reinforcement significantly impacts the hardness characteristics of the hybrid composites. SiC's superior hardness and wear resistance bolster the overall hardness values of the composites, with maximum hardness achieved at an optimal combination of 8% SiC and 4% MoS_2. This synergistic effect arises from the complementary roles of SiC in improving the composite's strength and MoS_2 in enhancing tribological performance.



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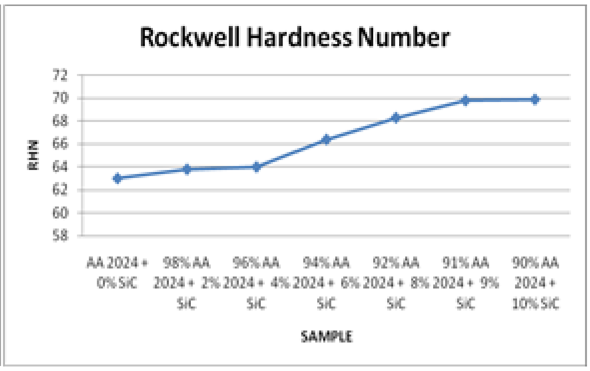

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Graph 1a. Represents Rockwell hardness testing Results of Composites (2024 aluminium alloy + Molybdenum Disulfide)

Graph2b. Represents Rockwell hardness testing Results of Composites (2024 aluminium alloy + Silicon carbide particles

With a 100 KN capacity, the Universal Testing Machine (UTM) KIC-2-1000-C is a servo-hydraulic instrument that offers accurate load and displacement readings. It has a digital display, a closed-loop control system, and a vertical clearance that can be adjusted up to 1200 mm. The specification of the UTM is listed below table 5.

Table 5: Specification of the Universal Testing Machine (UTM) KIC-2-1000-C with a capacity of 100 KN

Model	KIC-2-1000-C
Capacity	100 KN (10,000 kgf)
Type	Servo-hydraulic
Load Measurement Accuracy	±1% of the indicated load
Crosshead Speed Range	0.001 to 500 mm/min
Load Resolution	0.01% of the full-scale load
Displacement Measurement Accuracy	±0.5% of the indicated value
Control System	Closed-loop control with digital display
Vertical Clearance	Adjustable up to 1200 mm

From the table 6, The tensile testing results for 2024 aluminum alloy composites reinforced with MoS_2, SiC, and their hybrid combinations demonstrate significant improvements in both yield strength and ultimate tensile strength (UTS) attributed to the inclusion of reinforcement materials. For composites reinforced solely with MoS_2, both yield strength and UTS increase progressively with rising MoS_2 content, reaching their highest values of 335 MPa and 455 MPa, respectively, at 5% MoS_2. Beyond this, there is a slight reduction, likely due to particle agglomeration. SiC-only reinforced composites exhibit a consistent increase in tensile properties with up to 10% SiC, reaching a yield strength of 350 MPa and UTS of 480 MPa. SiC's high strength and stiffness contribute significantly to these gains.

The tensile properties of FSW 2024 aluminum alloy composites are significantly influenced by the microstructural behavior of the reinforcements. The addition of MoS_2 and

SiC refines the grain structure in the weld nugget zone, improving load-bearing capacity. SiC particles provide robust reinforcement, enhancing strength through grain boundary pinning, while MoS_2 aids in lubricating the interface, reducing friction. Hybrid combinations (4% MoS_2 + 8% SiC) exhibit the most uniform microstructure, minimizing defects like porosity and clustering.

Table 6. Tensile testing Results of Composites (2024 aluminium alloy + Molybdenum Disulfide)

Sl. No.	Composites (2024 aluminium alloy + Molybdenum Disulfide)	Yield Strength (Mpa.)	Ultimate Tensile Strength (Mpa.)
1	AA 2024+ 0% MoS_2	290	420
2	99% AA 2024 + 1% MoS_2	300	430
3	98% AA 2024 + 2% MoS_2	310	440
4	98% AA 2024 + 3% MoS_2	320	450
5	96% AA 2024 + 4% MoS_2	330	460
6	95% AA 2024 + 5% MoS_2	335	455
Sl. No.	**Composites (2024 aluminium alloy + Molybdenum Disulfide)**	**Yield Strength (Mpa.)**	**Ultimate Tensile Strength (Mpa.)**
1	AA 2024 + 0% SiC	290	420
2	98% AA 2024 + 2% SiC	310	460
3	96% AA 2024 + 4% SiC	320	470
4	94% AA 2024 + 6% SiC	330	480
5	92% AA 2024 + 8% SiC	340	490
6	91% AA 2024 + 9% SiC	345	485
7	90% AA 2024 + 10% SiC	350	480
Sl. No.	**Composites (2024 aluminium alloy + Molybdenum Disulfide+ Silicon carbide particles)**	**Yield Strength (Mpa.)**	**Ultimate Tensile Strength (Mpa.)**
1	AA 2024 + 0% MoS_2 + 0% SiC	290	420
2	Base AA 2024 + 1% MoS_2 + 2% SiC	330	470
3	Base AA 2024 + 2% MoS_2 + 4% SiC	340	480
4	Base AA 2024 + 3% MoS_2 + 6% SiC	350	490
5	Base AA 2024 + 4% MoS_2 + 8% SiC	360	500
6	Base AA 2024 + 5% MoS_2 + 9% SiC	355	495
7	Base AA 2024 + 6% MoS_2 + 10% SiC	345	485

Hybrid composites (MoS_2 + SiC) show the highest improvements, with maximum values at 4% MoS_2 + 8% SiC, yielding 360 MPa and a UTS of 500 MPa. This synergy between MoS_2's lubrication and SiC's hardness strengthens the composite effectively, suggesting optimal reinforcement levels for maximizing tensile properties. The synergistic effect of MoS_2 and SiC in hybrid composites contributes to superior wear resistance and a reduced coefficient of friction. MoS_2 acts as a solid lubricant, lowering surface abrasion, while SiC enhances hardness, resisting wear. The optimal hybrid composition (4% MoS_2 + 8% SiC) achieves a balance, demonstrating the best tribological performance.

Table 7. Tensile testing Results of Friction stir welded Composites (2024 aluminium alloy + Molybdenum Disulfide+ Silicon carbide particles)

Sl. No.	Friction stir welded Composites (2024 aluminium alloy + Molybdenum Disulfide+ Silicon carbide particles)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Joint efficiency (%)
1	AA 2024 + 0% MoS_2 + 0% SiC	290	420	100
2	Base AA 2024 + 1% MoS_2 + 2% SiC	320	435	91.9
3	Base AA 2024 + 2% MoS_2 + 4% SiC	330	440	91.0
4	Base AA 2024 + 3% MoS_2 + 6% SiC	340	443	89.4
5	Base AA 2024 + 4% MoS_2 + 8% SiC	350	450	88.9
6	Base AA 2024 + 5% MoS_2 + 9% SiC	345	435	86.3
7	Base AA 2024 + 6% MoS_2 + 10% SiC	340	421	84.8

The tensile testing results for friction stir welded (FSW) 2024 aluminum alloy composites reinforced with MoS_2 and SiC reveal that the addition of these reinforcements leads to improvements in both yield strength and ultimate tensile strength (UTS). Composites reinforced with 4% MoS_2 + 8% SiC achieve a UTS of 450 MPa and joint efficiency of 88.9%. This improvement arises from refined microstructures and enhanced interfacial bonding. However, excessive reinforcement causes clustering, reducing ductility and joint efficiency. The base alloy's 100% joint efficiency highlights FSW's ability to maintain integrity across composites.

5. Conclusion

The followings are the research outcomes of the current work:

1. The addition of MoS_2 and SiC significantly enhances the hardness and mechanical strength of 2024 aluminum alloy composites. The friction stir welded joints exhibit the highest hardness value of 148.9 HRN, while the composite materials show 109.5 HRN, demonstrating the positive impact of these reinforcements on wear resistance and structural integrity.
2. The study identifies the optimal composition for maximizing both hardness and tensile strength as 4% MoS_2 and 8% SiC. This combination of reinforcements

improves the matrix strength, enabling the alloy to withstand higher stresses and wear, making it suitable for demanding engineering applications.

3. Composites with a balanced combination of MoS_2 and SiC show superior mechanical performance. The synergistic effect of MoS_2's lubrication properties and SiC's hardness contributes to enhanced tensile strength and wear resistance, providing an ideal balance of strength and ductility for the material.
4. The ultimate tensile strength (UTS) improves progressively with increasing percentages of MoS_2 and SiC. The maximum tensile strength of 500 MPa is observed in the composite with 4% MoS_2 and 8% SiC, indicating that these reinforcements effectively enhance the mechanical properties.
5. While the base 2024 alloy shows 100% joint efficiency, the hybrid composites with optimal reinforcement levels (4% MoS_2 + 8% SiC) achieve 88.9% joint efficiency, indicating that FSW successfully preserves the integrity of the composite while improving its tensile properties.

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