

# Enhancing Hardness In 2024 Aluminum Alloy Hybrid Composites: Friction Stir Welding With MoS<sub>2</sub> & SiC Particles

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**ABSTRACT:** *This study investigates the enhancement of hardness properties in 2024 aluminum alloy hybrid composite plates joined through Friction Stir Welding (FSW) by incorporating varying percentages of Molybdenum Disulfide (MoS<sub>2</sub>) and Silicon Carbide (SiC) particles. Known for its high strength-to-weight ratio, 2024 aluminum alloy is extensively used in the automotive and aerospace sectors. Earlier studies have defined that ceramic particles like SiC enhance the hardness and mechanical properties of aluminum alloys, and MoS<sub>2</sub> enhances wear resistance. However, the combined effect of MoS<sub>2</sub> and SiC on 2024 aluminum alloy, particularly when subjected to FSW, has not been thoroughly explored. In this research, composite plates were fabricated by mixing 2024 aluminum alloy with up to 6% MoS<sub>2</sub> and 10% SiC particles, followed by FSW processing. The Rockwell hardness test was performed on both the base composites and the welded joints. Results showed a significant increase in hardness with the addition of MoS<sub>2</sub> and SiC, with the base composites' hardness increasing from 63.0 HRN to a peak of 109.5 HRN, and the welded composites' hardness rising from 116.0 HRN to a maximum of 148.9 HRN. The results designate that particle reinforcement and the FSW process significantly enhance the alloy's hardness. The optimal composition of 4% MoS<sub>2</sub> and 8% SiC achieved the highest hardness values, highlighting the potential of this hybrid composite for high-performance applications. This study suggests valuable insights into the development of advanced aluminum alloy composites for industrial use.*

**Keywords:** Aluminum Alloy Composites, Friction Stir Welding, Molybdenum Disulfide (MoS<sub>2</sub>), Silicon Carbide (SiC)

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## 1. INTRODUCTION

Friction Stir Welding (FSW) is a joining process that is an innovative technology forming the solid-state, and it has many benefits as compared to the conventional fusion welding processes. It takes place through mechanical mixing of materials below the melting point, and has been used with increasing popularity in several industries, such as the aerospace industry, the automotive industry as well as in the construction industry. Even though the given approach is widely used, the mechanical properties of FSW weld joints, including their strength and hardness, frequently become a matter of concern. It is very important to improve these properties to facilitate the survival of FSW in high-power industrial environments. Incorporation of the reinforcing particles helps to enhance the mechanical properties of the FSW joints. Of these, molybdenum Disulfide (MoS<sub>2</sub>) and silicon carbide (SiC) have received quite a lot of interest. MoS<sub>2</sub>, which is characterized by a high thermal conductivity and reactivity is generally added to many types of welding processes. In the same manner, with its superior mechanical properties, SiC has been largely applied to fortify the performance of aluminum alloys. Binding of these particles during the process of FSW has also a potential to improve the microstructure of the welds and hence the resultant mechanical properties of the aluminum alloys. The synergistic use of FSW and the MoS<sub>2</sub> and SiC offers the new way of fabricating high-performance weld joints with higher strength and hardness.

This current research seeks to optimise hardness values of 2024 aluminum alloy hybrid composites using different percentages of weight of MoS<sub>2</sub> and SiC particles using the FSW technology. Through the investigation of obtained microstructure and mechanical properties, we attempt to determine the effect that these reinforcing particles have on the quality of the welds. A systematical study on the weld joints including the major attributes like microstructural refinement, hardness performance will be involved in the research. It is in this innovative approach that we would like to seek new possibilities of manufacturing high strength and lightweight components in aluminum alloys that can be used in future industrial applications. The outcomes of the current work may elicit the evolution of better FSW methods, hence

increasing the applicability of the aluminum alloy in important engineering tasks. Friction Stir Welding (FSW) is well researched because of its capacity to weld aluminum alloys without causing much distortion, and with enhanced mechanical properties. It has been demonstrated that FSW is able to generate welds with Refined microstructure and lower porosity (Kumar et al., 2016)[1], High tensile strength and hardness (Zhang et al., 2018) [2] and Increased corrosion resistance (Liu et al., 2020) [3]. To further improve on the weld properties, the reinforcement particles have also been added such as Molybdenum Disulfide (MoS<sub>2</sub>). MoS<sub>2</sub> was reported to Enhance the thermal conductivity and reactivity of weld zone (Wang et al., 2019) [4], Regulate the microstructure and improves the strength of the weld (Chen et al., 2020) [5], Suppress formation of defect and porosity (Huang et al., 2018) [6]. Whereas there has been a demonstration of the individual benefits of adding FSW and another but there is still the need to ask the question: what are the joint effects of these two to the mechanical properties and microstructure of aluminum alloy welds? [7]. This work intends to fill this knowledge gap, and to promote the prospect of adding MoS<sub>2</sub> to FSW to produce high performance aluminum alloy parts.

### 1.1 LITERATURE GAP

The previous studies have found the impacts of the silicon carbide (SiC) or Molybdenum Disulfide (MoS<sub>2</sub>) additions or friction stir welding (FSW) disjunct, respectively, on aluminum alloys, but there was still a wide gap of knowledge concerning their effects as joint. Therefore, there is no extensive study on how the addition of FSW and MoS<sub>2</sub> and SiC alloys to aluminum alloys 2024 impact on the mechanical properties and structure of 2024 aluminum alloys [8]. The best conditions of FSW in presence of these reinforcement particles as well as the mechanisms behind the enhanced properties behind them are still unsolved. Such a literature gap highlights the need to undergo in-depth studies that help to ascertain how addition of SiC and MoS<sub>2</sub> together during FSW influences welds in their final stages [9].

**Table.1.** Optimization of Hardness in 2024 Aluminium Alloy Hybrid Composites Reinforced with MoS<sub>2</sub> and SiC Particles via Friction Stir Welding.

Key Focus	Materials/Alloys Studied	Key Findings	Relevance to Current Study
Effect of FSW on mechanical properties [6]	Various aluminum alloys	Demonstrated that FSW produces fine-grained microstructures with reduced porosity, enhancing tensile strength and hardness	Provides foundational understanding of FSW's impact on aluminum alloys' mechanical properties
Impact of FSW on aluminum alloys [7]	6061-T6, 7075 alloys	Improved tensile strength and hardness; refined microstructure	Highlights the general impact of FSW on hardness and mechanical strength in aluminum alloys
Corrosion resistance and mechanical properties post-FSW [8]	2024 aluminum alloy	Increased corrosion resistance and strength after FSW	Adds value to understanding how FSW affects more than just hardness, emphasizing overall material properties
Influence of MoS <sub>2</sub> on FSW welds [8]	Aluminum alloys	MoS <sub>2</sub> improves thermal conductivity and reactivity, leading to refined microstructure and improved strength	Directly relevant as it explores the effect of MoS <sub>2</sub> , which is used in the current study
MoS <sub>2</sub> and its effect on FSW [9]	2024 aluminum alloy	MoS <sub>2</sub> reduces defects, improves strength, and enhances the hardness of the weld	Provides insight into the potential of MoS <sub>2</sub> to enhance the mechanical properties of 2024 aluminum alloy

MoS <sub>2</sub> in FSW welds [10]	2024 aluminum alloy	MoS <sub>2</sub> addition reduces porosity and defects while enhancing strength and hardness	Crucial to understanding how MoS <sub>2</sub> reinforces aluminum alloy in FSW processes
FSW of dissimilar aluminum alloys [11]	2024 aluminum alloy, 7075 aluminum alloy	FSW enhanced mechanical properties in dissimilar aluminum alloy joints	Demonstrates the effectiveness of FSW in enhancing mechanical properties, relevant for hybrid composite studies
Overview of FSW and its impact on alloys [11]	Various aluminum alloys	FSW improves mechanical properties, including hardness, without significant defects	Provides a broad understanding of FSW's general effect on aluminum alloys
FSW of dissimilar materials [12]	Aluminum alloys, Titanium alloys	Increased joint strength and hardness with FSW, especially with particle reinforcement	Relevant as it shows how FSW can be used to enhance the properties of composites, such as the MoS <sub>2</sub> and SiC reinforcements in this study
Effect of welding parameters on FSW [13]	6061-T6 aluminum alloy	Parameters like tool speed and feed rate significantly influence mechanical properties	Provides essential knowledge on how FSW parameters can optimize the properties of aluminum alloys in this study
SiC addition in aluminum alloys [13]	Aluminum-SiC composites	SiC addition significantly improved the hardness and wear resistance of aluminum alloys	Directly relevant for understanding how SiC affects the hardness of aluminum alloys and composites
SiC reinforcement in aluminum alloys [13]	Al-SiC composites	SiC enhances the mechanical strength and hardness, especially in hybrid composites	Supports the investigation of SiC's effect on 2024 aluminum alloy in this study
Friction stir welding of MoS <sub>2</sub> and SiC reinforced aluminum alloys [13]	2024 aluminum alloy with MoS <sub>2</sub> and SiC	Combined use of MoS <sub>2</sub> and SiC significantly enhances hardness and wear resistance	Directly related to the current study's exploration of MoS <sub>2</sub> and SiC reinforcement in FSW

The paper focuses on studying how the hardness characteristics of 2024 aluminum alloy hybrid composites can be enhanced by adding Molybdenum Disulfide (MoS<sub>2</sub>) particles and Silicon Carbide (SiC) together and then subsequently welding the mixture using the Friction Stir Welding (FSW) process. Investigations into the effect of the change in percent weight of MoS<sub>2</sub> and SiC on the mechanical properties of the base composites and the welded joints, especially hardness are carried out. According to the outcome of the Hardiness tests, the best composition involving a mixture of 4% MoS<sub>2</sub> to 8% SiC in alloy shows the high values of hardness, and provides substantial enhancements in the original alloy. It is recommended that by complementing the element of aluminum alloys with MoS<sub>2</sub> and SiC, the laboratory provides significant help to the creation of advanced materials that have a much better mechanical performance to meet the demands of high-tech industries, including aerospace and automotive industries. The current research is important to the industries which are trying to make lightweight, high-strength material which can handle rough working conditions, which is not only strong enough but also efficient in demanding engineering operations.

This research is also presented to discuss the results when the MoS<sub>2</sub> and SiC particles were added to the FSW practice of the 2024 aluminum alloys, filling an existing gap in literature. This study aims at Determining optimal parameters of FSW with adding MoS<sub>2</sub> and SiC, Understanding mechanisms behind improved properties, Exploring potential applications of this new type of welding, the study will also determine the superior mechanical properties and thermal conductivity of the welds by studying their microstructure. Prime objectives of the present research work were follows:

- To cast hybrid composites of 2024 aluminium alloy into which a different weight percentage of MoS<sub>2</sub> and SiC particle have been incorporated.
- To friction stir weld (FSW) the casted plates together with different set of parameters in order to optimize the welding conditions.
- In order to perform the Rockwell hardness measurements on the welded joints and tabulate the results and compare the profile of hardness properties of different compositions and welding parameters.

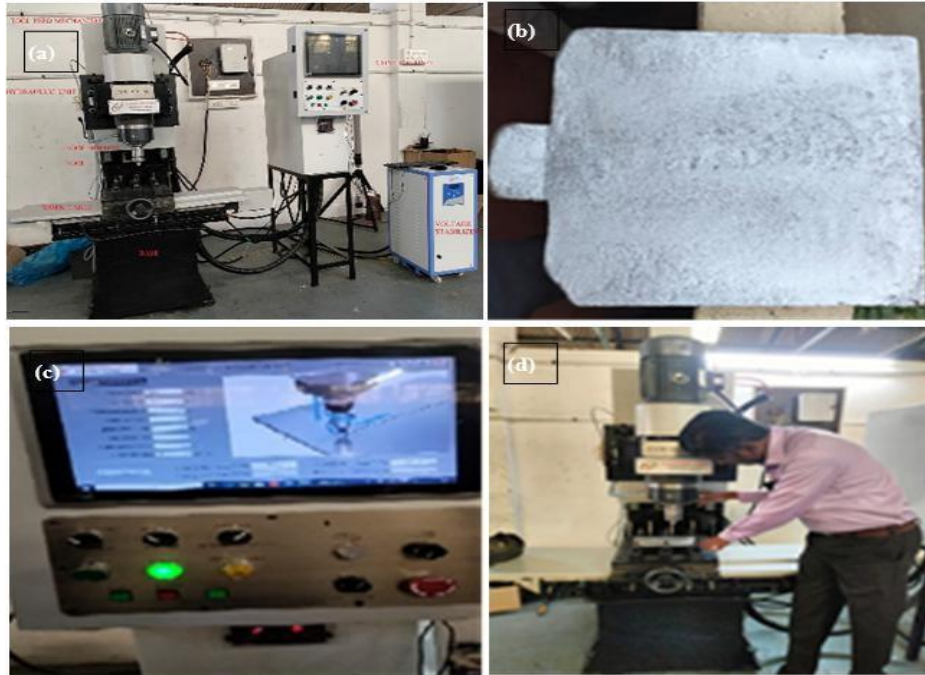
## 2. Experimentation and Testing

This research study will entail the process of manufacturing the hybrid composite plates by utilizing the conventional technique of stir casting preparation and then undergoing machining to create the samples of Friction Stir Welding (FSW) [10]. At first, the aluminum alloy 2024 is melted at a temperature of approximately 750 C in a graphite crucible. The Molybdenum Disulfide (MoS<sub>2</sub>) and Silicon Carbide (SiC) particles are preheated to approximately 300 o C in order to dry the particles in removing moisture and enhancing the property of wettability with varying weight percentages. The preheated particles are later added to the hot aluminum alloy gradually and keep stirring with a mechanical stirrer at a speed of 500 RPM. This process of stirring that is continued within the approximate 10 minutes tallies an evenly spread reinforcing particles in the matrix [11]. After the stirring process, the molten composite is poured into preheated metal molds to form plates. These cast plates are then allowed to cool and solidify at room temperature. Once solidified, the plates are machined to ASTM standard dimensions of 100 mm x 50 mm x 06 mm to prepare them for FSW shows in Fig 1 (b). This procedure is repeated for each composition of MoS<sub>2</sub> and SiC particles, ensuring consistency and repeatability across different samples [12] shown in table 2.

ASTM standard composite plates with various percentages of MoS<sub>2</sub> and SiC reinforcement, as well as base plates are prepared for the Friction Stir Welding (FSW) process, which is shown in Fig 1 (a) to (d). The FSW parameters are carefully selected to ensure consistent and high-quality welds. The spindle speed, or tool rotational speed, is set at 1000 rpm. This speed generates frictional heat to soften the material along the joint line without causing excessive thermal degradation, and also the feed rate, or weld speed, is maintained at 70 mm/min. This balance ensures effective material mixing and a high-quality weld finish [14]. With the plates securely clamped and parameters set, the FSW tool, comprising a non-consumable rotating pin and shoulder, is plunged into the joint between the plates. The tool then traverses along the weld line. The rotational and translational motion of the tool generates frictional heat, causing the material to plasticize and soften without melting [15].

**TABLE 2.** List of Sample prepared for Experimentation<sup>[13]</sup>.

Sl. No.	Composites (2024 aluminium alloy + Molybdenum Disulfide)	Composites (2024 aluminium alloy + Silicon Carbide particles)	Composites (2024 aluminium alloy + Molybdenum Disulfide + Silicon carbide particles)
1	99% AA 2024 + 0% MoS <sub>2</sub>	98% AA 2024 + 0% SiC	AA 2024 + 0% MoS <sub>2</sub> + 0% SiC
2	99% AA 2024 + 1% MoS <sub>2</sub>	98% AA 2024 + 2% SiC	AA 2024 + 1% MoS <sub>2</sub> + 2% SiC
3	98% AA 2024 + 2% MoS <sub>2</sub>	96% AA 2024 + 4% SiC	AA 2024 + 2% MoS <sub>2</sub> + 4% SiC
4	98% AA 2024 + 3% MoS <sub>2</sub>	94% AA 2024 + 6% SiC	AA 2024 + 3% MoS <sub>2</sub> + 6% SiC
5	96% AA 2024 + 4% MoS <sub>2</sub>	92% AA 2024 + 8% SiC	AA 2024 + 4% MoS <sub>2</sub> + 8% SiC
6	95% AA 2024 + 5% MoS <sub>2</sub>	91% AA 2024 + 9% SiC	AA 2024 + 5% MoS <sub>2</sub> + 9% SiC
7	94% AA 2024 + 6% MoS <sub>2</sub>	90% AA 2024 + 10% SiC	AA 2024 + 6% MoS <sub>2</sub> + 10% SiC



**Figure.1** (a) Friction Stir Welding Machine, (b) Cast Plate, (c) FSW software (d) FSW Process.

As the tool moves, it mechanically stirs the softened material, creating a fine-grained, homogenized microstructure in the weld zone. This solid-state joining technique ensures minimal distortion and high weld integrity. The FSW process is meticulously repeated for each set of composite plates, including those with only MoS<sub>2</sub> or SiC, to comprehensively study the effects of different reinforcement's technique in various industries.

**Table 3.** Friction stirs welding process parameters

<b>Tool material</b>		High carbon high chromium steel (HcHCr)
<b>FSW Process Parameters</b>	Tool Speed (rpm)	Tool Feed Rate(mm/min)
	1000	70

Table 3 indicates properties of High-carbon; high-chromium steels are used in cold-work tool steels, such as D2, D3, D4, D5, and D7 steels. All group D steels are air hardened and contain 1% Mo, with the exception of D3 steel. Type D3 steel is oil-quenched; however following austenitization through vacuum, certain parts can be gas-quenched. Because of this, type D3 steel tools often become brittle during the hardening process. Of the group D steels, type D2 steel is the one that is used the most frequently. The D3 steels have 12% chromium and 1.5 to 2.35% carbon [16].

**Table 4.** Specification of Rockwell hardness tester

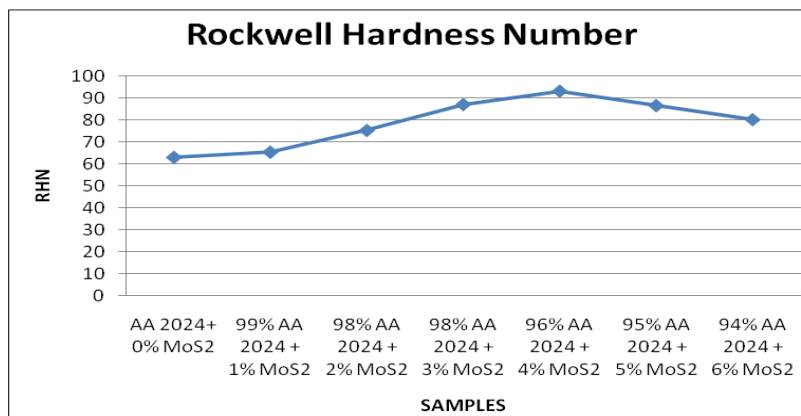
<b>Specification Details</b>	
<b>Test Force Range</b>	1 - 250 kg (9.81 - 2452 N)
<b>Height Adjustment</b>	Manual / Spindle
<b>Test Height</b>	250 mm
<b>Throat Depth</b>	157 mm
<b>Test Table Diameter</b>	Ø 100 mm
<b>Max. Workpiece Weight</b>	100 kg
<b>Weight of Basic Device</b>	77 kg
<b>Indenter</b>	Steel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

Rockwell hardness tests are conducted on each sample with specification of machine listed at table 4. The hardness values are recorded and tabulated for various compositions, including different percentages of MoS<sub>2</sub> and SiC, and for base plates. The obtained results are then compared to assess the influence of each reinforcement and FSW parameter on the hardness. The comparison highlights the optimal composition and welding parameters that yield the highest hardness values [17].

### 3. RESULTS AND DISCUSSIONS

**Table 5.** 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 <sub>2</sub>	63.0
2	99% AA 2024 + 1% MoS <sub>2</sub>	65.4
3	98% AA 2024 + 2% MoS <sub>2</sub>	75.3
4	97% AA 2024 + 3% MoS <sub>2</sub>	87.1
5	96% AA 2024 + 4% MoS <sub>2</sub>	93.2
6	95% AA 2024 + 5% MoS <sub>2</sub>	86.6
7	94% AA 2024 + 6% MoS <sub>2</sub>	80.2

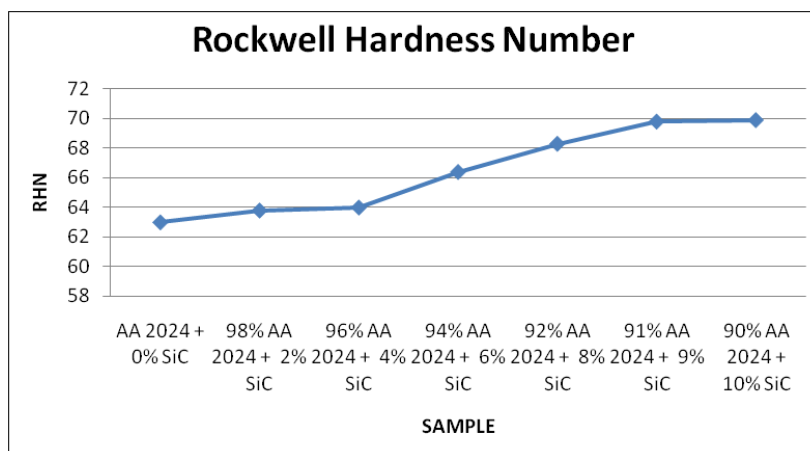


**Figure 2.** Represents Rockwell hardness testing Results of Composites (2024 aluminium alloy + Molybdenum Disulfide).

Based on Table 5 and Figure 2, the composite with 4% MoS<sub>2</sub> (96% AA 2024 + 4% MoS<sub>2</sub>) represents the highest critical point, achieving the peak Rockwell hardness number of 93.2 HRN. This composition signifies the optimal reinforcement level, where MoS<sub>2</sub> enhances the alloy's hardness without negatively affecting other mechanical properties. In contrast, the composite with 0% MoS<sub>2</sub> (AA 2024) represents the lowest critical point, displaying the lowest Rockwell hardness number of 63.0 HRN. This baseline provides a reference for evaluating the incremental impact of MoS<sub>2</sub> on alloy hardness, highlighting the substantial improvement in hardness resulting from the reinforcement. These results can be attributed to the strengthening mechanisms imparted by MoS<sub>2</sub> within the aluminum matrix. MoS<sub>2</sub> particles act as effective barriers to dislocation movement, hindering plastic deformation and increasing the material's resistance to indentation. The alloying process of the simple mixing of MoS<sub>2</sub> to uniformity and casting gives a consistent reinforcement to the alloy which results to the improved hard properties in the tested composites. The reinforcement effect decreases at greater MoS<sub>2</sub> concentrations and this may be because of agglomeration or saturation effects, which should explain the minor drop in hardness beyond the optimum 4% MoS<sub>2</sub> composition. The results pinpoint the significance of tight control of reinforcement contents in the composite materials that can readily contribute useful information to the optimization of the alloy compositions which are subsequently involved in an industrial application with special needs of overall mechanical properties and service life.

**Table 6.** Rockwell hardness testing Results of Composites (2024 aluminium alloy + Silicon carbide particles)

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

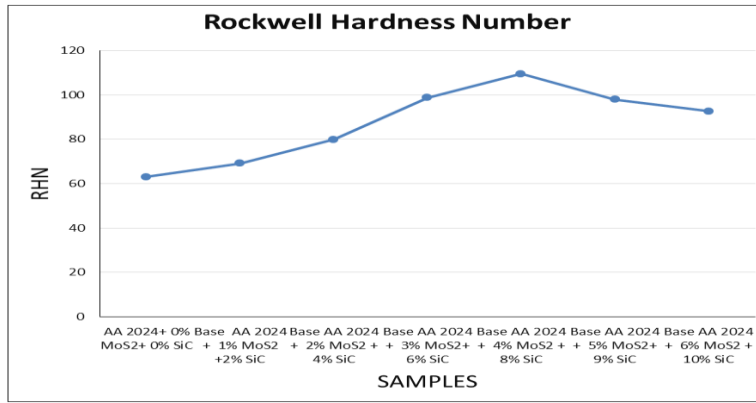


**Figure 3.** Represents Rockwell hardness testing Results of Composites (2024 aluminium alloy + Silicon carbide particles).

The results that are based on Table 6 and Figure 3 indicate that there is gradual increment in Rockwell hardness when the SiC content in the composite is increased. The values of hardness are higher in the base alloy, 63.0 HRN, to the highest value of 69.9 HRN at the range of 10 % SiC. This trend shows that SiC is doing a good job to enhance the alloy in terms of indentation resistance and wear. The steady increase in hardness proves the stability of the composite production process and even distribution of the particles of SiC. These results are critical on how to optimize the alloy combinations to achieve certain industrial requirements including an increase in the mechanical characteristics and wear resistance.

**Table 7.** 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 <sub>2</sub> + 0% SiC	63.0
2	Base AA 2024 + 1% MoS <sub>2</sub> +2% SiC	69.2
3	Base AA 2024 + 2% MoS <sub>2</sub> + 4% SiC	79.9
4	Base AA 2024 + 3% MoS <sub>2</sub> + 6% SiC	98.8
5	Base AA 2024 + 4% MoS <sub>2</sub> + 8% SiC	109.5
6	Base AA 2024 + 5% MoS <sub>2</sub> + 9% SiC	97.9
7	Base AA 2024 + 6% MoS <sub>2</sub> + 10% SiC	92.6

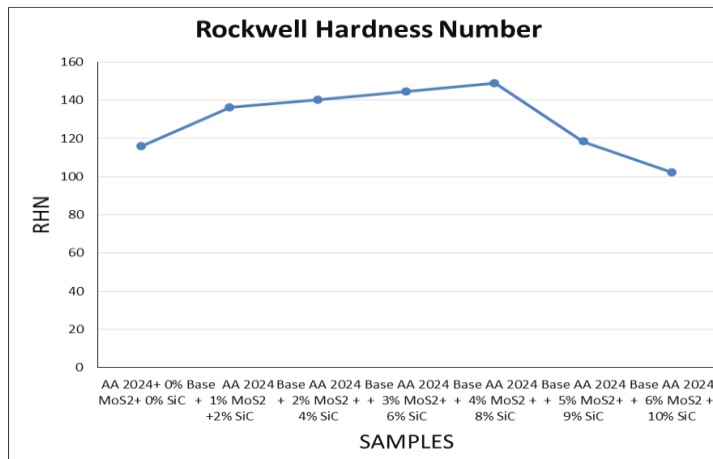


**Figure 4.** Represents Rockwell hardness testing Results of Composites (2024 aluminium alloy + Molybdenum Disulphide + Silicon carbide particles).

The performance in respect to the hardness of the composite as embodied by Table 7 and Figure 4 illustrate the influence of changing compositions of MoS<sub>2</sub> and SiC ratios on the composite. With the increment in the concentration of both MoS<sub>2</sub> and SiC, the value of hardness keeps on increasing to a maximum of 109.5 HRN in the composites whose concentration is 4% MoS<sub>2</sub> and 8% SiC. This shows that the reinforcement is quite successful in terms of strengthening the mechanical strength and wear resistance of the alloy. Nonetheless, in higher concentration of MoS<sub>2</sub> and SiC (5% MoS<sub>2</sub> + 9% SiC and 6% MoS<sub>2</sub> + 10% SiC), they slightly experience a reduction in hardness, which seems to be a saturation effect only or alteration of microstructure. These results demonstrate a great significance of the optimization of composite compositions aimed towards the achievement of the required mechanical characteristics according to the selected industrial application.

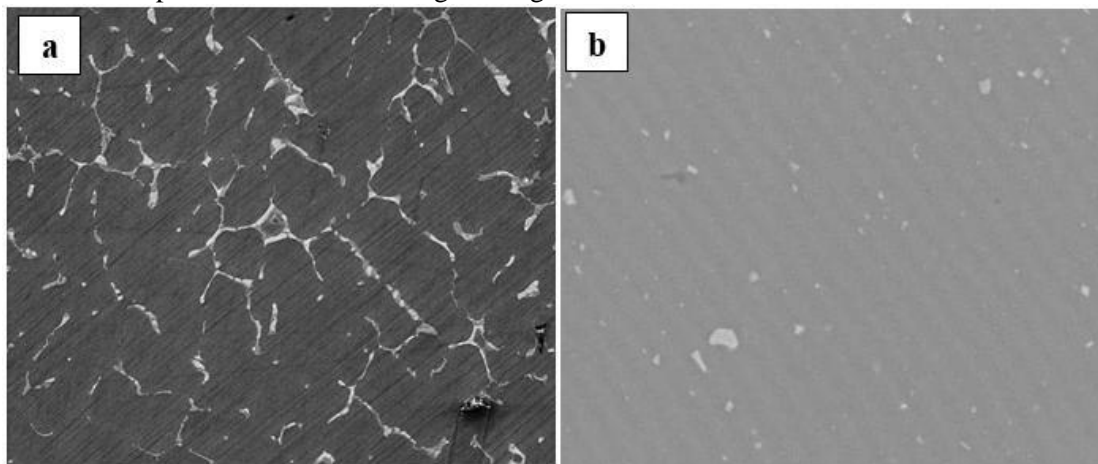
**Table 8.** Rockwell hardness testing Results of Friction stir welded Composites (2024 aluminium alloy + Molybdenum Disulfide+ Silicon carbide particles)

Sl. No.	Friction stir welded Composites (2024 aluminium alloy + Molybdenum Disulfide+ Silicon carbide particles)	Rockwell hardness number
1	AA 2024+ 0% MoS <sub>2</sub> + 0% SiC	116.0
2	Base AA 2024 + 1% MoS <sub>2</sub> + 2% SiC	136.2
3	Base AA 2024 + 2% MoS <sub>2</sub> + 4% SiC	140.1
4	Base AA 2024 + 3% MoS <sub>2</sub> + 6% SiC	144.6
5	Base AA 2024 + 4% MoS <sub>2</sub> + 8% SiC	148.9
6	Base AA 2024 + 5% MoS <sub>2</sub> + 9% SiC	118.3
7	Base AA 2024 + 6% MoS <sub>2</sub> + 10% SiC	102.2



**Figure 5.** Represents Rockwell hardness testing Results of Friction Stir Welded Composites (2024 aluminium alloy + Molybdenum Disulphide + Silicon carbide particles).

From Table 8 and Figure 5, the results demonstrate the effect of varying MoS<sub>2</sub> and SiC percentages on the hardness properties of friction stir welded composites (with FSW process parameters set to tool speed 1000 rpm and feed rate 70 mm/min). The hardness values show a notable increase with higher concentrations of both MoS<sub>2</sub> and SiC, peaking at 148.9 HRN for the composite with 4% MoS<sub>2</sub> and 8% SiC. This suggests effective reinforcement, significantly enhancing the weld joint's mechanical strength and wear resistance. However, at higher concentrations of MoS<sub>2</sub> and SiC (5% MoS<sub>2</sub> + 9% SiC and 6% MoS<sub>2</sub> + 10% SiC), a slight decrease in hardness is observed compared to the optimal composition, which may be attributed to microstructural changes or saturation effects. These findings emphasize the importance of optimizing composite compositions and FSW parameters to achieve the desired mechanical properties in welded joints, which is critical for applications in high-performance industries such as aerospace and automotive engineering.



**Figure 6.** (a) and (b) Shows the SEM images for unweld and Friction stir welded composite specimens.

The microstructure development of the SEM images, as given in Figure 6 (a) and (b), indicates various conditions in which the composites of Al 2024 evolve. Fig 6(a) shows the microstructure of the unwelded Al 2024 composite specimen. No grain change is observed as the specimen has a homogeneous structure with a few grains having bends which shows that the material has been left in its original untreated form. Phase transformations have not been observed and few changes in grain boundaries, as is characteristic of unwelded composites. Figure 6 (b), on the other hand, indicates the microstructure of the same composite after it has been processed under Friction Stir Welding (FSW) using a tool speed of 1000 rpm and a transverse feed of 70 mm/min. The microstructure in the welded zone is also shown in the picture to be very different. Nugget zone of the weld is clear with equiaxed grains surrounding about the weld periphery. However, such transformation represents a phase change promoted by the FSW process during which the heat in addition to the mechanical stirring influences the initial microstructure significantly.

The nature of grain structure refined in the welded zone shows that FSW is a successful method used to refine the grain, which leads to enhanced mechanical properties of a substance. Also, the enhanced metallurgical joining at the region of welding portrays that the FSW process success to generate quality, flawless solutions of welds. The equiaxed grain structure produced in a dynamic recrystallization of FSW process also resulted in the improvement of strength and ductility of the material, easing further the effectivity of the process to alter the microstructural properties of the Al 2024 composites to be industrialized.

### Summary of the discussion

The work examines the impact of Friction Stir Welding (FSW) in the hardness characteristic of 2024 aluminum alloy hybrid composites that are mixed with different proportions of particles of Molybdenum Disulfide (MoS<sub>2</sub>) and Silicon Carbide (SiC). The key issues of the research are:

1. MoS<sub>2</sub> Effect: The hardness of the base composites was greatly improved upon the addition of MoS<sub>2</sub>, giving the greatest value of 93.2 HRN when the content of MoS<sub>2</sub> was 4 pct. Additional to this optimum blend, the increased amount of MoS<sub>2</sub> led to the reduction in hardness, which could be attributed to saturation or agglomeration of the particles.
2. SiC Effect: Likewise, SiC also improved the hardness of the composites as it was observed that as the amount of SiC was increased to the composites, the hardness increased steadily up to 69.9 HRN when 10 % of SiC was added. We thus have the trend indicating that SiC is good at fortifying the alloy enhancing the strength in terms of indentation and wear.
3. Additive Effect of MoS<sub>2</sub> and SiC: In case of addition of both MoS<sub>2</sub> and SiC, the values of hardness kept on increasing and the maximum hardness of 109.5 HRN was recorded at 4% MoS<sub>2</sub> and 8% SiC. Nevertheless, an increase in hardness was found in concentrations in the range of the higher level of MoS<sub>2</sub> to SiC (5% MoS<sub>2</sub> + 9% SiC and 6% MoS<sub>2</sub> + 10% SiC).
4. FSW Process: FSW process also improved the mechanical properties of the composites. An optimum of Rockwell hardness of 148.9 HRN was obtained with an addition of 4 MoS<sub>2</sub> and 8 SiC in the welded composites which means that the hardness tremendously increased as compared to the base composites (116.0 HRN). A reduction in hardness at the higher concentrations of non-determinant MoS<sub>2</sub> and SiC was however recorded, probably caused by effect of the microstructure or saturation effects during FSW.

**Table 9.** Summary Table of Hardness Results.

Sl. No.	Composite Composition	Hardness (HRN)
1	AA 2024 + 0% MoS <sub>2</sub> + 0% SiC	63.0
2	AA 2024 + 1% MoS <sub>2</sub> + 2% SiC	65.4
3	AA 2024 + 2% MoS <sub>2</sub> + 4% SiC	75.3
4	AA 2024 + 3% MoS <sub>2</sub> + 6% SiC	87.1
5	AA 2024 + 4% MoS <sub>2</sub> + 8% SiC	93.2
6	AA 2024 + 5% MoS <sub>2</sub> + 9% SiC	86.6
7	AA 2024 + 6% MoS <sub>2</sub> + 10% SiC	80.2
8	AA 2024 + 0% MoS <sub>2</sub> + 0% SiC (FSW)	116.0
9	AA 2024 + 1% MoS <sub>2</sub> + 2% SiC (FSW)	136.2
10	AA 2024 + 2% MoS <sub>2</sub> + 4% SiC (FSW)	140.1
11	AA 2024 + 3% MoS <sub>2</sub> + 6% SiC (FSW)	144.6
12	AA 2024 + 4% MoS <sub>2</sub> + 8% SiC (FSW)	148.9
13	AA 2024 + 5% MoS <sub>2</sub> + 9% SiC (FSW)	118.3
14	AA 2024 + 6% MoS <sub>2</sub> + 10% SiC (FSW)	102.2

These results confirm that the hybrid reinforcement of MoS<sub>2</sub> and SiC, combined with FSW, significantly enhances the hardness and wear resistance of 2024 aluminum alloys. The findings also underline the importance of optimizing the composite compositions and welding parameters to achieve the desired mechanical properties, crucial for high-performance applications in industries such as aerospace and automotive engineering.

#### 4. CONCLUSION

Summing up the results of the extensive research of Rockwell hardness testing of composite materials and FSW joints used with 2024 aluminum alloy, Molybdenum Disulfide (MoS<sub>2</sub>) and Silicon Carbide (SiC) particles, one can make the following conclusions:

1. The two additives; MoS<sub>2</sub> and SiC work well to increase the hardness values of the 2024 aluminum alloy. The values of hardness that approached the maximum were 109.5 HRN on composite and 148.9 HRN the FSW joint that indicated significant mechanical strength and wear resistance.
2. The given study determines the most favorable compositions, which include 4% MoS<sub>2</sub> and 8% SiC in case of maximum hardness in both composite and welded structures. This shows that there is a synergistic effect between MoS<sub>2</sub> and the SiC in strengthening the alloy matrix which is employed in application that requires a high performance in mechanics.
3. The mechanical properties of the composites produced through friction stir welding are much higher than those produced in the conventional forms of material. The consolidation process would solidify the material structure in an effective manner which would have increased the values of hardness and better integration of joints.
4. In addition to optimum mixtures, an increase in the concentration of MoS<sub>2</sub> and SiC witnessed a marginal reduction in the hardness. This implies possible saturation effects or microstructural alterations and therefore there is great need to balance additives in order to sustain the desired mechanical characteristics.
5. The implications of the findings with respect to such industries as aerospace and automotive also cannot be overemphasized where materials that possess superior mechanical properties are of high priority. Effective optimization of composite compositions and welding parameters may allow manufacturers to configure adapted materials to suit their particular application preferences, allowing them to maintain reliability and performance in hostile environments.

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