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Optimisation of Friction Stir Welding Process Parameters to Enhance the Mechanical Properties in Stir Casting of Metal Matrix Composites (MMC)

G. Subhash[1], M. V. R. D. Prasad[1], M. Venkata Ramana[2]*, and B. V. R. Ravi Kumar[1]

[1]Department of Mechanical Engineering, VNR Vignana Jyothi Institute of Engineering and Technology, Hyderabad - 500090, Telangana, India

[2]Department of Automobile Engineering, VNR Vignana Jyothi Institute of Engineering and Technology, Hyderabad - 500090, Telangana, India; mandalavenki@gmail.com

Abstract

The present investigation is to improve the mechanical properties of Aluminium Metal Matrix Composites (AMCs) made of AA7075-T6 reinforced with Silicon Carbide (SiC) particles by optimising the Friction Stir Welding (FSW) process parameters. A range of SiC contents (3%, 5%, 7%, and 9%) was used in the stir casting process to create composites. Hexagonal and threaded hexagonal tool geometries were used in the FSW process. Axial force, traverse speed, tool rotating speed, and reinforcing percentage are the process parameters selected, and experiments were performed as per Taguchi's L16 orthogonal array design. Tensile and Charpy impact tests were conducted to assess mechanical properties. Using Energy-Dispersive X-Ray Spectroscopy (EDS) and Scanning Electron Microscopy (SEM), microstructural characterisation was performed to investigate bonding and particle distribution. According to the investigation, the threaded hexagonal tool performed noticeably better than the plain hexagonal tool in terms of particle dispersion and tensile strength. The maximum tensile strength of 163.15 N/mm^2 was obtained with the combination of 5% SiC reinforcement, 1100 rpm rotational speed, 30 mm/min traverse speed, and 850 kg axial force. The tool rotational speed and traverse speed contributed 40.59% and 31.17% respectively to maximise the tensile strength according to statistical analysis using ANOVA. The R^2 values are above 94%, and regression modelling confirmed that the selected factors are in good predictive capacity. Improved mechanical behaviour was a result of microstructural analyses that verified uniform SiC dispersion and reduced flaws under optimal process parameter conditions. The mechanical integrity of AA7075/SiC composites is considerably improved by efficient parameter optimisation in FSW. These results contribute to potential uses in the automobile and aerospace sectors.

Major Findings: *This study investigated the effects of hexagonal and threaded hexagonal tools on tensile strength and Charpy impact resistance while optimising friction stir welding parameters for AA7075-T6 aluminium alloy reinforced with Silicon Carbide. In comparison to the hexagonal tool, the threaded hexagonal tool demonstrated better material flow and a higher tensile strength.*

Keywords: *7075 Aluminium Alloy, Friction Stir Welding (FSW), Metal Matrix Composites, Silicon Carbide (SIC), Stir Casting, Taguchi Optimisation Technique*

1.0 Introduction

Friction Stir Welding (FSW) is a solid-state welding technique that joins the two workpieces without melting the material by using a non-consumable spinning tool. The rotating tool is moved along the weld path after being plunged into the joint line between the materials. The material can be mechanically combined and forged

*Author for correspondence

together under pressure because the heat produced by the friction between the tool and the workpieces softens the material. FSW eliminates common flaws like porosity, cracking, and deformation that are linked to conventional fusion welding techniques because it does not involve melting. This method works especially well for combining lightweight materials like magnesium and aluminium alloys, which makes it ideal for use in the shipbuilding, automotive, and aerospace sectors. High joint strength, superior metallurgical qualities, and environmental friendliness, because it doesn't include filler or shielding gases, are some of its benefits.

The effects of a hybrid pin-profiled tool on friction stir welding of thick AA2219-T6 aluminium alloy to address the problem of lower joint strength caused by precipitate dissolving. The hybrid tool›s conical threading and triangular cross-section improved mechanical properties and enabled seven times faster welding than conventional tools. Thermo-Mechanically Affected Zone (TMAZ) softening was reduced by minimising θ-particle aggregation and exposing smaller grains in the lower nugget zone, according to microstructure analysis. The investigation looked at the welds' mechanical performance and found that, in comparison to the conical threaded tool, the hybrid tool produced stronger and tougher welds. According to the findings, the hybrid tool may enhance the welding performance and optimise the weld strength[1]. Friction stir welding of different magnesium alloys (AZ91) and aluminium alloys (AA6061-T6) with TiC nanoparticles, examining wear behaviour, mechanical characteristics, and microstructure evolution. The best joining conditions were found at 850 rpm and 50 mm/min, which produced the highest tensile strength (168 MPa), ductility (1.25 %), and hardness (241 HV). Through dynamic recrystallisation and the pinning effect, the TiC particles were crucial in changing the microstructure. By analysing the weld properties, it was noticed that the optimised weld with its uniform particle distribution and refined grain size, had the lowest wear volume loss and friction coefficient. The study highlighted how important stir action and heat input are in determining the properties of the interfacial zone[2]. The aluminium matrix reinforced with brass in the nugget zone during Friction Stir Welding (FSW). This work focused on creating a novel model of mechanical properties based on microstructure to forecast mechanical and microstructural changes. Due to the pinning action of fractured brass particles, the results of the analysis indicated that the addition of brass enhanced the hardness by 10 HV and decreased average grain size by 34.8 %. It was discovered that the ideal welding parameters were a traverse speed of 25 mm/min, a rotation speed of 1000 rpm, and a brass thickness of 0.1 mm produced a yield strength of 243.6 MPa[3].

To predict the Ultimate Tensile Strength (UTS) of various AA7075 and AA5083 joints fused using friction stir welding. The study was supervised with machine learning regression models. Using data from 20 experimental runs, the study was evaluated with Machine Learning (ML) algorithms, with the Decision Tree (DT) model demonstrating the highest accuracy (R^2 = 0.97, MAE = 14.75, MSE = 408.63). The results showed that ML models can optimise welding process parameters, improving quality and efficiency. Even with a small dataset, the study showed how Machine Learning (ML) can lessen the need for physical trials while still producing accurate UTS predictions[4]. Friction Stir Welding (FSW) of Al 4.5%Cu/TiC in situ metal matrix composites using a hardened bimetallic tool with various shoulder shapes. This study examined the influence of tool geometry on grain refinement, reinforcement redistribution, and weld strength. X-ray diffraction confirmed the creation of $CuAlO_4$ and $CuAl_2$ in the stir zone, whereas fractography investigated the ductile fracture character. The study's investigation into welding parameter optimisation produced an 89% weld strength improvement when compared to the base material, proving the effectiveness of the process[5]. Utilising a pin-on-disc tribometer, the wear properties of hybrid composites based on Al-4032 reinforced with SiC and Granite Marble Powder (GMP) were examined. This study examined how reinforcing affected wear resistance and found that it improved up to 6% but thereafter declined because of particle aggregation.

Analysis of Variance (ANOVA), which looked at the contributing elements, revealed that composition had the biggest impact on wear behaviour. Normal load, sliding speed, and sliding time were next in line. SEM examination of abrasive wear mechanisms showed scratches and grooves on worn surfaces[6]. The impact of tool pin profile orientation and process variables on the mechanical characteristics of friction stir-welded AA6082-AA5083 joints was studied. This study also investigated the effects of hybrid tool pin profiles that yielded Ultimate Tensile Strengths (UTS) ranging from 160.05 MPa to 213.46

MPa, which were higher than those of conventional profiles. The ideal welding parameters were determined to be 1200 RPM, 8 kN force, and 60 mm/min speed. Weld efficiency was also examined in the study. The hybrid tool pin achieved up to 75.16%[7].

To optimise the process variables for friction, stir welding of rutile-reinforced AA 6061 matrix composites, a Taguchi L27 orthogonal design was used in this study. This study examined how important variables such as tool tilt angle, axial force, and rotational speed affect mechanical characteristics. Improvements in tensile strength, impact strength, and hardness were the main emphasis of the results; the ideal values were found to be 1400 rpm, 2-degree tilt, and 3 kN axial force. Investigating the effects of these parameters revealed that rotational speed and tilt angle significantly affected mechanical properties. The microstructures were examined using Scanning Electron Microscopy (SEM) to confirm the efficacy of the chosen welding conditions[8]. The mechanical properties of hybrid composite laminates reinforced with stainless steel wire mesh, glass fibres, perforated aluminium, and aluminium sheets, highlighting their suitability for structural components in aeroplanes. This study examined the hybrid composite's performance concerning Carbon Fibre-Reinforced Plastics (CFRP) and found that lower compressive and tensile strength, it significantly reduced weight and increased flexural strength. The study concentrated on the impact of reinforcing materials by investigating mechanical behaviour through experimental tests, such as tensile, compressive, and flexural evaluations. The findings examined the effects of stainless-steel wire mesh and perforated aluminium, showing an increase in load-bearing capability and emphasising the necessity for more study into sophisticated reinforcement methods[9].

The application of a novel double-sided welding technique for polypropylene Friction Stir Welding (FSW) was analysed. This study concentrated on how, in contrast to single-sided welding, this method greatly improves the mechanical characteristics of welded connections. Double-sided welding creates welds with uniform material flow while lowering torque and tensions, according to research on the impact of tool rotation speed on joint formation. The FTIR examination investigated the chemical composition and confirmed that the double-sided welds were identical to the base material. The study also looked at tensile and flexural strength, which were significantly higher than those of single-side welded connections. The outcomes showed that the double-sided FSW approach enhances polypropylene weld performance and quality[10]. The mechanical properties and interfacial microstructure of Friction Stir Lap Welded (FSLW) joints of dissimilar Al/Mg alloys were examined in this study concerning three different pin-tip profiles, such as cylinder (C-tool), square (S-tool), and triangular (T-tool). The findings indicate that the interface qualities are significantly influenced by the pin-tip profile. The S-tool's unique eutectic structure allows it to produce a maximum tensile-shearing load of 5.95 kN. By revealing distinct microstructures formed at the contact, the study highlights the advantages of using specific pin-tip designs to optimise the mechanical performance of welded connections[11].

Friction Stir Processing (FSP) to maximise welding strength and characterisation of hybrid composites with an aluminium alloy matrix, specifically AA8014 reinforced with Titanium Diboride (TiB_2) and zirconium dioxide (ZrO_2) particles. This study examined how the tensile strength of the welded structures was affected by four important process variables, such as the amount of reinforcement, tool speed, traverse speed, and axial force. The results revealed that with an axial force of 3 kN, a traverse speed of 40 mm/min, a tool speed of 1400 rpm, and an 8% reinforcing level obtained the tensile strength of 268 MPa was obtained. The study looked at how these factors improved mechanical performance and strengthened hybrid composites[12]. The researchers used the Taguchi method and regression analysis to investigate how the tool geometry, welding speed, and rotating speed affected the tensile strength, percentage elongation, and hardness on friction stir welding (FSW) parameters for aluminium alloy AA6061. Welding speed had a major impact on tensile strength (58.39 % contribution), while tool geometry had the most impact on hardness (50.1 % contribution). The study looked at the best welding circumstances and identified that the square pin profile with a tensile strength of 192.58 MPa had the highest strength[13].

To satisfy industrial demands for lightweight materials with exceptional hardness and thermal conductivity, several researchers have looked into the creation of Al7039/Cu/SiC metal matrix composites. In one investigation, 20 experimental runs were used to optimise the composition using Response Surface Methodology and analyse the impact of changing the Al7039, Cu, and

SiC content. With a thermal conductivity of 169.6 W/m·K and a hardness of 190.4 BHN, the results demonstrated a notable improvement in properties. These results highlight the composite's potential for cutting-edge uses in the automotive, thermal management, and aerospace industries[14].

Aluminium Metal Matrix Composites (AMMCs) are extensively utilised in the aerospace, marine, and automotive sectors because of their exceptional corrosion resistance and strength-to-weight ratio. In order to better understand how different SiC reinforcement levels (0%, 3.5%, and 7.0%) affected the mechanical and wear characteristics of Al matrices, researchers used stir casting. A higher SiC concentration was shown to improve hardness, tensile strength, and wear resistance; nevertheless, microstructures showed non-uniform particle dispersion and porosity[15].

This study uses a two-stage stir casting process to examine LM-4 Aluminium alloy composites reinforced with 0–12 % titanium carbide (TiC). As the TiC content increased, the mechanical and tribological qualities such as tensile strength, hardness, and wear resistance improved noticeably. The study looked at the effects of TiC reinforcement on density, porosity, and fracture behaviour. The best results were found at 9 % TiC, which increased hardness by 46.4% and tensile strength by 37.5%. In addition to analysing the microstructural and wear surface characteristics under varied loading and speed circumstances, SEM and EDS tests verified uniform TiC particle dispersion. The results also showed that higher TiC levels improved wear resistance, indicating a stronger load-bearing capability, even though they slightly increased porosity. Overall, the LM-4/TiC composites show strong potential for optimised use in high-strength and wear-critical engineering applications[16]. This work examined the fracture toughness behaviour of stir-cast hybrid composites made of AA7075 reinforced with alumina and silicon carbide. Using Taguchi's Design of Experiments and ANOVA, the work concentrated on improving important process factors such as specimen thickness, reinforcing composition, and crack length-to-width (a/W) ratio. It was shown that fracture toughness was considerably increased by 6 weight per cent reinforcement, 12 mm thickness, and an a/W ratio of 0.45. The most significant element, accounting for 94% of the total variation, was determined to be the a/w ratio. The improved parameters were validated by finite element simulations, which confirmed the experimental results with an error of less than 12%. The optimised composite demonstrated better mechanical performance overall, outperforming alternative reinforcement combinations[17].

Based on the literature and to maximize mechanical performance of AA7075-T6 aluminum metal matrix composites led to the selection of SiC reinforcement ranges (3%, 5%, 7%, and 9%). The study was able to evaluate how well it enhances the tensile strength and the possibility of particle clustering or flaws was balanced by these percentages. 5% SiC produced the best results; however, larger percentages resulted in weaker dispersion and decreased strength. Additionally, this range was useful for industrial applications such as the automotive and aerospace industries and appropriate for Taguchi-based optimisation. The Taguchi technique is used in this study to optimise the welding variables of the AA7075/SiC Metal Matrix Composites (MMC) on tensile strength while taking tool rotational speed, RS, RM, TTS, and L into account. The objective of the investigation is to examine the microstructure in the weld area. Additionally, ANOVA is utilised to construct the statistical correlations between the designated ranges of components and to assess the contributions of FSW factors in improving the Tensile Strength weld.

2.0 Experimentation

2.1 Materials

Aluminium alloy 7075, also referred to as AA 7075, is a high-strength, aerospace-grade aluminium alloy. AA7075 is a strong and versatile aluminium alloy that is widely used in demanding applications in a variety of industries. Because of its remarkable strength and lightweight properties, it is the ideal choice for a variety of industries, including sports equipment, automotive, aerospace, and others. The chemical composition of Aluminum alloy 7075 is shown in Table 1.

SiC is a highly adaptable material with exceptional chemical and physical characteristics. Its hardness and heat conductivity make it ideal for high demand. Despite its higher cost and manufacturing challenges, SiC is a valuable material for advanced technologies, particularly in high-power and high-temperature applications. To maximize mechanical performance of AA7075-T6 aluminum metal matrix composites led to the selection of SiC reinforcement ranges (3%, 5%, 7%, and 9%). The

Table 1. Chemical composition of Aluminium alloy 7075

Element	Composition
Zn	5.65
Mg	2.55
Cu	1.52
Cr	0.16
Si	0.18
Mn	0.11
Fe	0.21
Al	Remainder

study was able to evaluate how the tensile strength and the possibility of particle clustering or flaws were balanced by these percentages.

2.2 Fabrication of Metal Matrix Composites

In this work, the stir casting is used to fabricate Metal Matrix Composites (MMCs) based on AA7075 reinforced with Silicon Carbide (SIC) particles in different weight percentages of 3%, 5%, 7%, and 9%. After heating AA7075 to around 720°C to a molten state, SiC particles were added progressively to the melt while stirring to guarantee even dispersion. To minimise oxidation effect, the stirring process is performed under a controlled environment with argon inert gas, covering the molten metal with fluxes to keep it from coming into direct contact with air, and using appropriate ladling techniques to minimise oxidation and turbulence.

After that, the molten composite was placed into a 200 × 150 × 5 mm heated mould to create composite plates. Plates were cast for each percentage of reinforcement with producing two identical sets.

2.3 Preparation of Friction Stir Welding Tools

The hexagonal tool is made with H13 tool steel and is precisely crafted to satisfy both functional and dimensional criteria. For the purpose of controlling material flow and heat generation, it features a shank(collar) of 55 mm long and 15 mm in diameter, a shoulder of 5 mm long and 20 mm in diameter, and a shoulder of 15 mm long and 18 mm in diameter. A pin of 4.7 mm long, 5 mm in diameter, in hexagonal profile is shown in Figure 1. The hexagonal with threaded tool is a hybrid tool having High-quality materials, providing durability, wear resistance,



Figure 1. Hexagonal tool.

and high-temperature performance. The 55 mm long, 15 mm diameter shank (collar), 5 mm long, 20 mm diameter shoulder, and 15 mm long, 18 mm diameter shoulder are all precisely machined. For precision and smooth transitions, the pin is expertly made with a 2.3 mm hexagonal profile and a 2.3 mm threaded portion with 0.3 mm pitch. The hexagonal and threaded hexagonal tools were the particular focus of this investigation because of their demonstrated ability to improve material flow, heat generation, and particle dispersion during the Friction Stir Welding (FSW) process.

2.4 Performing Friction Stir Welding On MMC

Friction Stir Welding (FSW) is a solid-state joining method that uses a non-consumable tool to fuse two

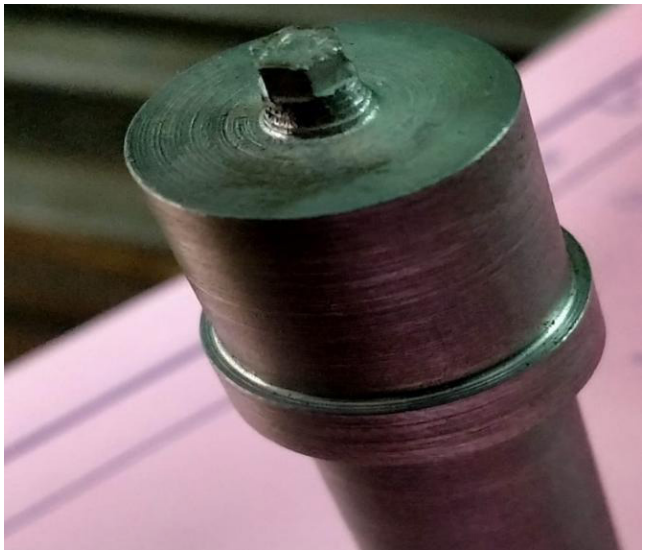


Figure 2. Threaded with hexagonal tool.

faces of the workpieces without melting. The FSW equipment used in this work is shown in Figure 3. FSW was performed on the fabricated MMCs using a hexagonal tool and threaded with a hexagonal tool. The welding experiments were conducted as per the experimental design and Input process parameters used in FSW given in Table 2. The levels for each parameter - axial force (700 to 850 kg), traverse speed (30 to 60 mm/min), tool rotational speed (900 to 1500 rpm), and SIC reinforcement (3%, 5%, 7%, and 9%) were chosen based on literature, workpiece and tool material properties as well as pilot experiments data. The specifications of FSW are given in Table 3. The experiments are performed using hexagonal and thread hexagonal tools as per the experiment data shown in Table 4. The tools were designed with a hexagonal pin tool and threaded with a hexagonal pin for effective material flow and heat generation. The experiment is conducted as per L16 orthogonal experimental design as given in Table 4. The welded specimens are shown in Figures 4 and 5. The tensile and impact strength specimens are prepared using Wire EDM as per the dimensions given in Figures 6 and 7. FSW welded specimens for tensile strength and impact test are prepared as per the dimensions of ASTM E8M-04 and ASTM D256 standards, respectively, shown in Figure 6 and Figure 7. FSW welded specimens for tensile strength are shown in Figures 8 and 9. FSW welded specimens for impact test specimens are shown in Figures 10 and 11. Experimental summary of tensile strength and Charpy impact results is given in Table 4.

Table 2. Input process parameters

Factors	Level-1	Level-2	Level-3	Level-4
Reinforcement %	3	5	7	9
Tool Speed (rpm)	900	1100	1300	1500
Traverse Speed (mm/min)	30	40	50	60
Axial Force (kg)	700	750	800	850

Table 3. Specifications of FSW machine

Elements	Range
Z axis load	10kN
Spindle nose	ISO 40
Spindle speed	300 to 3000 rpm
Z axis travel (vertical)	300 mm
Z axis velocity max.	1000 mm/min
X axis travel (longitudinal)	300 mm
X axis velocity max	3000 mm/min
Y axis travel	50/100 mm (manual)
Head tilt angle	+ (or) – 5 degrees (manual)

Impact strength, particularly with the hexagonal tool observed 2 Joules and it is consistent under most circumstances, indicates that SIC has little effect on toughness. At 9% SIC, 1300 rpm, 40 mm/min traverse speed, and 850 kg axial force, the threaded hexagonal tool produced the axial force, the threaded hexagonal tool produced the maximum impact strength of 6 Joules. SIC reinforcement increases tensile strength but not impact toughness.

In this investigation, the proportion of SiC particles had a direct impact on the AA7075 composites' tensile and impact strengths. Due to enhanced particle matrix bonding, improved load transfer, and grain refinement, tensile strength increased with SiC addition up to 5%. Particle agglomeration and poor dispersion resulted above 5%, which resulted in microstructural flaws and decreased strength. However, because the toughness of the material is limited by brittle SiC particles, impact strength varied very little and remained almost constant, particularly when using the hexagonal tool.

This indicates that the modest percentage of SiC increases tensile strength but has little effect on impact



Figure 3. Friction Stir Welding set up.

resistance since ceramic reinforcements are inherently brittle.

The levels for each parameter axial force (700 to 850 kg), traverse speed (30 to 60 mm/min), tool rotational speed (900 to 1500 rpm), and SiC reinforcement (3%, 5%, 7%, and 9%) were chosen based on literature, workpiece and tool material properties as well as pilot experiments data to provide a wide but feasible range for Friction Stir Welding of AA7075/SiC composites. In order to observe the effects of both lower and higher extremes on material flow, heat generation, and mechanical properties, these values were selected. Finding the ideal conditions for higher tensile strength and reducing flaws was made possible by the ranges that were chosen because they

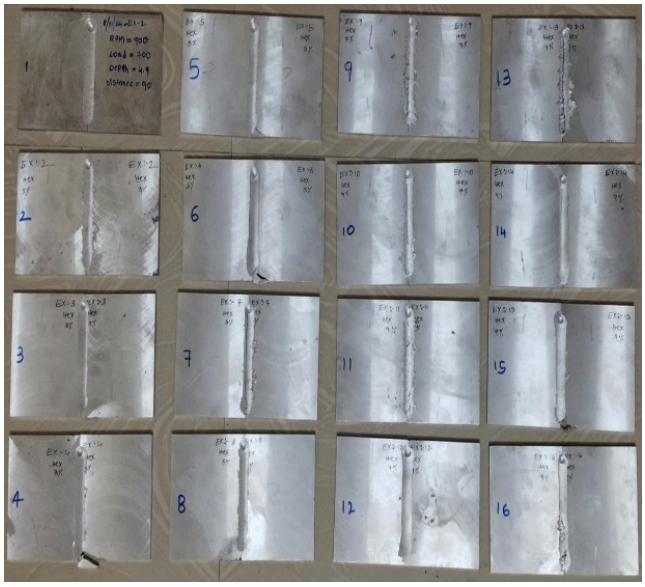


Figure 4. Welded Metals MMC with hexagonal tool specimen.



Figure 5. Welded metals MMC with threaded hexagonal tool specimen.

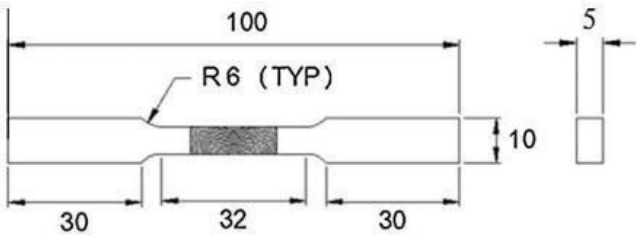


Figure 6. ASTM E8M-04 standards.

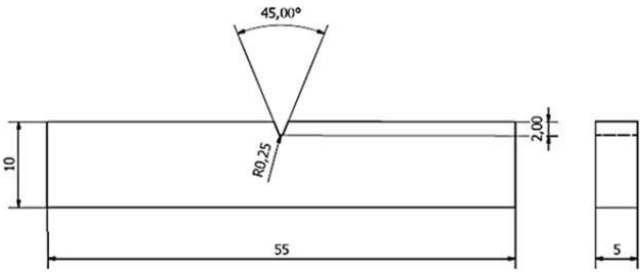


Figure 7. ASTM D256 standards.



Figure 8. Welded MMC with Hexagonal tool for tensile strength.

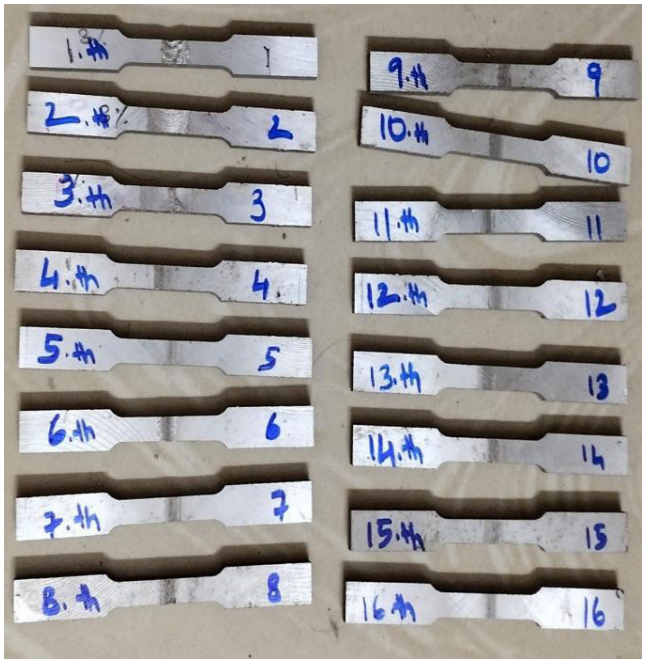


Figure 9. Welded MMC with Threaded hexagonal tool for tensile strength.

ensure efficient material mixing without resulting in tool wear or excessive heat input. To minimise oxidation effect, the stirring process is performed under a controlled

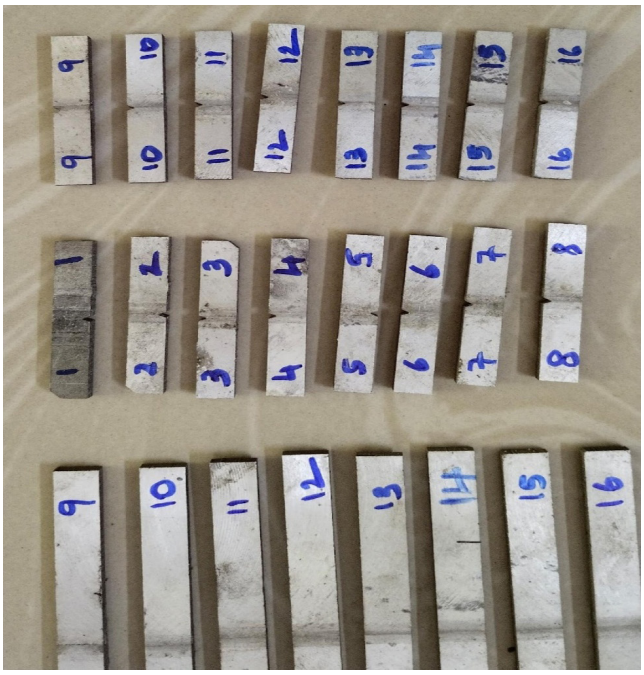


Figure 10. Welded MMC with hexagonal tool for impact strength.

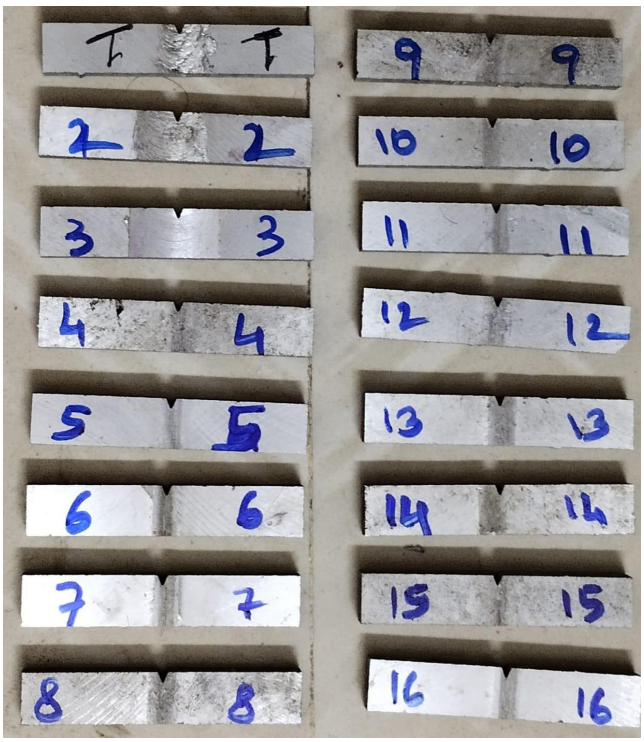


Figure 11. Welded MMC with Threaded hexagonal tool for impact strength.

environment (e.g., with inert gases like nitrogen or argon), covering the molten metal with fluxes to keep it from coming into direct contact with air, and using

Table 4. Experimental summary of tensile strength and Charpy impact results

Experiment No	Reinforcement %	Tool Speed (rpm)	Traverse Speed (mm/min)	Axial force(kg)	Tensile strength (N/mm²)	
					hexagonal tool	threaded with a hexagonal tool
1	3	900	30	700	48.10	43.57
2	3	1100	40	750	53.51	125.77
3	3	1300	50	800	60.77	79.37
4	3	1500	60	850	41.30	92.37
5	5	900	40	800	71.19	100.44
6	5	1100	30	850	101.90	163.15
7	5	1300	60	700	34.32	52.91
8	5	1500	50	750	97.98	111.15
9	7	900	50	850	43.31	98.26
10	7	1100	60	800	48.87	47.74
11	7	1300	30	750	66.92	50.29
12	7	1500	40	700	90.36	102.69
13	9	900	60	750	30.12	40.92
14	9	1100	50	700	40.180	106.751
15	9	1300	40	850	79.42	119.00
16	9	1500	30	800	50.01	99.43

appropriate ladling techniques to minimise oxidation and turbulence.

2.5 Optimization Methodology

The L16 orthogonal design has four levels and four factors are used for the experiment as given in Table 2. Tool speed, traverse speed, and axial force are the regulated parameters of FSW for welding. Variation of SiC particle percent such as 3%, 5%,7% and 9% is another process parameter. Based on the experiment results of the Taguchi technique, the means of mean analysis is carried out for performance characteristics. Taguchi's method is the most straightforward and methodical approach to optimize the process parameters. It is utilized to achieve good performance design, low cost, and high quality with satisfactory outcomes. The output parameters like tensile strength were analysed. The objective of this paper is to optimize the process parameters and maximize the tensile strength and the study of the impact strength of the prepared different composites with variation in percentage of SiC. The "larger-the-better" criterion is selected to maximize the response for tensile strength.

In this study, Taguchi's Design of Experiments (DOE) and regression analysis were used to optimize the FSW parameters. The performance characteristic is chosen in this study is tensile strength, this has to be maximized. Therefore, "higher the better" type quality characteristic has been chosen for this response. This characteristic is given in Equation (1)

$$\text{Higher the better} = -10^{*} \log(\Sigma(1/Y^{2}) / n) \quad (1)$$

Four factors were carefully studied at four levels each: axial force, tool rotating speed, traverse speed, and SiC reinforcement percentage, using a Taguchi L16 orthogonal array. In order to predict the tensile strength as a function of linear, quadratic, and interaction terms of these parameters, mathematical models were developed using multiple regression equations for both hexagonal and threaded hexagonal tools (Table 4).

3.0 Results and Discussions

The means of mean is applied to find the optimum process parameter for Tensile Strength (TS) under the "larger-the-better" condition. Reinforcement per

cent of SiC (RM), Tool Speed (RS), Traverse Speed (TTS), and Axial Force (L) influence tensile strength. Therefore, proper selection of these parameters improves tensile strength, product quality and reduces production costs.

3.1 Optimisation of Process Parameters using Hexagonal Tool

The means of the mean plot with the hexagonal tool are shown in Figure 12. The optimal parameters are 5% RM, 1300 rpm RS, 30 mm/min TTS, and 850 N. The Reinforcement Percentage (RM), the tensile strength is high at 5%, indicating a significant improvement over 3% and 7%, and 9%. This suggests that the mechanical performance of the composite is improved by a moderate quantity of reinforcement of SiC particles' ideal distribution and bonding inside the matrix. The tensile strength rises with an increase in rotational speed up to 1300 rpm, then declines at 1500 rpm as seen in the main effects plot shown in Figure. 12. This implies that excessive heat production at faster rates could have a detrimental effect on the quality of the weld and material consolidation. Tool traverse speed also exhibits a non-linear trend, with the response maximum at 30 mm/min, progressively declining at 40 and 50 mm/min, and sharply increasing at 60 mm/min. This suggests that lower traverse speeds improve material consolidation and joint strength because they require more heat input and stirring time. The tensile strength is high axial load of 850 N An increasing trend is seen from 750 N to 850 N, indicating that larger axial forces enhance material consolidation and *forging* in the weld zone. These results demonstrate how important it is to balance heat input, material flow, and pressure to produce high-strength friction stir welds with defects.

3.2 Optimisation of Process Parameters Using Hexagonal with Threaded Tool

The means of the mean plot using a hexagonal with threaded tool is shown in Figure 13. The optimal parameters are 7% RM, 1100 rpm RS, 40 mm/min TTS, and 850 N. The percentage of reinforcement has a nonlinear effect on the tensile strength; the tensile strength is maximum at 5% RM, which denotes the ideal distribution of reinforcement particles in the matrix at this level. Particle agglomeration or inadequate reinforcing are probably the causes of the decreased strengths at both lower and higher percentages (3% and 7%). Due to enhanced particle matrix bonding, improved load transfer, and grain refinement, tensile strength increased with SiC addition up to 5%. Particle agglomeration and poor dispersion resulted in above 5%, which resulted in microstructural flaws and decreased strength. Tensile strength increased from 900 rpm to 1100 rpm, then decreased from 1100 rpm to 1300 rpm, then increased from 1300 rpm to 1500 rpm of rotational speed. This implies that the best heat generation and stirring action is appropriate for material consolidation at 1100 rpm. Defects or poor bonding may result from too high or too low heat applied at greater or lower speeds, respectively. The tensile strength rises with tool traverse speed from 30 mm/min to 40 mm/min, then

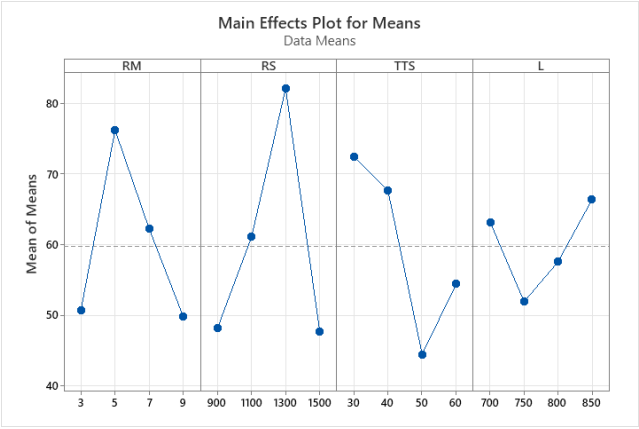


Figure 12. Main effects plot for tensile strength using hexagonal tool.

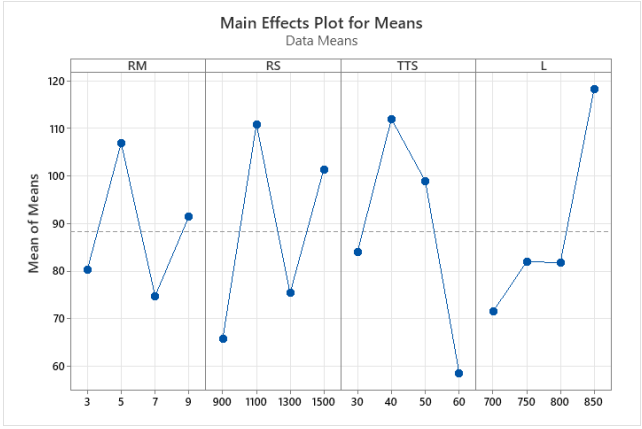


Figure 13. Main effects plot for tensile strength using a hexagonal with threaded tool.

declines slightly from 40 mm/min to 60 mm/min. The weld quality is improved at lower to moderate traverse speeds, which creates better material consolidation and sufficient heat input. Higher speeds result in inadequate bonding time and weaker welds. Axial load is applied, the response increases sharply and peaks at 850 N, suggesting that greater axial forces enhance material consolidation and remove voids in the weld zone. Research results demonstrate that the most important factors in obtaining increased tensile strength in friction stir welded joints are the tool traverse speed, rotating speed, and axial load. The optimal parameters offer the ideal ratio of heat input, material flow, and mechanical consolidation required to create welds with high strength.

3.3 Influence of Process Parameters on Tensile Strength using Hexagonal Tool

The Analysis of Variance (ANOVA) offers important information on the way process parameters affect the observed response in friction stir welding. The Axial Load (L) accounts for 6.29% of the total variation, Tool Traverse Speed (TTS) for 25.20%, Reinforcement Percentage (RM) for 23.75%, and rotational speed. (RS) for 40.59% influenced the tensile strength. The model efficiency is evidenced by the low residual error of 4.16 %. The effects of FSW parameters on tensile strength are given in Table 5.

3.4 Influence of Process Parameters on Tensile Strength using Hexagonal with Threaded Tool

The Analysis of Variance (ANOVA) indicates the influence of the friction stir welding process parameters on the tensile strength. According to the ANOVA results, Tool Traverse Speed (TTS) was the largest contributor to the overall variation in the response (31.17%), closely followed by Axial Load (L) (24.8%), Rotational Speed (RS) (26.71%), and Reinforcement Percentage (RM) (11.94%). The fitted model was found to be adequate and reliable, as evidenced by the experimental error accounting for 5.32%. The effects of FSW parameters on tensile strength are given in Table 6.

Table 5. Influence of FSW parameters on tensile strength using ANOVA with hexagonal tool

Process Parameters	DF	Adj SS	Adj MS	F-Value	P-Value	% of contribution
RM	3	3650.7	1216.8	36.18	0.000	23.747
RS	3	6241.1	2080.3	61.85	0.000	40.59
TTS	3	3874.0	1291.3	38.39	0.000	25.20
L	3	968.1	322.71	9.59	0.000	6.297
Error	19	639.0	33.63			4.156
Lack-of-Fit	3	637.4	212.46	2031.51	0.000	4.146
Pure Error	16	1.7	0.10			0.011
Total	31	15372.9				100

Table 6. Influence of FSW parameters on tensile strength using ANOVA with threaded hexagonal tool

Process Parameters	DF	Adj SS	Adj MS	F-Value	P-Value	% of contribution
RM	3	4839.8	1613.2	14.22	0.000	11.941
RS	3	10827.1	3609.0	31.81	0.000	26.71
TTS	3	12634.9	4211.6	37.13	0.000	31.174
L	3	10072.5	3357.5	29.60	0.000	24.852
Error	19	2155.4	113.44			5.318
Lack-of-Fit	3	2155.4	718.47	6298884	0.000	5.318
Pure Error	16	0.0	0.00			
Total	31	40529.8				100

3.5 Mathematical Model for Tensile Strength with Hexagonal Tool

The regression analysis is used to determine the nature and strength of the relationship between a dependent variable and one or more independent variables. Conversely, broader mathematical models can depict and evaluate complicated events that transcend simple relationships using simulations, optimisation frameworks, or systems of equations. The mathematical model developed for tensile strength using a hexagonal tool is given in Equation (2)

$$TS = 19.0\,RM + 0.881\,RS + 1.70\,TTS - 1.292\,L - 0.89\,RM * RM - 0.000235\,RS * RS + 0.0603\,TTS * TTS + 0.001351\,L * L - 0.0087\,RM * RS - 0.412\,RM * TTS + 0.0255\,RM * L + 0.00162\,RS * TTS - 0.000469\,RS * L - 0.00979\,TTS * L \quad (2)$$

The average departure is indicated by the Standard Deviation (S) from the fitted regression line, which is 11.4521. The R^2 value demonstrates the accuracy of the prediction. The R^2 obtained for the regression model for tensile strength is 98.18% variable. While the Predicted R^2 indicates how well the model predicts fresh data is 94.34%, the adjusted R^2 takes into account the number of predictors. The adjusted R^2 is 96.76% the ideal number. The value indicates that the prediction accuracy is higher.

The Regression fitted line plot displays a good correlation between the predicted and actual values, illuminating the relationship between predicted tensile strength and experimental tensile strength. The fitted line plot is shown in Figure 14. Tensile strength prediction accuracy is shown by the regression line, with data points closely following the trend.

Indicating the average of the data points from the fitted regression line, the standard deviation (S) is 4.61536. The R^2 of 95.8%, the model is highly accurate. The evaluation of the model's performance is provided by the Adjusted R^2 is 95.7% and considers the number of predictors.

The standard deviation (4.61536) is the lowest value, indicating that the model has little error. The model's great predictive power is demonstrated by the highest R^2 value of 95.8%. The Adjusted R^2 (95.7%) is the ideal number since it strikes a compromise between model complexity and accuracy.

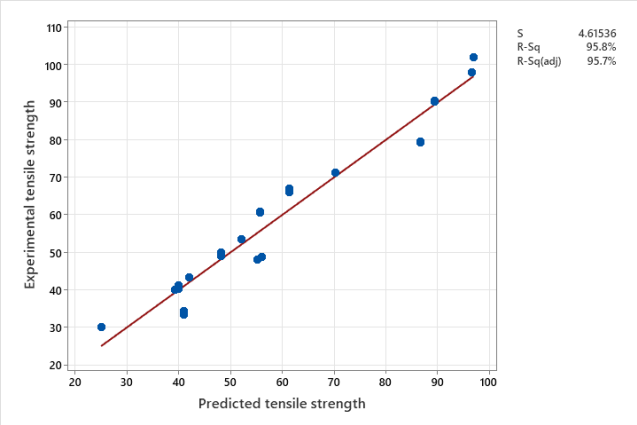


Figure 14. Predicted and experimental tensile strength graphs.

3.6 Mathematical Model for Tensile Strength with Hexagonal Threaded Tool

The mathematical model developed for tensile strength using a threaded hexagonal tool is given in Equation (3)

$$TS = 35.7\,RM - 0.207\,RS + 32.96\,TTS - 2.103\,L + 0.01\,RM * RM + 0.000052\,RS * RS - 0.1751\,TTS * TTS + 0.002819\,L * L + 0.0206\,RM * RS + 0.666\,RM * TTS - 0.1209\,RM * L - 0.00057\,RS * TTS + 0.000089\,RS * L - 0.02729\,TTS * L \quad (3)$$

The average deviation is indicated by the Standard Deviation (S) from the fitted regression line, which is 16.5197. The R^2 Value demonstrates the accuracy of the prediction. The regression model's R^2 value for tensile strength is 98.31% variable. The adjusted R^2 accounts for the number of predictors, whereas the predicted R^2, which shows how well the model predicts new data, is 96.99%. Since it guarantees a balance between accuracy and model complexity, the lowest value is R^2 pred (96.35%), the highest is R^2 (98.31%), and the ideal value is R^2 adj (96.99%). Predicted and experimental tensile strength are shown to be strongly correlated in the Regression Fitted Line Plot. The data points closely follow the trend, and the regression line shows how well the model predicts tension strength. The average deviation of data points from the fitted regression line is measured by the Standard Deviation (S) is 8.47624. The R^2 value of 94.7%, the model is very accurate and can account for 94.7% of the variation in tensile strength. Figure 15 shows a fitted line plot. Furthermore, the Adjusted R^2 is 94.5%, which

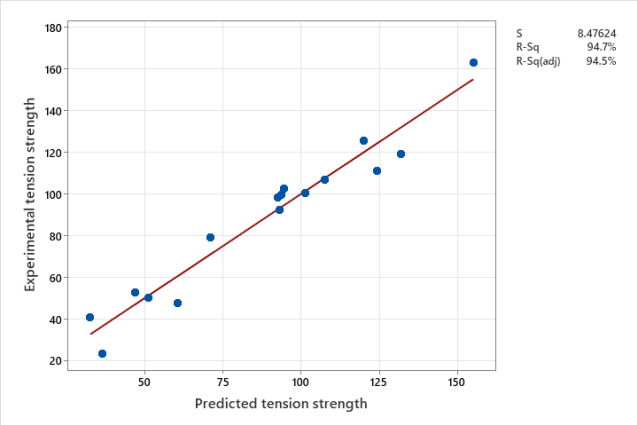


Figure 15. Predicted and experimental tensile strength graph for a hexagonal with a threaded tool.

takes into consideration the number of predictors and guarantees that the model maintains its dependability without going into overfit. The standard deviation obtained is 8.47624, which is the lowest of these numbers since a lower standard deviation indicates a better model fit. R^2 has the greatest value of 94.7%. This indicates high predictive accuracy. The adjusted R^2 is 94.5%, the ideal number since it strikes a compromise between the model's complexity and accuracy. The capacity of a material or welded junction to sustain its strength, stability, and structural performance under applied loads and operating circumstances without failing is known as mechanical integrity. Mechanical integrity, as used in this work, refers to how well the AA7075/SiC composite joints tolerate tensile and impact loads after Friction Stir Welding (FSW). It displays the degree of bonding, the even dispersion of SiC particles, and the lack of flaws like fractures or porosity. Improved tensile strength and consistent performance, particularly with the threaded hexagonal tool, were the results of optimising FSW parameters to obtain enhanced mechanical integrity.

3.7 Microstructural Characterisation and Energy Dispersive Spectroscopy of Welded Joints

The SEM image of the weld zone under the experimental conditions 13 is shown in Figure 16. AA7075/SiC particle clustering, voids, and microcracks are shown by SEM analysis, indicating insufficient material flow and incorrect heat input. Mechanical degradation is also influenced by oxidation and material separation. The SEM image of the

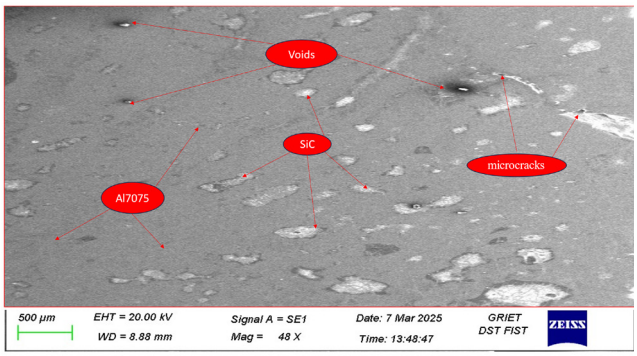


Figure 16. SEM image of weld specimen.

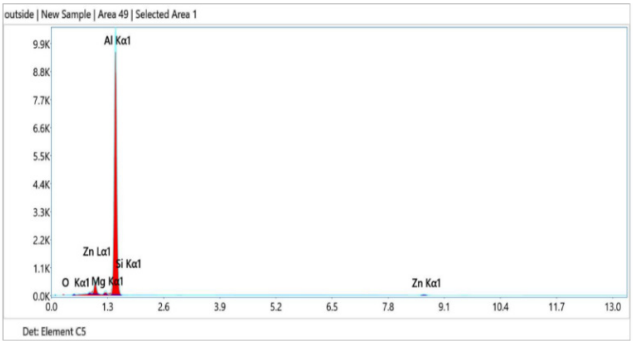


Figure 17. EDS analysis on the welded specimen.

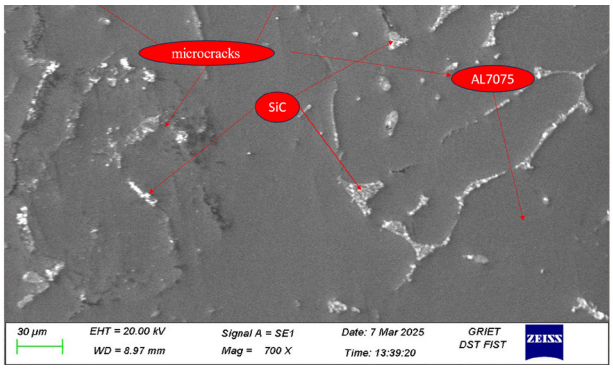


Figure 18. SEM image of weld specimen.

weld zone under the experimental condition 6 is shown in Figure 18. Particle clustering, microcracks, and voids are potential flaws seen in the weld zone. This SEM indicates the mechanical characteristics and grain refinement. It was influenced by SiC particles. Better dispersion of SiC particles and enhanced bonding in the weld zone were observed. The SEM image of the weld zone under experimental conditions 13 is shown in Figure 20. An aluminium matrix composite (AA7075/SiC) reinforced with 9% SiC underwent Friction Stir Welding (FSW). A

threaded hexagonal tool was used for the welding process. The lowest tensile strength of 40.92 N/mm² was observed under these conditions. Important material properties are revealed by the microstructural examination of the weld area. With a magnified view of the welded surface, the image highlights potential flaws, material behaviour, and the distribution of SiC particles. Inhomogeneous SiC dispersion, voids, and cracks are visible, and these could all be factors in the mechanical characteristics. Weak interface formation could result from insufficient bonding between the SiC particles and the aluminium matrix, which would reduce the weld's overall strength.

The SEM image of the weld zone under experimental conditions 6 is shown in Figure 22. A threaded hexagonal tool was used to perform Friction Stir Welding (FSW) on aluminium matrix composite (AA7075/SiC). The welded joint's microstructural examination showed notable material behaviour, such as the distribution of SiC particles and the development of defects. Potential flaws that could have been caused by insufficient heat generation or incorrect material flow during the welding process included cracks and voids. The SiC reinforcement particles were also dispersed throughout the matrix. Plastic deformation causes grain refinement in the weld nugget region, except that SiC aggregation affects the homogeneity of the reinforcement. Figure 17 shows the EDS analysis on the welded specimen; low silicon concentration indicates poor SiC retention, while the presence of Al (90.3 wt %), Zn (6.2 wt %), O_2 (2.2 wt %), Mg (1.3 wt %), and Si (0.1 wt %) is revealed. Oxygen's presence implies oxidation, which could damage the joint. This element leads to low tensile strength. The microstructural examination of the weld zone reveals the material behaviour, SiC particle distribution, and any flaws. The elemental composition is confirmed by the Energy Dispersive Spectroscopy (EDS) study, which reveals that aluminium (85.9%), silicon (0.2%), magnesium (2.8%), copper (2.4%), zinc (5.1%), iron (0.7%), and oxygen (4.0%) are significantly present. This suggests possible oxidation and the presence of reinforcement particles. Figure 19 shows the EDS analysis on the welded specimen. This elemental analysis indicates that weld's mechanical properties are greatly influenced by the process parameter and SiC reinforcement, helping to increase strength. To reduce flaws and improve the material's performance, more optimisation is necessary.

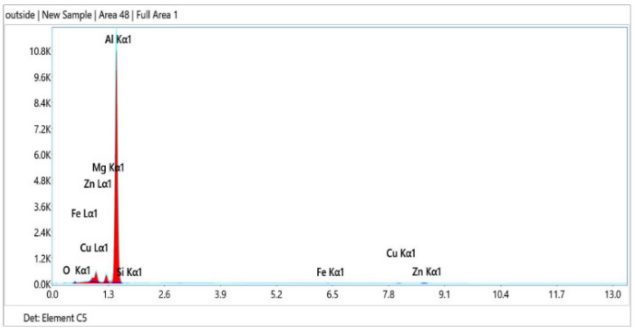


Figure 19. EDS analysis on the welded specimen.

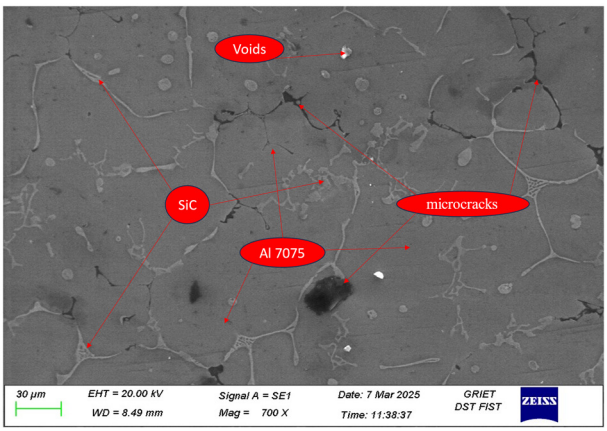


Figure 20. SEM image of weld specimen.

The elemental composition of the welded region is confirmed by the Energy Dispersive Spectroscopy (EDS) investigation. Al (86.6%), O_2 (2.6%), Mg (2.6%), Cu (2.5%), Zn (5.4%), and Si (0.3%) are the main ingredients found, suggesting the existence of matrix alloying elements and reinforcement phases. It demonstrates how welding process parameters affect the AA7075/SiC composite mechanical properties. Figure 21 shows the EDS analysis on the welded specimen. The chemical composition analysis of the sample was performed using EDAX, identified the presence of various elements, including oxygen (4.6%), magnesium (3.2%), aluminum (81.0%), silicon (0.7%), titanium (0.8%), iron (0.9%), copper (3.2%), and zinc (5.5%). These elements play a crucial role in defining the strength, corrosion resistance, and overall performance of the composite material. Figure 23 shows the EDS analysis on the welded specimen.

The distribution and behaviour of SiC particles in the weld zone are greatly influenced by Friction Stir Welding (FSW). Particularly when employing the threaded hexagonal tool, the vigorous stirring action

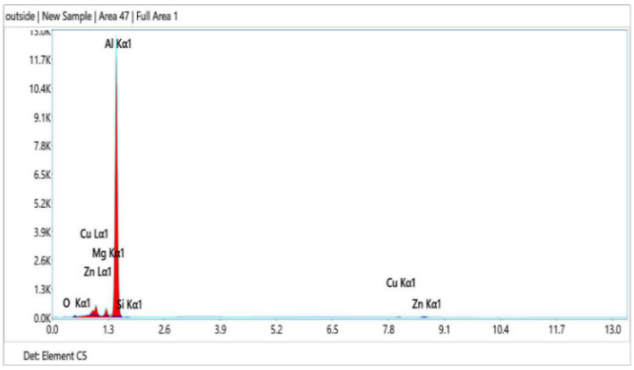


Figure 21. EDS analysis on the welded specimen.

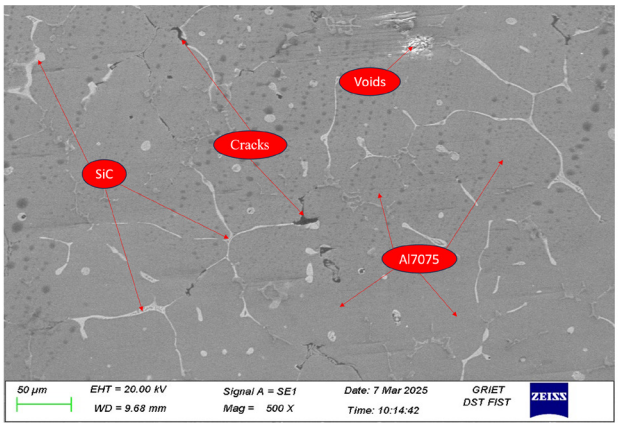


Figure 22. SEM image of weld specimen.

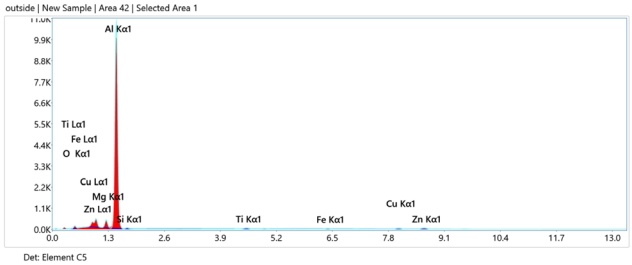


Figure 23. EDS analysis on the welded specimen.

and heat generation during FSW improve particle matrix interaction, decrease clustering, and increase the dispersion of SiC particles. According to SEM studies, FSW increases mechanical characteristics by producing a finer grain structure and a more uniform dispersion of SiC under ideal conditions. However, weld quality was adversely affected by particle agglomeration, voids, and cracks that were detected at greater SiC contents. Therefore, when appropriately adjusted, FSW is essential for improving the microstructure and performance of the composite. The hexagonal and threaded hexagonal tools were the particular focus of this investigation because of their demonstrated ability to improve material flow, heat generation, and particle dispersion during the Friction Stir Welding (FSW) process. For welding aluminium metal matrix composites supplemented with SiC, the hexagonal profile was chosen due to its sharp edges and flat faces, which encourage intense stirring and plastic deformation. Although the literature has extensively examined alternative pin profiles, such as square, conical, or cylindrical, the objective of this study was to use Taguchi design to evaluate and improve the performance of the hexagonal tool and the threaded hexagonal tool for AA7075/SiC composites.

4.0 Conclusions

The following conclusions are drawn from the experimental results.

1. This study investigated the effects of hexagonal and threaded hexagonal tools on tensile strength and Charpy impact resistance while optimising Friction Stir Welding (FSW) parameters for AA7075-T6 aluminium alloy reinforced with Silicon Carbide (SiC).
2. In comparison to the hexagonal tool, the threaded hexagonal tool demonstrated better material flow and a higher tensile strength. Using the threaded hexagonal tool at 5% SiC reinforcement, 1100 rpm tool speed, 30 mm/min traverse speed, and 850 kg axial force, the maximum tensile strength observed was 163.15 N/mm^2. On the other hand, under 9% reinforcement, 900 rpm tool speed, 60 mm/min traverse speed, and 750 kg axial force with the same tool, the lowest tensile strength recorded was 40.92 N/mm^2. The threaded hexagonal tool's superiority in weld strength was further supported by the hexagonal tool's maximum tensile strength of 101.90 N/mm^2 and minimum of 30.12 N/mm^2.
3. Using the threaded hexagonal tool, the maximum impact strength was observed as 6 Joules at 9% SiC reinforcement, 1300 rpm tool speed, 40 mm/min traverse speed, and 850 kg axial force. SiC reinforcement increases strength but has little influence on toughness, as evidenced by the impact strength, which remains constant, i.e. 2 Joules under all the situations for the plain hexagonal tool.

4. Particle clustering and porosity decreased mechanical properties were observed with microstructural investigation when the SiC content was more than 7%. In addition to lowering flaws and improving overall mechanical properties, the threaded hexagonal tool improved SiC dispersion.
5. The analyses demonstrated that AA7075-T6/SiC composites' tensile strength considerably increased by optimising the FSW parameters, which qualifies them for use in automotive and aerospace applications.
6. The variation of SiC in AA7075 impact strength is low, and mostly it is observed as constant in the case of the hexagonal tool. This is due to the influence of SiC particles in AA7075 alloy being negligible.
7. Rotational speed was the most significant factor influencing tensile strength for hexagonal tools (40.59 %), followed by traverse speed (25.20%), reinforcing percentage (23.75%), and axial force (6.29%). The most important element for threaded hexagonal tools was traverse speed (31.17%), with axial force (24.85%), rotational speed (26.71%), and reinforcing percentage (11.94%) also making substantial contributions. The residual error in both models was less than 6%, demonstrating the high dependability of the experimental data.
8. The strong association between real and anticipated tensile strengths was confirmed by the regression models, which demonstrated great prediction accuracy with R^2 values above 94% for both tools. The instances of the threaded tool model and the hexagonal tool model demonstrated exceptional predictive abilities for process optimisation, with R^2 values of 98.31% and 98.18%, respectively.

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