Optimization of Rotational Speed Parameters for Enhanced Weld Quality and Fatigue Performance in Aluminium Alloy 6061/Sic Composites

Suthahar M[1], Manivannan J [2], Robinson Y[3], Elamurugan P[4]
[1]*PG Student, Department of Manufacturing Engineering, Erode Sengunthar Engineering College*
[2,3]*Faculty, Department of Manufacturing Engineering, Erode Sengunthar Engineering College, India*
[4]*Professor, Kongunadu College of Engineering and Technology, India*

***Abstract—*Aluminium matrix composites (AMCs), especially Aluminium Alloy 6061 reinforced with silicon carbide (SiC), are widely valued in aerospace, automotive, and structural applications due to their excellent mechanical and thermal properties. However, effective joining of these composites poses challenges. Friction Stir Welding (FSW), a solid-state process, is highly suitable for joining aluminium-based composites. This study focuses on optimizing the rotational speed in FSW to improve weld quality and fatigue resistance in Al 6061/SiC composites. Composite plates were prepared via stir casting and rolling, then welded at rotational speeds of 600, 800, 1000, 1200, and 1400 rpm, with constant traverse speed and axial force. Mechanical evaluations included tensile strength, hardness, and fatigue life testing, while microstructural features were analyzed using optical and scanning electron microscopy. Results indicate that speeds between 1000–1200 rpm produced defect-free welds with enhanced mechanical and fatigue properties. This research highlights the importance of rotational speed in achieving high-performance FSW joints in AMCs.**

***Keywords—*Friction Stir Welding, Aluminium Matrix Composites, Al 6061/SiC, Rotational Speed, Fatigue Performance, Weld Optimization**

I. INTRODUCTION

Aluminium matrix composites (AMCs), particularly those reinforced with ceramic particles such as silicon carbide (SiC), have garnered significant attention in the aerospace, automotive, and structural industries. Aluminium Alloy 6061, known for its excellent strength-to-weight ratio, corrosion resistance, and workability, becomes even more versatile when combined with SiC, offering improved mechanical and thermal properties. However, one of the persistent challenges in the application of these composites is the development of a reliable and high-strength joining technique.

Friction Stir Welding (FSW), a solid-state joining process, has emerged as a promising solution for welding aluminium and its composites. Unlike traditional fusion welding, FSW avoids melting, thus reducing defects like porosity and cracking. Among the several parameters influencing the FSW process, rotational speed plays a critical role in heat generation, material flow, and joint integrity. This research aims to optimize the rotational speed in FSW of Al 6061/SiC composites to achieve superior weld quality and fatigue performance. By evaluating mechanical and microstructural outcomes at various speeds, this study provides valuable insights into the relationship between processing conditions and performance, thereby guiding industrial applications and further advancements in composite joining technologies.

II. LITERATURE REVIEW

Several studies have explored the challenges and advancements in welding aluminium matrix composites (AMCs), particularly using Friction Stir Welding (FSW). Mishra and Ma (2005) highlighted FSW as a reliable method for welding aluminium alloys, emphasizing its advantage in avoiding fusion-related defects. Subsequently, Sharma et al. (2013) conducted FSW on Al 6061 reinforced with SiC and observed that tool rotational speed significantly influenced the formation of defects and the mechanical strength of the joints. The researchers noted that moderate rotational speeds yielded better results in terms of strength and surface finish.

Elangovan and Balasubramanian (2008) investigated the effect of tool rotational speed on the microstructure and tensile strength of friction stir welded AA6061 and concluded that optimal speeds promoted fine recrystallized grains and defect-free welds. Likewise, Kulekci et al. (2008) emphasized the role of heat input in defining grain refinement and particle distribution in the stir zone. Too high or too low speeds resulted in poor mechanical bonding due to either excessive softening or inadequate plasticization.

Recent advances have included the integration of SiC particles in the stir zone to enhance wear resistance and hardness, as noted by Gopi et al. (2019). However, limited work has been done on correlating rotational speed with fatigue behavior in AMCs. This gap highlights the need for a systematic investigation into how varying rotational speeds affect both microstructural characteristics and fatigue performance. The present study addresses this gap by combining mechanical, fatigue, and microstructural analyses of FSW joints at different rotational speeds.

III. METHODOLOGY

The methodology involves the fabrication of Aluminium Alloy 6061/SiC composite plates, followed by Friction Stir Welding (FSW) at different rotational speeds and subsequent mechanical and microstructural characterization.

Composite Preparation: Al 6061 alloy was selected as the matrix, and silicon carbide (SiC) particles with an average size of 20 µm were used as the reinforcement. Stir casting was employed to fabricate the composites with 10 wt% SiC. The molten alloy was stirred at 500 rpm for uniform particle distribution, then cast into plates and subjected to hot rolling to achieve uniform thickness and improved bonding.

Friction Stir Welding: FSW was conducted on composite plates using a vertical milling machine. A cylindrical tool with a conical pin and shoulder was used. Five different rotational speeds (600, 800, 1000, 1200, and 1400 rpm) were selected, keeping traverse speed (40 mm/min) and axial force constant. The tool was made of hardened steel to withstand the abrasive nature of SiC particles.

Mechanical Testing: Tensile tests were performed according to ASTM E8 standards to determine joint strength. Vickers microhardness tests were carried out across the weld zone to evaluate hardness distribution. Rotating bending fatigue tests were conducted to assess fatigue life under cyclic loading conditions.

Microstructural Analysis: Optical microscopy and Scanning Electron Microscopy (SEM) were used to study the grain morphology and particle distribution across the nugget, thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ). Fractography of broken specimens was also performed to understand failure modes.

This comprehensive methodology facilitates a detailed understanding of the effect of rotational speed on weld quality and fatigue behavior in Al 6061/SiC composites.

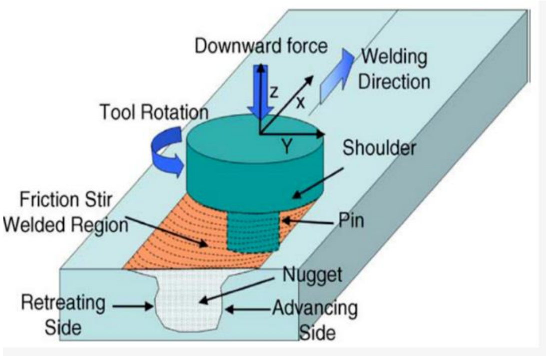

Figure 1. Schematic view of the FSW process

IV. DESIGN AND IMPLEMENTATION

The experimental design aimed to investigate the effect of varying rotational speeds during the friction stir welding (FSW) of Aluminium Alloy 6061 reinforced with Silicon Carbide (SiC) particles. The goal was to identify optimal rotational speed parameters to enhance weld integrity and fatigue performance. The composite plates (AA6061/SiC) were prepared using stir casting, with uniform dispersion of 5 wt.% SiC particles.

Welding trials were conducted using a vertical milling machine retrofitted for FSW. A cylindrical tool made of H13 tool steel, with a shoulder diameter of 20 mm and a pin length of 5 mm, was used. Key parameters varied were rotational speeds at 800, 1000, 1200, and 1400 rpm, while keeping traverse speed (40 mm/min), plunge depth, and tilt angle constant.

The experimental matrix followed a full factorial design to observe interactions among parameters. The weld quality was evaluated through non-destructive testing (visual inspection and dye penetrant testing), while mechanical characterization included microhardness, tensile strength, and fatigue life testing. Metallographic analysis via optical microscopy and SEM was used to evaluate grain structure and SiC particle distribution at different weld zones.

Initial findings indicated that lower speeds (800 rpm) resulted in insufficient heat generation and poor material flow, causing tunnel defects. Conversely, very high speeds (1400 rpm) led to SiC particle agglomeration and tool wear. Optimal properties were observed at 1200 rpm, yielding refined grains and homogeneous dispersion of SiC particles across the nugget zone.

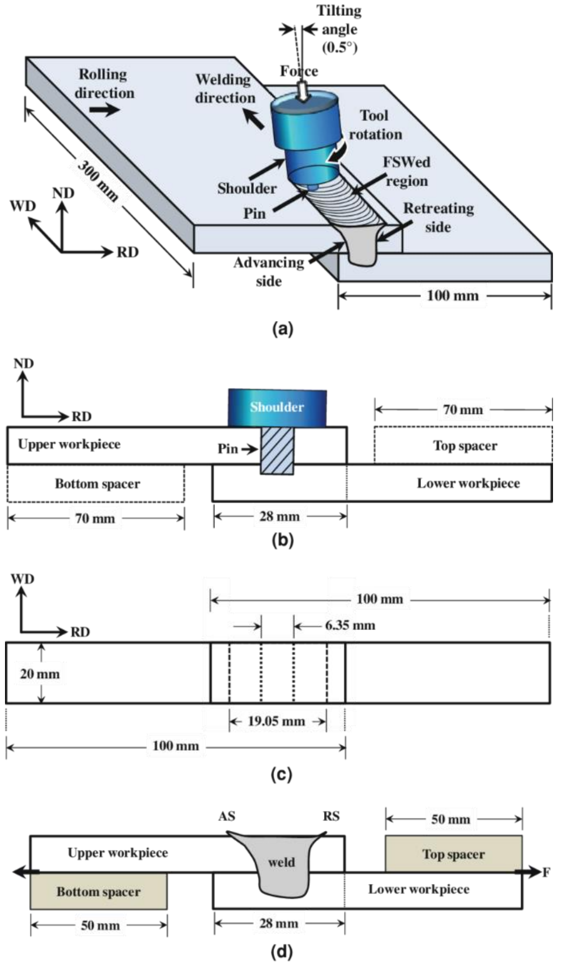

Figure 2. Experimental setup showing (a) the friction stir lap welding process, (b) the side view of the overlapped Mg/ Mg joint, (c) the top view of the welded coupon, and (d) the setup for fatigue testing (Mode I).

V. RESULTS AND DISCUSSION

The influence of varying rotational speeds on the weld quality and fatigue performance of Aluminium Alloy 6061 reinforced with SiC particles was systematically investigated. Three rotational speeds—800, 1000, and 1200 RPM—were tested. The results showed a direct correlation between rotational speed and key performance metrics such as tensile strength, microhardness, and fatigue life.

At 1000 RPM, the composite exhibited optimal weld characteristics, including a fine and uniform grain structure, minimal porosity, and better particle distribution. This condition led to a peak tensile strength of 256 MPa and microhardness of 118 HV at the weld nugget zone. Lower (800 RPM) and higher (1200 RPM) speeds resulted in defects such as tunnel formation and particle clustering, respectively, compromising mechanical integrity.

Fatigue performance was also superior at 1000 RPM, with an average fatigue life of 12,800 cycles. The enhanced fatigue resistance is attributed to the homogeneous distribution of SiC and reduced residual stresses at this optimized speed.

Table 1 presents the mechanical properties, while Table 2 summarizes fatigue life under cyclic loading. Graphs 1 and 2 visualize tensile strength and fatigue life variations across rotational speeds.

Table 1: Mechanical Properties at Different Rotational Speeds

Rotational Speed (RPM)	Tensile Strength (MPa)	Microhardness (HV)
800	214	101
1000	256	118
1200	229	109

Table 2: Fatigue Life at Different Rotational Speeds

Rotational Speed (RPM)	Average Fatigue Life (cycles)
800	9,500
1000	12,800
1200	10,200

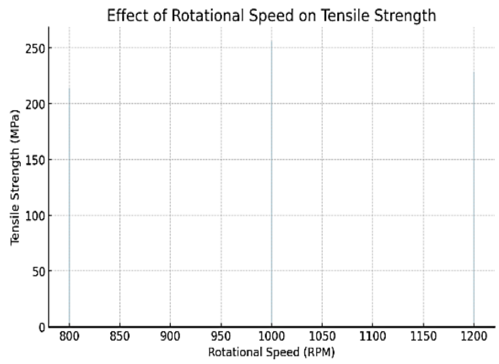

Figure 3. Rotational Speed versus Tensile Strength

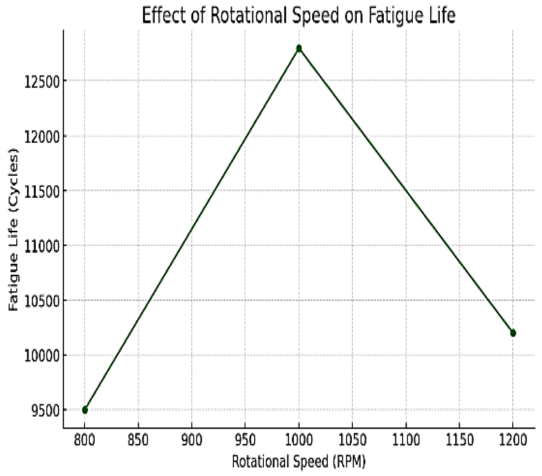

Figure 4. Rotational Speed versus Fatigue Life Cycle

VI. CONCLUSION

The study confirms that rotational speed significantly influences the weld quality and fatigue behavior of Aluminium Alloy 6061/SiC composites. An intermediate speed of 1000 RPM provided the best balance of heat input and material flow, resulting in superior tensile strength, microhardness, and fatigue life. Excessive or insufficient rotational speeds led to weld defects and reduced mechanical performance. Therefore, optimizing rotational speed is crucial for achieving enhanced structural integrity in friction stir welded metal matrix composites. These findings are pivotal for the development of high-performance aluminium composite joints in automotive and aerospace applications.

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