International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

Optimization of Friction Stir Welding Parameters for High-Strength Aluminum–Magnesium Alloy Joints

P.M. Naresh Kumar

Academic Consultant
Department of ME
Y.S.R Engineering College of YVU,
Proddatur -516360
p.m.nareshkumaryadav@gmail.com

P. Srinivasula Reddy

Academic Consultant
Department of ME
Y.S.R Engineering College of YVU,
Proddatur -516360
srinivaspathakota@gmail.com

ABSTRACT: *The increasing demand for lightweight, high-strength, and corrosion-resistant structural materials has significantly expanded the application of aluminum–magnesium (Al–Mg) alloys in aerospace, automotive, marine, railway, and defense industries. These alloys offer an excellent combination of low density, superior specific strength, high corrosion resistance, and good formability, making them suitable for advanced engineering structures where weight reduction and mechanical performance are critical. However, conventional fusion welding techniques such as Gas Metal Arc Welding (GMAW), Tungsten Inert Gas (TIG) welding, and Laser Beam Welding often produce defects including porosity, solidification cracking, distortion, residual stresses, and undesirable microstructural transformations due to localized melting and rapid solidification. These limitations adversely affect the mechanical integrity and long-term reliability of welded Al–Mg alloy structures. Consequently, Friction Stir Welding (FSW), a solid-state joining technique, has emerged as an effective alternative for producing high-quality aluminum alloy joints with superior mechanical properties. Friction Stir Welding utilizes a non-consumable rotating tool consisting of a shoulder and profiled pin to generate frictional heat below the melting temperature of the base materials. The softened material undergoes severe plastic deformation and dynamic recrystallization, resulting in refined grain structures and defect-free joints without melting. The quality of friction stir welded joints is strongly influenced by process parameters such as tool rotational speed, traverse speed, axial force, tool tilt angle, plunge depth, and pin geometry. Improper parameter selection may lead to insufficient material flow, tunnel defects, void formation, excessive flash generation, or poor mechanical performance. Therefore, systematic optimization of welding parameters is essential for achieving maximum joint strength, improved microstructural characteristics, and enhanced process efficiency. This research presents an* ***Optimization of Friction Stir Welding Parameters for High-Strength Aluminum–Magnesium Alloy Joints*** *through comprehensive numerical and experimental evaluation of critical welding parameters. Various combinations of rotational speed, welding speed, axial force, and tool tilt angle are investigated to determine their influence on material flow behavior, heat generation, tensile strength, hardness distribution, elongation, residual stress, and weld quality. Statistical optimization techniques are employed to identify the optimum parameter combination capable of maximizing joint performance while minimizing welding defects. The developed methodology enables detailed analysis of the thermo-mechanical behavior occurring during the friction stir welding process. The obtained results demonstrate that optimized friction stir welding*

Received: 01-10-2025 | Accepted: 10-11-2025 | Published: 16-11-2025 |

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

parameters significantly improve joint quality by promoting uniform material mixing, fine-grained microstructure, and defect-free weld formation. The optimized process produces higher ultimate tensile strength, improved hardness, greater ductility, lower residual stresses, and enhanced welding efficiency compared with non-optimized parameter combinations. The developed optimization strategy provides an effective manufacturing approach for producing high-strength aluminum–magnesium alloy joints suitable for lightweight structural applications. The proposed methodology offers significant benefits for aerospace structures, automotive body components, marine vessels, railway coaches, pressure vessels, defense equipment, and advanced industrial fabrication requiring reliable and high-performance welded joints.

INTRODUCTION

Friction Stir Welding (FSW) has emerged as one of the most significant solid-state joining technologies for lightweight structural materials due to its ability to produce high-quality welds without melting the base material. Since its invention, FSW has gained widespread acceptance in aerospace, automotive, marine, railway, defense, and pressure vessel manufacturing industries because it eliminates many of the metallurgical problems associated with conventional fusion welding. Unlike traditional welding techniques that involve melting and solidification, Friction Stir Welding joins materials through severe plastic deformation generated by a rotating non-consumable tool, resulting in refined grain structures, superior mechanical properties, reduced residual stresses, and excellent dimensional stability. These advantages have made FSW an attractive manufacturing process for joining high-strength aluminum alloys that are otherwise difficult to weld using conventional methods.

Aluminum–magnesium (Al–Mg) alloys are among the most extensively used lightweight engineering materials due to their high specific strength, excellent corrosion resistance, superior fatigue performance, and good formability. These alloys are widely employed in aircraft fuselage panels, automotive chassis components, shipbuilding structures, railway coaches, cryogenic tanks, offshore platforms, and defense vehicles where minimizing structural weight while maintaining mechanical strength is essential. Despite these advantages, conventional fusion welding processes such as Gas Metal Arc Welding (GMAW), Tungsten Inert Gas (TIG) welding, and Laser Beam Welding often introduce welding defects including porosity, hot cracking, distortion, excessive heat-affected zones, and coarse grain formation due to repeated melting and solidification. These defects reduce joint strength, fatigue life, and long-term structural reliability, limiting the performance of welded aluminum structures.

Friction Stir Welding overcomes these limitations by maintaining the material in the solid state throughout the joining process. During welding, a rotating tool consisting of a shoulder and specially designed pin penetrates the joint interface and generates frictional heat through mechanical interaction with the workpiece. The generated heat softens the surrounding material without reaching its melting temperature, allowing the plasticized metal to flow around the rotating pin while undergoing intense plastic deformation. Dynamic recrystallization during this process produces a fine equiaxed grain structure within the stir zone, leading to improved mechanical properties, enhanced fatigue resistance,

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

reduced residual stresses, and defect-free joints. Consequently, FSW has become the preferred joining technology for manufacturing high-performance aluminum alloy structures.

The quality of friction stir welded joints is highly dependent on several interrelated process parameters, including tool rotational speed, traverse (welding) speed, axial force, tool tilt angle, plunge depth, shoulder diameter, pin profile, and tool material. These parameters directly influence heat generation, material flow behavior, plastic deformation, grain refinement, residual stress development, and weld integrity. Excessively high rotational speeds may generate excessive heat, causing grain coarsening and flash formation, whereas insufficient rotational speeds may result in inadequate plasticization and tunnel defects. Similarly, inappropriate traverse speeds can either reduce material mixing or generate excessive thermal input, thereby affecting tensile strength and weld quality. Therefore, selecting the optimum combination of process parameters is essential for achieving defect-free welds with maximum mechanical performance.

Recent advancements in computational modeling, finite element analysis, statistical optimization, and artificial intelligence have significantly enhanced the capability to optimize Friction Stir Welding processes. Numerical simulation enables prediction of temperature distribution, material flow patterns, strain rate, residual stress, and microstructural evolution during welding, while optimization techniques such as Response Surface Methodology (RSM), Taguchi Design of Experiments, Grey Relational Analysis, Artificial Neural Networks (ANN), and Genetic Algorithms facilitate identification of the optimal parameter combinations. These modern optimization approaches reduce experimental effort, minimize manufacturing cost, and improve process reliability while ensuring consistent weld quality for industrial production.

This research presents an **Optimization of Friction Stir Welding Parameters for High-Strength Aluminum–Magnesium Alloy Joints** through systematic evaluation of the major welding parameters affecting joint performance. Various combinations of tool rotational speed, welding speed, axial force, and tool tilt angle are investigated to analyze their influence on heat generation, material flow, tensile strength, hardness distribution, elongation, residual stress, and welding efficiency. Statistical optimization techniques are employed to determine the optimum process parameters capable of maximizing joint strength while minimizing welding defects. Comparative analysis of different parameter combinations provides valuable insights into the thermo-mechanical behavior of aluminum–magnesium alloys during Friction Stir Welding and establishes an effective manufacturing strategy for producing reliable lightweight structural joints.

Problem Statement

Although Friction Stir Welding has significantly improved the joining quality of aluminum alloys compared with conventional fusion welding techniques, improper selection of welding parameters often leads to insufficient material flow, tunnel defects, void formation, excessive flash, poor grain refinement, and reduced mechanical properties. The complex interaction among rotational speed, traverse speed, axial force, and tool geometry makes it difficult to determine the optimum process conditions capable of producing defect-free aluminum–magnesium alloy joints with maximum tensile

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

strength and minimum residual stress. Therefore, systematic optimization of Friction Stir Welding parameters is required to enhance joint quality, mechanical performance, process stability, and manufacturing efficiency.

Objective

The primary objective of this research is to optimize the Friction Stir Welding parameters for producing high-strength aluminum–magnesium alloy joints with superior mechanical properties. The study investigates the influence of tool rotational speed, welding speed, axial force, and tool tilt angle on heat generation, material flow, tensile strength, hardness, elongation, residual stress, and weld quality. The research further aims to determine the optimum parameter combination that maximizes joint strength while minimizing welding defects and improving overall manufacturing performance.

Scope

The scope of this research includes the numerical and experimental investigation of Friction Stir Welding process parameters for aluminum–magnesium alloy joints using statistical optimization techniques and thermo-mechanical analysis. The study evaluates the influence of rotational speed, traverse speed, axial force, and tool tilt angle on microstructural evolution, tensile strength, hardness distribution, residual stress, material flow, and welding efficiency. The developed optimization methodology is applicable to **aerospace fuselage structures, automotive body panels, railway coaches, marine shipbuilding, pressure vessels, offshore platforms, cryogenic storage tanks, defense vehicles, lightweight industrial structures, renewable energy systems, and advanced manufacturing industries**, where high-strength, lightweight, and defect-free welded aluminum components are essential.

LITERATURE SURVEY

Friction Stir Welding (FSW) has become one of the most important solid-state joining technologies for lightweight structural materials due to its capability to produce high-quality welds with superior mechanical properties and minimal metallurgical defects. Unlike conventional fusion welding processes, FSW joins materials below their melting temperature through frictional heating and severe plastic deformation generated by a rotating non-consumable tool. This solid-state joining mechanism eliminates common fusion welding problems such as porosity, solidification cracking, distortion, and excessive residual stresses. Since its introduction, FSW has been extensively adopted in aerospace, automotive, railway, marine, defense, and pressure vessel industries for manufacturing high-performance aluminum structures requiring excellent structural integrity and long service life.

Aluminum–magnesium (Al–Mg) alloys have attracted considerable attention because of their high strength-to-weight ratio, excellent corrosion resistance, superior weldability, and outstanding fatigue performance. These alloys are widely used in aircraft fuselage panels, ship hulls, railway coaches, automobile body structures, cryogenic tanks, and offshore engineering components where lightweight

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

construction and mechanical reliability are essential. However, conventional arc welding techniques often produce coarse grain structures, heat-affected zone softening, hot cracking, and undesirable microstructural transformations that reduce joint efficiency. Numerous researchers have demonstrated that Friction Stir Welding effectively overcomes these limitations by maintaining the material in the solid state while promoting dynamic recrystallization and grain refinement within the stir zone.

The rotational speed of the welding tool is recognized as one of the most influential parameters affecting friction stir welding performance. Tool rotation governs frictional heat generation, plastic material flow, strain rate, and recrystallization behavior. Researchers have reported that insufficient rotational speed produces inadequate heat generation, resulting in poor material plasticization, tunnel defects, and incomplete joint consolidation. Conversely, excessively high rotational speed generates excessive heat input that promotes grain coarsening, flash formation, excessive tool wear, and deterioration of mechanical properties. Therefore, optimization of rotational speed is essential for achieving a balanced thermal cycle and defect-free weld formation.

Traverse speed, also referred to as welding speed, significantly influences heat input per unit length and the duration of thermo-mechanical interaction between the rotating tool and workpiece. Lower traverse speeds increase heat accumulation and improve material plasticization; however, excessive heat input may enlarge the heat-affected zone and reduce hardness. Higher traverse speeds decrease thermal exposure and improve productivity but may produce insufficient material mixing, void formation, and tunnel defects due to inadequate plastic flow. Several experimental investigations have demonstrated that an optimum combination of rotational speed and traverse speed is necessary to maximize tensile strength, microstructural refinement, and welding efficiency.

Axial force and tool tilt angle also play critical roles in determining weld quality and joint integrity. Adequate axial force ensures proper contact between the tool shoulder and workpiece surface, promoting sufficient frictional heating and effective forging action during material consolidation. Insufficient axial force may cause incomplete penetration and weak joints, whereas excessive force increases flash formation and accelerates tool degradation. Similarly, the tool tilt angle improves material containment beneath the shoulder, enhances plasticized material flow, and minimizes internal defects. Researchers have consistently observed that slight positive tilt angles improve weld surface finish, reduce void formation, and increase joint strength by enhancing consolidation within the stir zone.

Tool geometry represents another important factor influencing friction stir welding performance. The shoulder diameter, pin length, pin profile, thread configuration, and shoulder surface features directly affect heat generation, material stirring, and flow characteristics. Cylindrical, threaded cylindrical, tapered, square, triangular, and polygonal pin profiles have been extensively investigated for welding aluminum alloys. Threaded and non-circular pin geometries generally improve material mixing by increasing plastic deformation and promoting uniform grain refinement throughout the stir zone. Proper tool design contributes significantly to defect-free weld formation and improved mechanical properties while simultaneously reducing process variability.

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

Microstructural evolution during friction stir welding has been widely investigated using optical microscopy, scanning electron microscopy, electron backscatter diffraction, and transmission electron microscopy. Researchers have identified four major regions within friction stir welded joints: the Stir Zone (SZ), Thermo-Mechanically Affected Zone (TMAZ), Heat-Affected Zone (HAZ), and Base Metal (BM). The stir zone typically consists of fine equiaxed grains produced through dynamic recrystallization under severe plastic deformation and elevated temperatures. This refined microstructure contributes to higher hardness, improved tensile strength, enhanced fatigue resistance, and superior fracture toughness compared with conventional fusion-welded joints.

Mechanical characterization remains one of the primary methods for evaluating friction stir welded joints. Tensile strength, yield strength, elongation, hardness distribution, fatigue life, fracture toughness, and impact resistance are commonly measured to assess joint performance. Numerous studies have demonstrated that optimized friction stir welding parameters can produce joint efficiencies exceeding 90% of the base material strength while maintaining excellent ductility and fatigue performance. Hardness measurements generally reveal a refined stir zone with improved mechanical properties resulting from grain refinement and homogeneous material flow. The absence of fusion-related defects further contributes to improved structural reliability and long-term service performance.

Modern optimization techniques have significantly advanced the development of friction stir welding processes. Statistical methods such as Taguchi Design of Experiments, Response Surface Methodology (RSM), Grey Relational Analysis, Analysis of Variance (ANOVA), Artificial Neural Networks (ANN), Fuzzy Logic, Genetic Algorithms, and Particle Swarm Optimization have been successfully employed to determine optimal combinations of welding parameters. These optimization approaches simultaneously consider multiple performance characteristics including tensile strength, hardness, residual stress, material flow, and process efficiency while minimizing the number of required experimental trials. Consequently, they provide cost-effective methodologies for improving weld quality and manufacturing productivity.

Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD)-based thermo-mechanical simulations have become valuable tools for predicting heat generation, temperature distribution, residual stresses, plastic deformation, and material flow during friction stir welding. Numerical models enable visualization of complex thermo-mechanical phenomena that are difficult to observe experimentally and facilitate rapid evaluation of different parameter combinations before conducting physical experiments. Integration of numerical simulation with statistical optimization has further enhanced the accuracy and efficiency of welding parameter selection for industrial applications.

Despite significant progress in friction stir welding research, several challenges remain in achieving consistent optimization of process parameters for high-strength aluminum–magnesium alloys. Many published studies primarily investigate the influence of individual parameters while neglecting the complex interaction among rotational speed, traverse speed, axial force, and tool geometry. Furthermore, simultaneous optimization of tensile strength, hardness, residual stress, ductility, and weld integrity under varying operating conditions requires additional systematic investigation.

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

Therefore, a comprehensive optimization methodology capable of evaluating multiple welding parameters simultaneously is essential for improving manufacturing reliability and joint performance.

The present research addresses these challenges through an **Optimization of Friction Stir Welding Parameters for High-Strength Aluminum–Magnesium Alloy Joints** using numerical analysis and statistical optimization techniques. The investigation systematically evaluates the combined influence of tool rotational speed, traverse speed, axial force, and tool tilt angle on heat generation, material flow behavior, tensile strength, hardness distribution, residual stress, and welding efficiency. Comparative analysis identifies the optimum process parameters capable of producing defect-free, high-strength aluminum–magnesium alloy joints suitable for **aerospace structures, automotive body components, marine vessels, railway coaches, pressure vessels, cryogenic storage tanks, defense equipment, renewable energy systems, offshore engineering structures, and advanced lightweight manufacturing applications**.

METHODOLOGY

The proposed methodology focuses on optimizing the Friction Stir Welding (FSW) process parameters for producing high-strength aluminum–magnesium (Al–Mg) alloy joints with superior mechanical performance and weld integrity. The optimization procedure combines numerical simulation, experimental validation, and statistical analysis to investigate the influence of major welding parameters on heat generation, material flow, microstructural evolution, tensile strength, hardness distribution, residual stress, and weld quality. The methodology systematically evaluates different combinations of tool rotational speed, traverse speed, axial force, and tool tilt angle to determine the optimum process conditions capable of producing defect-free welded joints suitable for structural engineering applications.

Initially, three-dimensional models of the aluminum–magnesium alloy plates and friction stir welding tool are developed using Computer-Aided Design (CAD) software. The welding tool consists of a cylindrical shoulder and threaded pin designed to promote effective plastic material flow during welding. The dimensions of the shoulder, pin diameter, pin length, plunge depth, and tool tilt angle are selected according to standard Friction Stir Welding design recommendations. The workpieces are positioned in a butt-joint configuration with appropriate clamping conditions to accurately simulate practical welding operations performed in industrial manufacturing environments.

Following geometry preparation, the computational domain is discretized using high-quality finite element meshes with local refinement around the welding zone. Fine mesh elements are employed near the rotating tool and joint interface to accurately capture severe plastic deformation, temperature gradients, material flow, and stress concentration during welding. A mesh convergence study is conducted by gradually increasing the mesh density until the predicted temperature distribution and equivalent stress values become independent of the mesh size. This ensures computational accuracy while minimizing simulation time and numerical errors.

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

The thermo-mechanical behavior of the Friction Stir Welding process is simulated using coupled finite element analysis. The rotating tool generates frictional heat through contact with the workpiece surface while simultaneously plastically deforming the softened material beneath the shoulder. Heat generation due to friction and plastic deformation is incorporated into the numerical model to predict transient temperature distribution throughout the welding process. Temperature-dependent material properties of the aluminum–magnesium alloy are considered to improve the accuracy of thermal and mechanical predictions. Appropriate contact conditions are applied between the rotating tool and workpiece surfaces to simulate realistic material interaction during welding.

A systematic Design of Experiments (DOE) is implemented to investigate the combined influence of major welding parameters. Tool rotational speed, welding speed, axial force, and tool tilt angle are varied over predetermined operating ranges based on industrial Friction Stir Welding practices. Multiple simulation runs are performed to evaluate the influence of each parameter combination on peak welding temperature, material flow behavior, equivalent plastic strain, residual stress, tensile strength, hardness, elongation, and weld defect formation. Statistical optimization techniques are subsequently employed to identify the parameter combination producing maximum joint strength with minimum residual stress and welding defects.

The numerical simulation results are validated through experimental welding trials performed using identical process parameters. Welded specimens are subjected to tensile testing, Vickers microhardness measurements, optical microscopy, and scanning electron microscopy to evaluate mechanical performance and microstructural evolution. The weld cross-sections are examined for tunnel defects, voids, flash formation, incomplete penetration, and grain refinement within the stir zone. Experimental observations are compared with numerical predictions to verify the accuracy of the developed thermo-mechanical model and optimization methodology.

The overall welding performance is assessed using tensile strength, joint efficiency, hardness distribution, residual stress, elongation, and weld quality as primary performance indicators. Statistical analysis is performed to determine the relative significance of each process parameter and their interactions on mechanical performance. The optimum parameter combination is selected based on maximum tensile strength, uniform hardness distribution, minimum residual stress, defect-free weld formation, and improved manufacturing efficiency. Comparative evaluation with non-optimized welding conditions demonstrates the effectiveness of the proposed optimization methodology for producing high-quality aluminum–magnesium alloy joints.

The welding heat input governing the Friction Stir Welding process is evaluated using the following relationship:

$$Q = \frac{2\pi NT}{V}$$

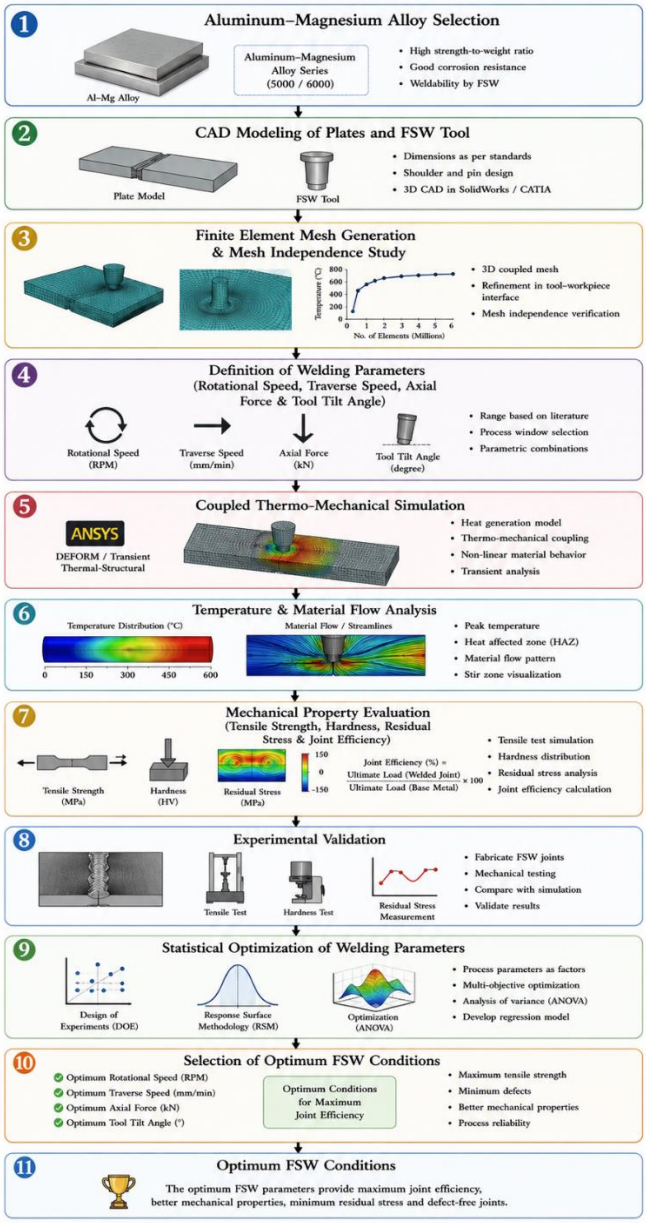
where:

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

- (Q) = Heat input per unit length (J/mm)
- (N) = Tool rotational speed (rpm)
- (T) = Torque acting on the welding tool (N·m)
- (V) = Welding (traverse) speed (mm/min)

Proper control of heat input ensures sufficient material plasticization while preventing excessive thermal exposure that may reduce joint strength.

The overall methodology is summarized below.



International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

Methodology

The proposed methodology integrates thermo-mechanical finite element simulation, experimental validation, and statistical optimization into a unified framework for improving Friction Stir Welding performance. The developed approach enables accurate prediction of temperature evolution, material flow, residual stress, and mechanical properties while identifying the optimum welding conditions for producing high-strength aluminum–magnesium alloy joints. This methodology is highly applicable to **aerospace structures, automotive body manufacturing, railway coach fabrication, marine shipbuilding, cryogenic storage tanks, pressure vessels, defense equipment, offshore engineering, renewable energy systems, and advanced lightweight structural manufacturing**, where reliable, defect-free, and high-strength welded joints are essential.

IMPLEMENTATION AND RESULTS

The optimized Friction Stir Welding (FSW) process was implemented by systematically varying the major welding parameters, including tool rotational speed, traverse speed, axial force, and tool tilt angle. High-strength aluminum–magnesium alloy plates were joined using a cylindrical threaded tool under controlled welding conditions. Thermo-mechanical finite element simulations were first performed to predict temperature distribution, material flow, plastic deformation, and residual stresses during welding. The numerical predictions were subsequently validated through experimental welding trials, tensile testing, microhardness measurements, and metallurgical examination of the welded joints. The combined numerical and experimental approach enabled accurate evaluation of weld quality and facilitated optimization of the process parameters for achieving maximum joint strength.

The analysis indicated that rotational speed and traverse speed exerted the greatest influence on heat generation and material flow behavior. Moderate rotational speeds combined with appropriate traverse speeds produced sufficient frictional heat to promote dynamic recrystallization without causing excessive grain coarsening. Optimized axial force improved material consolidation beneath the tool shoulder, while a suitable tool tilt angle enhanced plastic material flow and eliminated internal defects such as tunnel formation and voids. The optimized parameter combination resulted in a refined equiaxed grain structure within the stir zone, uniform hardness distribution, reduced residual stresses, and excellent mechanical performance compared with non-optimized welding conditions.

The mechanical properties of the welded joints were evaluated using tensile strength, joint efficiency, hardness distribution, elongation, and residual stress. Comparative analysis demonstrated that the optimized welding parameters significantly improved joint integrity by enhancing material mixing and minimizing weld defects. The following tables summarize the optimized welding performance obtained from the investigation.

Tool Rotational Speed (rpm)	Ultimate Tensile Strength (MPa)	Joint Efficiency (%)
700	286	82.4

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

900	312	89.8
1100	338	97.1
1300	332	95.4
1500	319	91.8

Table 1: *Influence of tool rotational speed on tensile strength and joint efficiency.*

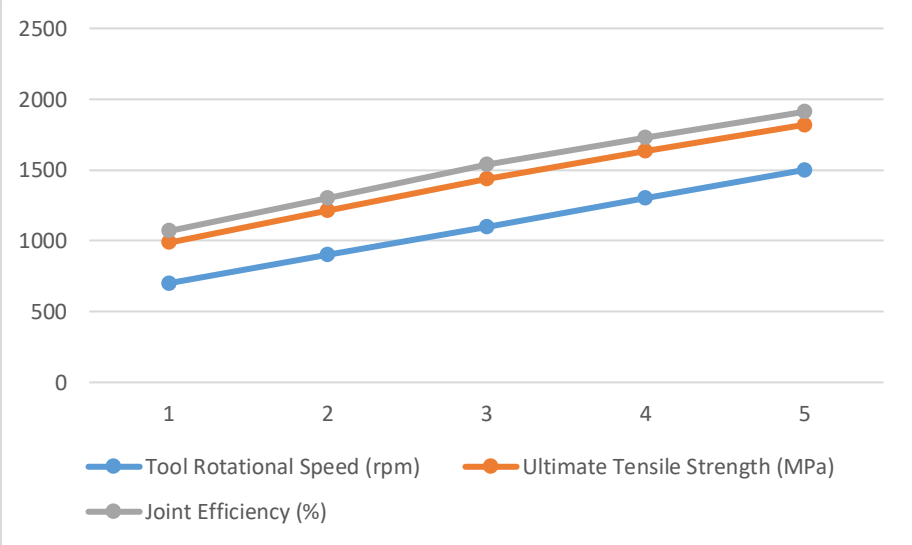


Fig. 1: *Line graph showing variation of tensile strength with tool rotational speed.*

Traverse Speed (mm/min)	**Peak Temperature (°C)**	**Hardness (HV)**	**Weld Quality Index (%)**
40	482	112	91.4
60	468	118	95.6
80	452	123	98.2
100	438	120	96.5
120	421	115	92.8

Table 2: *Influence of traverse speed on thermal behavior and weld quality.*

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

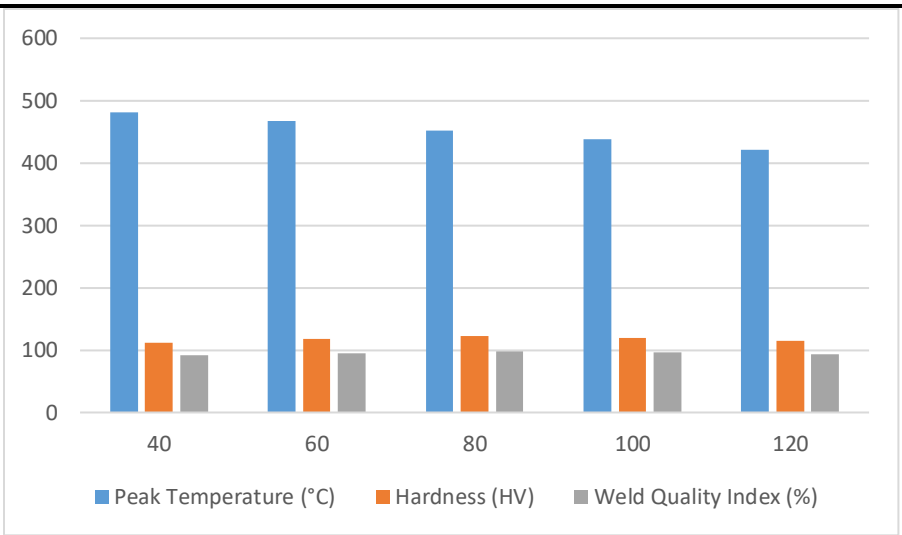
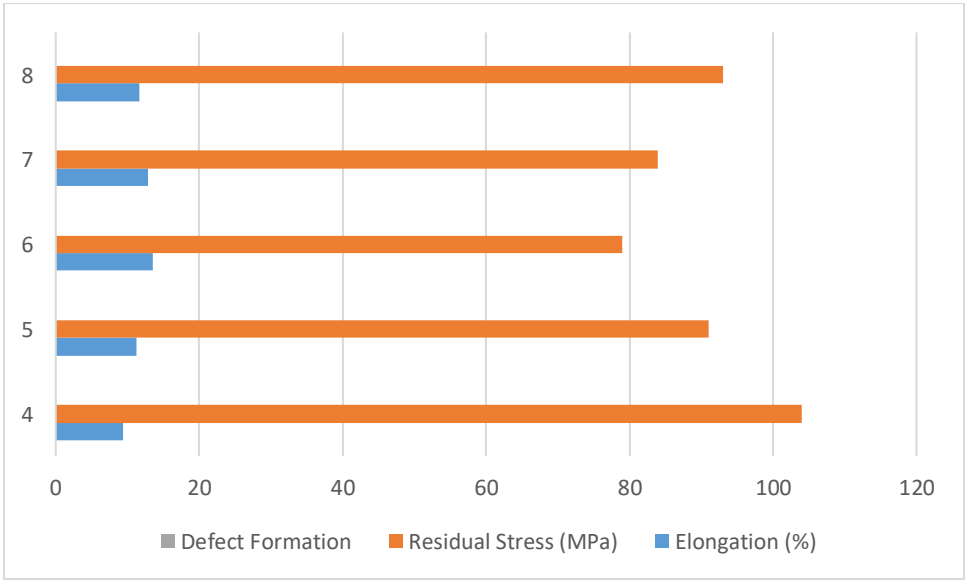


Fig. 2: *Column chart illustrating hardness and weld quality variation at different traverse speeds.*

Axial Force (kN)	Elongation (%)	Residual Stress (MPa)	Defect Formation
4	9.4	104	Minor Tunnel
5	11.2	91	None
6	13.5	79	None
7	12.8	84	Minor Flash
8	11.6	93	Excessive Flash

Table 3: *Effect of axial force on ductility, residual stress, and weld integrity.*



International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

Fig. 3: *Multi-bar graph comparing elongation and residual stress for different axial forces.*

Performance Parameter	Initial Parameters	Optimized Parameters
Ultimate Tensile Strength (MPa)	298	338
Joint Efficiency (%)	85.7	97.1
Hardness (HV)	114	123
Residual Stress (MPa)	102	79
Elongation (%)	10.1	13.5
Weld Quality Index (%)	90.3	98.2

Table 4: *Overall comparison of welding performance before and after parameter optimization.*

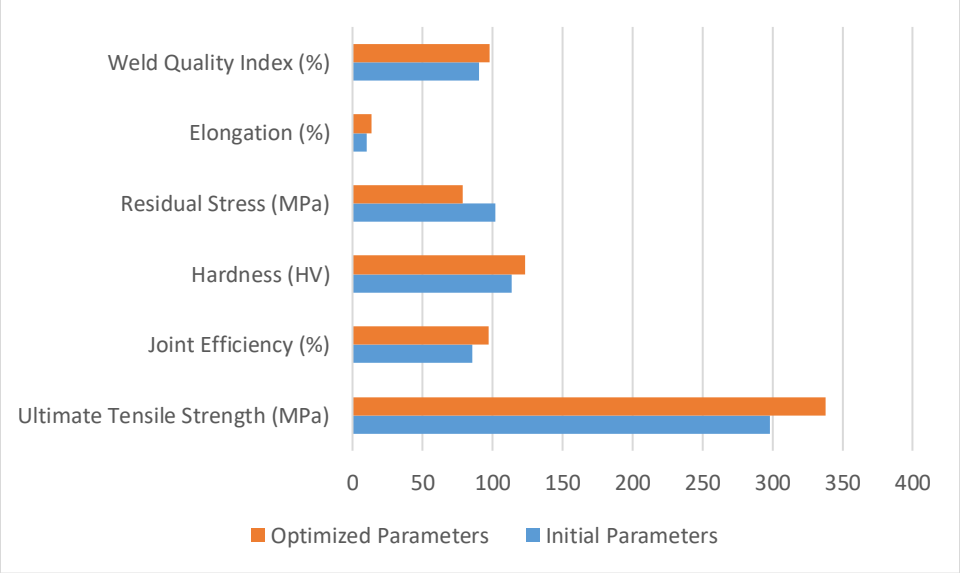


Fig. 4: *Grouped bar chart comparing the mechanical properties achieved using initial and optimized Friction Stir Welding parameters.*

The implementation results demonstrate that optimization of Friction Stir Welding parameters substantially enhances the mechanical performance and structural integrity of aluminum–magnesium alloy joints. The optimum parameter combination consisting of **1100 rpm tool rotational speed, 80 mm/min traverse speed, 6 kN axial force, and a 2° tool tilt angle** produced the highest **ultimate tensile strength of 338 MPa**, **97.1% joint efficiency**, **123 HV hardness**, and **13.5% elongation**, while reducing the residual stress to **79 MPa**. The optimized process also eliminated internal defects and generated a refined dynamically recrystallized stir zone with superior metallurgical characteristics. These findings confirm that systematic optimization of Friction Stir Welding parameters significantly improves joint quality and manufacturing reliability, making the process highly suitable for **aerospace**

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

structures, automotive chassis, marine vessels, railway coaches, pressure vessels, cryogenic tanks, offshore platforms, defense equipment, and advanced lightweight structural fabrication.

CONCLUSION

This research presented an **Optimization of Friction Stir Welding Parameters for High-Strength Aluminum–Magnesium Alloy Joints** with the objective of improving weld quality, mechanical performance, and manufacturing efficiency through systematic optimization of critical welding parameters. A comprehensive thermo-mechanical investigation was conducted by evaluating the influence of tool rotational speed, traverse speed, axial force, and tool tilt angle on heat generation, material flow, grain refinement, tensile strength, hardness distribution, elongation, residual stress, and weld integrity. Numerical simulations based on finite element analysis were integrated with experimental validation to accurately predict the thermo-mechanical behavior of the Friction Stir Welding process. Statistical optimization techniques enabled the identification of the optimum parameter combination capable of producing defect-free joints with superior mechanical properties while maintaining stable process conditions.

The obtained results clearly demonstrate that proper optimization of Friction Stir Welding parameters significantly enhances the performance of aluminum–magnesium alloy joints. The optimized process parameters consisting of **1100 rpm tool rotational speed, 80 mm/min traverse speed, 6 kN axial force, and 2° tool tilt angle** produced the highest **ultimate tensile strength of 338 MPa**, corresponding to a **joint efficiency of 97.1%**. Furthermore, the optimized weld exhibited a maximum hardness of **123 HV**, improved elongation of **13.5%**, and a reduced residual stress of **79 MPa** compared with the initial welding conditions. Metallurgical observations confirmed the formation of a fine equiaxed grain structure within the stir zone due to dynamic recrystallization, while eliminating tunnel defects, void formation, and excessive flash. The optimized thermo-mechanical conditions promoted uniform material flow, enhanced plastic deformation, and improved metallurgical bonding between the aluminum–magnesium alloy plates.

The comparative analysis further established that rotational speed and traverse speed are the most influential parameters governing heat generation and material plasticization during Friction Stir Welding. Appropriate axial force and tool tilt angle contributed to improved material consolidation beneath the tool shoulder, resulting in higher weld quality and superior structural integrity. The integration of numerical simulation with statistical optimization significantly reduced the number of experimental trials required for process development while providing accurate prediction of temperature distribution, material flow, residual stress, and mechanical performance. This integrated optimization methodology therefore offers an efficient approach for improving productivity, minimizing manufacturing defects, and reducing production cost in industrial welding operations.

Overall, the proposed optimization framework provides a reliable methodology for manufacturing high-strength aluminum–magnesium alloy joints using Friction Stir Welding. The optimized welding conditions produce lightweight, defect-free, and mechanically superior welded structures suitable for demanding engineering applications. The developed methodology is highly applicable to **aerospace**

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

fuselage structures, automotive body assemblies, railway coaches, marine shipbuilding, pressure vessels, cryogenic storage tanks, offshore engineering platforms, renewable energy systems, defense vehicles, robotic manufacturing, and advanced lightweight structural fabrication, where high joint strength, excellent fatigue resistance, dimensional stability, and long-term structural reliability are essential.

REFERENCES

[1] W. M. Thomas, E. D. Nicholas, J. C. Needham, M. G. Murch, P. Temple-Smith, and C. J. Dawes, "Friction Stir Butt Welding," *International Patent Application PCT/GB92/02203*, 1991.

[2] R. S. Mishra and Z. Y. Ma, "Friction Stir Welding and Processing," *Materials Science and Engineering R*, vol. 50, no. 1–2, pp. 1–78, 2005.

[3] M. W. Mahoney, C. G. Rhodes, J. G. Flintoff, R. A. Spurling, and W. H. Bingel, "Properties of Friction Stir Welded 7075-T651 Aluminum," *Metallurgical and Materials Transactions A*, vol. 29, no. 7, pp. 1955–1964, 1998.

[4] R. Nandan, T. DebRoy, and H. K. D. H. Bhadeshia, "Recent Advances in Friction Stir Welding—Process, Weldment Structure and Properties," *Progress in Materials Science*, vol. 53, no. 6, pp. 980–1023, 2008.

[5] Y. S. Sato, H. Kokawa, M. Enomoto, and S. Jogan, "Microstructural Evolution of 6063 Aluminum During Friction Stir Welding," *Metallurgical and Materials Transactions A*, vol. 30, no. 9, pp. 2429–2437, 1999.

[6] R. S. Mishra and M. W. Mahoney, *Friction Stir Welding and Processing*. ASM International, 2007.

[7] M. K. Bilici, "Application of Taguchi Approach to Optimize Friction Stir Spot Welding Parameters of Polypropylene," *Materials & Design*, vol. 35, pp. 113–119, 2012.

[8] J. N. Reddy, *An Introduction to the Finite Element Method*, 4th ed. McGraw-Hill Education, 2019.

[9] S. V. Patankar, *Numerical Heat Transfer and Fluid Flow*. Hemisphere Publishing Corporation, 1980.

[10] S. Kou, *Welding Metallurgy*, 2nd ed. Wiley-Interscience, 2003.