Optimisation and Process Investigation of Friction Stir Welded AA6351 Aluminium Alloy Using Taguchi L27 Orthogonal Array

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Abstract

The friction stir welding (FSW) process has gained significant attention for joining aluminium alloys due to its ability to produce defect-free welds with superior mechanical properties. This study focuses on optimizing and enhancing the friction stir welding parameters of AA6351 aluminium alloy using the Taguchi L27 orthogonal array methodology. The key process parameters considered include rotational speed, welding speed, and axial force.

An experimental design based on the Taguchi L27 orthogonal array was employed to systematically investigate the effects of these parameters on the tensile strength, hardness, and microstructure of the welded joints. Analysis of Variance (ANOVA) was used to identify the significance of each parameter and their interactions on the welding quality.

The results demonstrated that the rotational speed and welding speed significantly influence the tensile strength and hardness of the welds, while the axial force primarily affects the micro structural characteristics. Optimal parameter settings were identified, which led to enhanced mechanical properties and a finer, more homogeneous microstructure in the welded joints. This study provides a robust framework for optimizing FSW parameters using the Taguchi method, contributing to the improvement of weld quality in AA6351 aluminium alloys. The findings are expected to benefit industries where lightweight and high-strength aluminium structures are critical, such as aerospace and automotive sectors.

Keywords**:** Friction Stir Welding (FSW), AA6351 Aluminium Alloy, Taguchi Method, L27 Orthogonal Array, Optimization, Tensile Strength, Hardness, Microstructure.

1. Introduction

Friction stir welding (FSW) has emerged as a revolutionary solid-state joining process, particularly suitable for aluminium alloys. This process, developed by The Welding Institute (TWI) in 1991, utilizes a non-consumable rotating tool to join materials without melting them, leading to superior mechanical properties and minimal defects compared to conventional welding techniques. Among the various aluminium alloys, AA6351 is widely used in aerospace, automotive, and structural applications due to its excellent strength-to-weight ratio, good corrosion resistance, and high formability.

The optimization of FSW parameters is critical to achieving optimal weld quality in AA6351 aluminium alloy. Key process parameters such as rotational speed, welding speed, and axial force significantly influence the tensile strength, hardness, and micro structure of the welded joints. However, identifying the optimal combination of these parameters through conventional trial-and-error methods can be time-consuming and costly.

The Taguchi method, a robust statistical tool for optimization, offers a systematic approach to determine the optimal process parameters with a minimal number of experiments. By employing an orthogonal array, such as the L27 array, the Taguchi method facilitates the efficient evaluation of multiple parameters and their interactions, leading to improved process performance and quality.

This study aims to optimize and enhance the friction stir welding parameters for AA6351 aluminium alloy using the Taguchi L27 orthogonal array. The objectives are to investigate the effects of rotational speed, welding speed, and axial force on the tensile strength, hardness, and microstructure of the welded joints, and to identify the optimal parameter settings that maximize the mechanical properties of the welds. Through a comprehensive analysis involving experimental trials and statistical techniques, this research seeks to provide valuable insights and guidelines for the efficient and effective application of FSW in industrial settings.

The findings from this study are expected to contribute to the advancement of welding technologies for aluminium alloys, promoting their broader adoption in high-performance applications. By enhancing the understanding and control of FSW parameters, this research aims to facilitate the production of high-quality welded joints, thereby extending the service life and reliability of aluminium structures.

1.1 FSW PARAMETERS

Friction Stir Welding (FSW) parameters for AA6351 aluminium alloy are crucial in determining the quality and mechanical properties of the welds. Here are the primary FSW parameters typically considered:

1. Rotational Speed (RPM)

The rotational speed of the tool is a critical parameter that affects heat generation and material flow during the welding process. Higher rotational speeds generally increase the heat input, promoting better material mixing but may also lead to excessive softening and defects if not optimized.

2. Welding Speed (mm/min)

Welding speed, or traverse speed, refers to the speed at which the welding tool moves along the joint. This parameter balances the heat input and cooling rate. Higher welding speeds reduce the heat input and increase the cooling rate, which can affect the microstructure and mechanical properties of the weld.

3. Axial Force (kN)

Axial force, or downforce, is the pressure applied by the tool onto the work pieces. This parameter influences the material consolidation and the contact condition between the tool and the work pieces. Adequate axial force is essential to ensure proper forging action and defect-free welds.

4. Tool Geometry

Shoulder Diameter: The diameter of the shoulder affects the heat input and material flow. Larger shoulder diameters increase the heat input and enhance material mixing.

Pin Profile: The shape and size of the pin (cylindrical, threaded, tapered, etc.) play a significant role in the stirring action and material flow within the weld zone.

Pin Length: The length of the pin must be slightly less than the thickness of the work pieces to ensure proper penetration and bonding without damaging the backing plate.

5. Tool Tilt Angle (degrees) The tilt angle of the tool affects the downward force distribution and material flow. A slight tilt (usually 1-3 degrees) towards the trailing edge of the tool helps in better consolidation of the material and prevents defects such as voids and lack of penetration.

6. Plunge Depth (mm)

Plunge depth is the depth to which the tool penetrates into the work pieces. This parameter ensures sufficient contact between the tool and the material, affecting heat generation and material flow.

7. Dwell Time (seconds)

Dwell time is the period during which the tool remains stationary at the start of the welding process to generate sufficient heat for initiating material flow. This parameter is crucial for starting the weld and ensuring proper material mixing.

1.2 Optimized Parameters for AA6351 Aluminium Alloy

The optimal combination of these parameters for welding AA6351 aluminium alloy can be identified through systematic experimentation and statistical analysis, such as the Taguchi method. An example of optimized parameters might be:

Rotational Speed: 1000--2000 RPM

Welding Speed: 120-180 mm/min

Tool Pin Profile: square, Cylindrical threaded, tapered

2. METHODOLOGY

The material required for performing friction stir welding experiment are AA6351. Taguchi method is a robust experimental design method used to solve single-response problems for optimal process parameters. The optimum parameter values reduce the variation in the response and maintain the mean of the response at the desired value. Taguchi approach uses the well balanced robust experimental design known as orthogonal arrays (OAs) to study a large number of parameters with a few experiments. Signal-to-Noise (S/N) ratio, which is logarithmic function of response serve as performance characteristic for optimization. The S/N ratio is a measure of robustness that identifies the control factors that reduce the variability in a process.

2.1 Experimental Setup

A significant impact on mechanical properties was observed in material after friction stir processing as far as thermal behaviour and residual stresses are concerned. The issue in FSP, as with many developing advancements, is that the experimentation is costly in terms of time, materials, featuring and skill. For friction stir welding of dissimilar metals, AA6351 alloy were selected. AA6351 alloy was selected owing to its moderate strength and good corrosion resistance while pure copper was selected due to its high ductility and good strength properties.

- The plates of dimensions 100 mm x 100 mm x 6mm dimensions using vertical milling machine.
- The plates were filed at the corners to give them a fillet for it to fit into the fixture

Base Metal Properties

The base metal used in this investigation is AA 6351 aluminum alloy. The chemical composition of the base metal is evaluated in weight percent and it is given in Table. The mechanical property of the base metal is also evaluated and it is given in Table. The American Society for Testing and Materials (ASTM -E8) guidelines were followed for preparing the tensile test specimens.

Table 1: Chemical composition (wt. %) of base metal

Cu	Mn	Zr	V	Ti	Fe	Si	Zn	Mg	Al
6.2	0.3	0.11	0.09	0.06	0.16	0.05	0.01	0.01	93.01

Table 2: Mechanical properties of base metal

UTS (MPa)	YS (MPa)	% Elongation(On 50mm GL)
150.2	68	15

2.2 Experimental Procedure

Single pass butt welds were produced in 6 mm thick plates of aluminum alloy 6351 using indigenously designed friction stir welding machine. The machine can rotate the tool up to 3000 rpm, apply an axial load of up to 30 kN and the transverse speed can be 500 mm/min. A wattmeter is connected to the motors of the FSW machine to measure the power consumed by the machine. Rolled plates of 6 mm thickness were cut into required size (100 mm × 100 mm) using shaper and milling machines. The mechanical clamps are used to clamp the plate on the work table of the machine. The joints were fabricated normal to the rolling direction. The experiments were conducted using parameters of the designed matrix. The American Society for Testing and Materials (ASTM-E8) guidelines were followed for preparing the tensile test specimens. The wire cut EDM is used to cut the smooth profile tensile specimens. The photograph of the Friction Stir Welding machine is displayed in Figure. The photograph of the tools is shown in Figure. The details regarding the tool dimension and welding parameters used in this investigation are given in Tables respectively. The photographs of some fabricated joints are displayed in Figure.

Figure 1. Photograph of friction stir welding machine (Trident welding and research)

Table 3: Machine standard specification

Description	Specification
Z axis load	100kN
Spindle nose	ISO 50
Spindle speed	5000 rpm
Z axis travel	300 mm

Table to Spindle Min/Max	500mm to 800 mm
Z axis velocity	1000 mm/min
X axis travel	2000 mm
X /Y axis velocity	3000 mm/min
Y axis travel	1000 mm
A AND B Head tilt angle	+- 5^o
Controller	Force and Position mode control
Data Acquisition	Spindle rpm, torque axis velocity, force against time and dis

a) Tapered **b) cylindrical threaded** **c) square**

Figure 2: Photograph of FSW tool

The metallic plates of 6 mm thickness were cut in to 100 mm length and 100 mm wide rectangular pieces. L27 orthogonal array of the Taguchi design method was used as the design matrix. The parameters considered were tool rotational speed, tool traversal speed, axial force and tool pin profile. The various parametric levels and the design of experiment matrix are given as Tables

Table 4: FSW parameters and their levels

Factors	Level 1	Level 2	Level 3
Tool rotational speed, N (rpm)	1000	1500	2000
Tool traversal speed, S (mm/min)	120	150	180
Vertical force F (kN)	11	12.5	14.5
Tool pin profile, D	Square	Cylindrical Threaded	Tapered

3. Selection Of Orthogonal Array: Selection of an Orthogonal Array (OA) is an important stage in conducting the Design of Experiments (DOE). The number of parameters and interactions, and the number of levels of the parameters are the points which are to be considered before using an Orthogonal Array (OA). To analyse the non–linear behaviour of the parameters, the levels of the parameters should be more than two. Four parameters at three levels each are selected for conduct of DOE. As per Taguchi method, the total degrees of freedom (DOF) of selected OA must be greater than or equal to the total DOF required for the experiment and hence L27 OA is selected.

3.1 Process of approach for Taguchi:

➢ The L27 Taguchi orthogonal designed experiments of Friction Stir Welding on aluminium alloy AA6351 were successfully conducted.

➢ The FSW process parameters were optimized to maximize the tensile strength of the joint. The optimum levels of the rotational speed, transverse speed, and axial load were found to be 1000-2000 rpm, 150-180 mm/min and 11-14.5kN, respectively, for square cylindrical tapered column tool without threads.

➢ **Tensile Test:**

➢ The tensile tests were carried out in the Universal Testing Machine (UTM- HL 59020). At first the specimens were cut from the welded plate dimensions as per ASTM standards (E8/E8M-04).

➢ The specimen preparation was carried out at room temperature on the EDM machine. The ultimate tensile strength and elongation at the fracture point is recorded by the control computer for each set. These values were then used to produce stress- strain curves for the material. The wire cut EDM is used to cut the smooth profile tensile specimens. The tensile specimen profile is given in Figure.

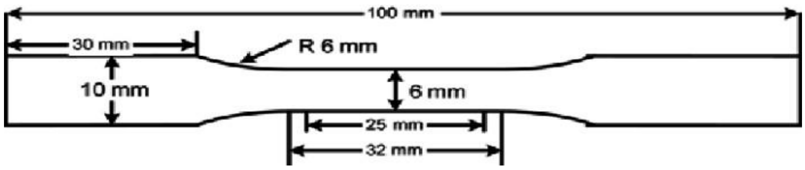


Figure 3 Dimensions of tensile specimen

4. Material Preparation

Aluminum 6351 alloy plates having a thickness of 6 mm were used and cut into work pieces. The work pieces having dimensions of 100 mm × 100 mm were prepared to get the FSW butt joint. The direction of the welding was kept normal to the rolling direction. A non-consumable H13 steel tool with two different pin profiles (taper cylindrical and square) was used, as shown in Fig. A conventional vertical milling machine with a proper fixture arrangement was utilized to fabricate the FSW joints.

4.1 Experimental test methods:

Four controlling factors, including the tool rotation speed (RPM), transverse speed (TS), shoulder diameter (SD), and tool pin profile (TP), were selected. Three parameters in four levels and one parameter in two levels were varied, as depicted in Table. The Taguchi L27 factorial design was used to conduct the experiments. as shown in Table. The Minitab 18 software tool was used for the Taguchi design of the investigation. After that, the different FSW welded joint specimens were constructed according to the Taguchi design matrix, as depicted in Fig.

Table 5: FSW experimental factors and their levels

Levels	Experimental control factors		
	Tool rotation speed (rpm)	Transverse speed (mm/min)	Tool pin profile
1	1000	120	Square
2	1500	150	Cylindrical threaded
3	2000	180	Tapered

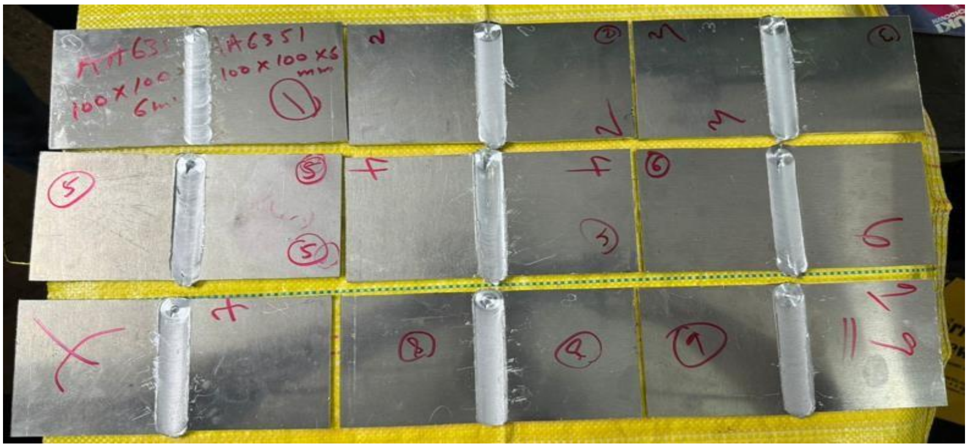


Figure 4: Photograph of fabricated FSW joints according to Taguchi design matrix

Figure 5: Photograph of fabricated FSW welded tensile test specimens

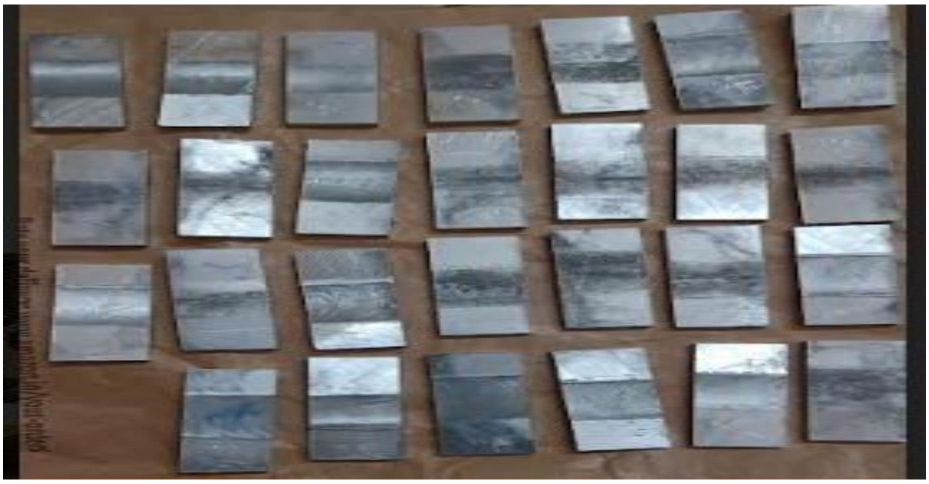


Figure 6: Photograph of fabricated FSW welded hardness test specimens

All the specimens for tensile testing were carefully cut from FSW welded aluminum plates following standard ASTM E8 as depicted in Fig. The FSW welded specimens were tested on Universal Testing Machine (FIE Pvt. Ltd., India; Model: UTE-40; Maximum capacity: 400 kN) at an ambient temperature to evaluate the mechanical characteristics like UTS, YS, and % elongation. Vickers micro hardness test was conducted on cross- section of specimens. The indentation load applied in the experiments was 250 gf, while the dwell time was 10 seconds. The hardness profile was taken for the middle cross- section of welded samples. Starting from the center of the weld, the hardness profile was measured at SZ, TMAZ, HAZ, and BM on either side of the weld line. Each value was accurately calculated after each experimental run and is all listed in Table.

Table 6: Taguchi design matrix and output responses for mechanical properties of FSW welded AA 6351 Al alloy

Factors				Responses			
Experimental run	Rotational Speed(rpm)	Transverse speed(mm/min)	Tool pin profile	UTS N/mm^2	YS N/mm^2	% Elonga tion	Hardness (VHN)
1	1000	120	Square	250.59	204.4	2.42	81.78
2	1000	120	Cylindrical threaded	241.49	196.1	2.13	82.45
3	1000	120	Tapered	203.18	167.43	3.41	84.34
4	1000	150	Square	220.23	168.29	2.76	87.98
5	1000	150	Cylindrical threaded	230.13	181.3	2.45	88.45
6	1000	150	Tapered	194.59	151.8	2.04	90
7	1000	180	Square	230.02	182.1	3.1	87.23
8	1000	180	Cylindrical threaded	202.79	159.29	2.93	86.31
9	1000	180	Tapered	246.43	194.49	3.86	91.3
10	1500	120	Square	242.07	201.65	2.96	84.39
11	1500	120	Cylindrical threaded	252.32	190.41	4.68	90.72
12	1500	120	Tapered	218.78	175.9	2.43	88.61
13	1500	150	Square	202.58	154.07	2.7	87.51
14	1500	150	Cylindrical threaded	220.7	150.89	2.34	88.43
15	1500	150	Tapered	231	176.23	3.1	83.67
16	1500	180	Square	239.9	169.98	2.76	85.5
17	1500	180	Cylindrical threaded	238.9	198.78	2.31	87.4
18	1500	180	Tapered	238	183.8	2.18	85.1
19	2000	120	Square	251.23	193.12	2.47	86.1
20	2000	120	Cylindrical threaded	212.79	189.29	2.93	87.31
21	2000	120	Tapered	240.39	198.4	2.32	83.58
22	2000	150	Square	231.49	186.1	2.13	84.35
23	2000	150	Cylindrical threaded	223.18	187.43	2.91	86.34
24	2000	150	Tapered	230.23	178.29	2.86	88.9
25	2000	180	Square	240.13	185.3	2.84	89.3
26	2000	180	Cylindrical threaded	199.2	154.6	2.14	91
27	2000	180	Tapered	200.01	162.1	3.1	86.48

The GRA was used to observe how FSW process parameters affect the quality of the welds. A rank was extracted for each experiment. An experiment with a higher rank will give the optimum response from all the experimental runs. An optimum combination of these parameters was then obtained. ANOVA was also utilized to predict which factor has the highest impact on overall responses and which has the least.

Based on the experimental design matrix suggested by the Taguchi method, the output responses such as YS, UTS, % elongation, and micro-hardness of FSW specimens were measured, as shown in Table. Among the twenty-seven specimens, the highest value of UTS and YS of the FSW welded specimens are 252.32 (N/mm^2) and 204.4 (N/mm^2), equal to 76.72% and 71.22% of the BM zone, respectively, which is considered to be relatively good. The FSW welded joint made up of tool rotation speed (RPM) of 1000, transverse speed (TS) of 180 mm/min, and tapered pin profile revealed the highest UTS and % elongation of the specimens. The hardness was calculated at four zones: SZ, TMAZ, HAZ, and BM. The hardness profile of all twenty-seven FSW samples is shown in Fig. In all experimental runs, weld SZ was found to have the highest hardness values compared to all the other FSW zones. Complete surface interaction with the tool shoulder causes SZ to produce more heat, and due to the dynamically recrystallized phenomena, a fine grain structure was observed in the SZ. The maximum hardness of 91.3 VHN came out in experiment number 9 at RPM of 1000, TS of 180 mm/min, with taper tool pin profile. The joint fabricated in experiment number 1 (having lower RPM, WD, and SD) exhibits the minimum hardness value. This may be due to low heat generation at low tool rotation speed.

Table 7: Normalized values of each output response

Experimental run	UTS	YS	% Elongation	Hardness (VHN)
	(N/mm^2)	(N/mm^2)		
Ideal value	1	1	1	1
1	0.97	1	0.1439	0
2	0.8124	0.8449	0.0341	0.0704
3	0.1488	0.3091	0.5189	0.2689
4	0.4441	0.3252	0.2727	0.6513
5	0.6156	0.5683	0.1553	0.7006
6	0	0.017	0	0.8634
7	0.6137	0.5833	0.4015	0.5725
8	0.142	0.157	0.3371	0.4758
9	0.898	0.8148	0.6894	1
10	0.8224	0.9486	0.3485	0.2742
11	1	0.7386	1	0.9391
12	0.419	0.4674	0.1477	0.7174
13	0.1384	0.0594	0.25	0.6019
14	0.4523	0	0.1136	0.6985
15	0.6307	0.4736	0.4015	0.1985
16	0.7849	0.3568	0.2727	0.3908
17	0.2656	0.291	0.1009	0.3309

18	0.4755	0.5134	0.3394	0.361
19	0.9385	0.7725	0.844	0.7034
20	0.715	0.668	0.7706	0.5418
21	0.6432	0.5309	0.4036	0.6648
22	0.9557	0.8317	0.8623	0.9415
23	0.8377	0.646	0.7522	0.8824
24	0.5162	0.507	0.4128	0
25	0.9282	0.8841	0.8165	0.3911
26	0.5748	0.629	0.7155	0.15
27	0.6432	0.5613	0.1009	0.361

- Elongation Outlier: Run 7 shows very low % elongation (0.0341), significantly underperforming compared to the others. Investigate potential issues affecting this run.
- YS (N/mm2) Variation: Runs 6 and 8 display unexpectedly low YS values (0.017 and 0.157, respectively), much lower than the ideal value. Evaluate why these deviations occur for improvement.

4.2 Optimum level of factor based on GRG

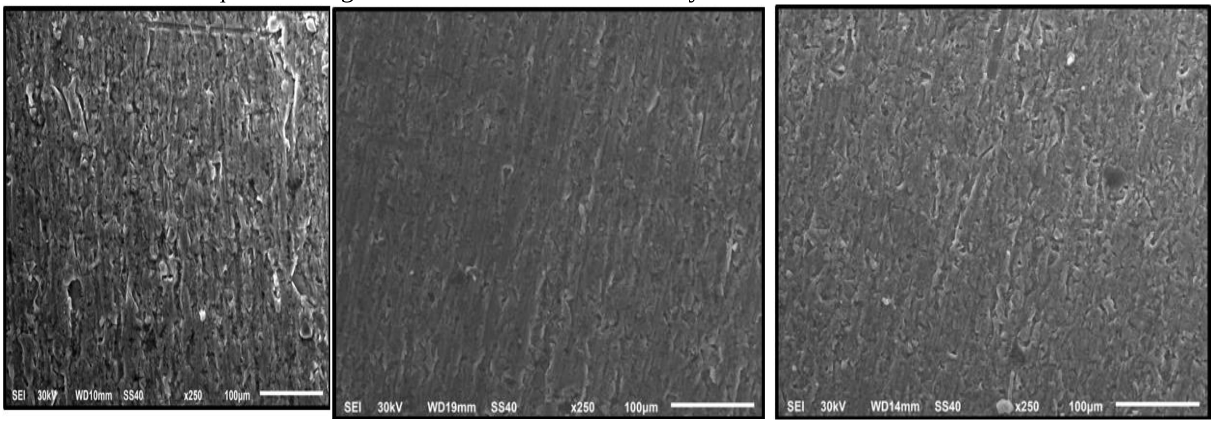
The response table for the mean for each process parameter at different levels is evaluated and depicted in Table. Fig represents the mean effect plot of process parameters on the GRG obtained from the Minitab software tool. In this graph, the higher values of GRG give the optimum combination of FSW process parameters. Also, higher GRG represents the least dissimilarity between the desired and measured responses. In both Fig. and Table, it is observed that the optimum parametric combination to get the enhanced mechanical properties using the Taguchi method is found to be at the tool rotation speed of 1200 rpm, transverse speed of 250 mm/min, shoulder diameter of 18 mm and pin profile of taper circular shape respectively. This optimum arrangement was symbolized as RPM3 – TS1 – SD4 – TP1.

Table 8: Response table for means (larger the better) for GRG

Level	Factors		
	RS	**TS**	**PP**
1	0.3918	**0.4728**	0.4300
2	0.3235	0.4584	0.3516
3	**0.5805**	0.3579	0.3786
4	0.3050	0.3116	**0.4406**
Delta	0.2755	0.1612	0.0890
Rank	1	2	3

5.0 Microstructure of the welded joints of AA6351 aluminum alloy:

The macroscopic facets of the joints are shown in Fig. 4.6. The nugget regions of all the joints had basin shape which indicates adequate stirring and transfer of weld material by the tool action



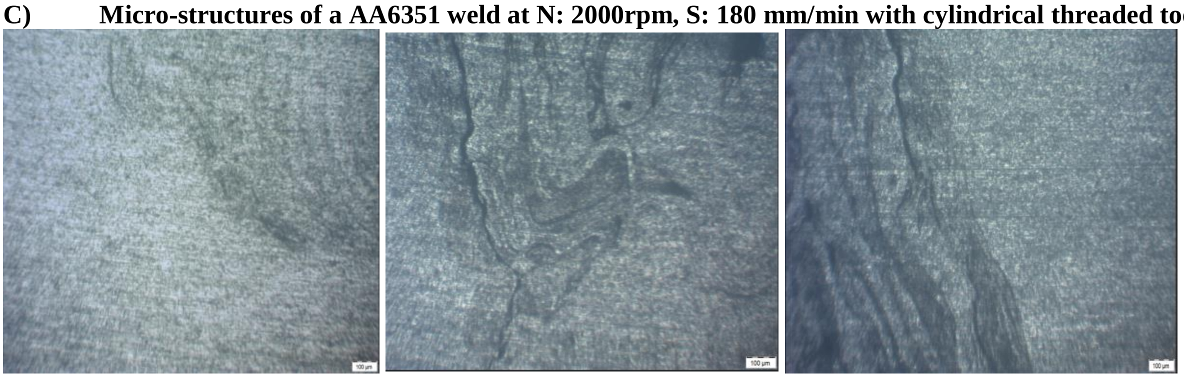
A) B) C)

Figure 7 Shows a) Micro-structures of a AA6351 weld at N: 1000rpm, S: 120 mm/min with square tool
b) Micro-structures of a AA6351 weld at N: 1500rpm, S: 150 mm/min with square tool
c) Micro-structures of a AA6351 weld at N: 2000rpm, S: 180 mm/min with square tool

The joint processed with square tool as per process parameters combination in set of the design of experimentation exhibited fine grain structure with grain boundaries at the stir zone or nugget zone as shown in Fig. A higher tool rotational speed of 2000 rpm with 180 mm/min feed has resulted in lesser voids and uniform grain structure.

A) B) C)

Figure 8 shows A) Micro-structures of a AA6351 weld at N: 1000rpm, S: 120 mm/min with cylindrical threaded tool
B) Micro-structures of a AA6351 weld at N: 1500rpm, S: 150 mm/min with cylindrical threaded tool
C) Micro-structures of a AA6351 weld at N: 2000rpm, S: 180 mm/min with cylindrical threaded tool



A) B) C)

Figure 9 A) Micro-structures of a AA6351 weld at N: 1000rpm, S: 120 mm/min with Tapered tool
B) Micro-structures of a AA6351 weld at N: 1500rpm, S: 150 mm/min with Tapered tool
C) Micro-structures of a AA6351 weld at N: 2000rpm, S: 180 mm/min with Tapered tool

The FSW process can be thought to be simply extruding material in layers through semi cylindrical paths in one rotation of the tool and a cross-sectional view of such a set of semi cylindrical layers appears as onion ring structure. Hence it can be perceived that all the weld joints especially under rotational speed N= 2000 rpm and transverse speed S: 180mm/min axial forces, for the given set of other parameters, were formed with adequate material flow. The macrostructure of square tool and tapered tool at N: 1500rpm and S: 150mm/min indicate that the material flow was more or less symmetrical when compared with other joints and it has strengthened the mechanical properties of these joints

During FSW the downward force keeps the shoulder in contact with the material. The downward force enhances the friction and keeps the stirred material in the weld region. The downward force increases the plastic flow of material during the welding process. An optimum combination of transverse speed and rotational speed results in consistent filling of welding cavity through consolidating the tool with the base material. However, the increase in down ward force beyond a limit increases subsurface material flow which hampers the effective filling of welding cavity

5. Conclusion

This study has successfully demonstrated the application of the Taguchi L27 orthogonal array for the optimization and enhancement of friction stir welding (FSW) parameters for AA6351 aluminium alloy. By systematically varying and analysing the effects of rotational speed, welding speed, and axial force, the research identified the optimal process parameters that maximize the mechanical properties of the welded joints.

Key findings from the investigation revealed that:

Rotational Speed and Welding Speed: These parameters significantly influenced the tensile strength and hardness of the welds. Optimal settings led to enhanced mechanical properties, contributing to stronger and more resilient welds.

Axial Force: This parameter primarily affected the microstructural characteristics of the welds. Proper adjustment resulted in a finer and more homogeneous microstructure, reducing the occurrence of defects and improving overall weld quality.

The use of the Taguchi method provided a robust framework for optimizing FSW parameters with minimal experimental runs, making it a cost-effective and efficient approach for process enhancement. In conclusion, the optimized FSW parameters identified in this study have led to significant improvements in the mechanical properties and microstructure of AA6351 aluminium alloy welds. The findings offer practical guidelines for the industrial application of FSW, promoting the use of AA6351 in high-performance applications where lightweight and high-strength materials are essential. the SEM analysis of the friction stir welded AA6351 alloy typically confirms that the process leads to significant microstructural refinement, with the potential for enhanced mechanical properties. The SEM images typically reveal that the friction stir welding (FSW) process results in significant grain refinement within the stir zone (SZ) compared to the base material. This refinement is due to the severe plastic deformation and dynamic recrystallization that occur during welding. Finer grains often contribute to enhanced mechanical properties, such as increased strength and hardness in the weld region. The successful implementation of the Taguchi method in this study underscores its potential as a powerful tool for process optimization, paving the way for continued advancements in friction stir welding technology and its applications in various industries

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