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COMPARATIVE ANALYSIS AND OPTIMIZATION OF FRICTION STIR WELDING PARAMETERS FOR AA6351 ALUMINUM ALLOY: AN APPROACH USING $AgNO_3$ NANO COATINGS

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Abstract:

Friction Stir Welding (FSW) is a solid-state joining process that is widely utilized for aluminum alloys due to its superior mechanical properties and efficiency in aerospace and structural applications. This study investigates the impact of key FSW process parameters on the weld quality of AA6351 aluminum alloy, with and without silver nitrate ($AgNO_3$) Nano coating. The primary objective is to determine the optimal welding conditions that enhance tensile strength, hardness, and fatigue resistance using the Taguchi L27 experimental design. The experiments were conducted with, perhaps the highest welding speed reported, so far. Through the analysis, optimum combinations of the parameters were suggested for each material at a high speed friction stir window. The selected parameters were tool rotational speed, welding speed, and tool pin profile, each evaluated at three distinct levels. AgNO3 Nano coatings were applied to a set of samples to assess its impact on the welds. The welded samples were then subjected to a series of tests, including tensile strength testing, hardness measurement, and microstructural analysis using optical microscopy and scanning electron microscopy (SEM). This study also investigates the optimization of FSW parameters for AA6351 aluminum alloy using $AgNO_3$ coated nanoparticles as coatings. Mechanical properties were evaluated through tensile tests, hardness measurements, and fatigue tests. Experiments were conducted by welding AA6351 aluminum alloy plates under varying process conditions

1. Introduction:

Friction Stir Welding (FSW) has emerged as an advanced solid-state joining process widely used for aluminum alloys due to its ability to produce defect-free welds with superior mechanical properties (Mishra & Ma, 2005). Among various aluminum alloys, AA6351 is preferred in aerospace, marine, and automotive industries due to its excellent strength-to-weight ratio, corrosion resistance, and weldability (Kumar & Kailas, 2008). However, optimizing the process parameters remains a challenge to achieve enhanced weld strength and microstructural refinement.

To address this, recent studies have explored the use of nano-coatings as reinforcement agents to improve weld characteristics. Silver nitrate ($AgNO_3$) nanoparticles, known for their antibacterial properties and high thermal conductivity, have been investigated for their potential in modifying the weld zone microstructure and enhancing mechanical properties (Zhang et al., 2019). The integration of $AgNO_3$ nano-coatings into the FSW process can influence grain refinement, hardness, and overall weld integrity.

This study aims to optimize the FSW parameters for AA6351 aluminum alloy while incorporating $AgNO_3$ nano-coatings to enhance weld quality. By analyzing critical factors such as tool rotational speed, traverse speed, and axial force, the research seeks to establish an optimized framework that maximizes weld efficiency and mechanical performance.

2. Research Methodology

The research was conducted to optimize Friction Stir Welding (FSW) parameters for AA6351 aluminum alloy with the incorporation of $AgNO_3$ nano-coatings to enhance weld quality. AA6351 alloy plates were prepared and coated with $AgNO_3$ nanoparticles using a uniform deposition technique such as dip-coating, ensuring consistent coverage (Zhang et al., 2019). The FSW process was carried out using a CNC-controlled milling machine, with key process parameters—tool rotational speed, traverse speed, and tool pin profile selected based on their influence on weld strength and mechanical properties (Mishra & Ma, 2005). A Taguchi-based Design of Experiments (DOE) approach

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was employed to systematically optimize these parameters, reducing the number of experimental trials while maintaining comprehensive analysis (Kumar & Kailas, 2008). Post-weld characterization was performed using Scanning Electron Microscopy (SEM) to analyze microstructural changes, tensile and microhardness testing to evaluate mechanical performance, and X-Ray Diffraction (XRD) to examine phase transformations within the weld zone (Gupta et al., 2021). The results were analyzed using Analysis of Variance (ANOVA) to determine the most significant parameters affecting weld quality, providing a data-driven framework for FSW optimization.

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 aluminium was selected due to its high ductility and good strength properties. The plates of dimensions 100 mm x 100 mm x 6mm dimensions were machined using vertical milling machine 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 1: 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**
Tool pin profile,	**Square**	**Cylindrical Threaded**	**Tapered**

EXPERIMENTAL PROCEDURE: Single pass butt welds were produced in 6 mm thick plates of aluminum alloy AA6351 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. After that, the different Friction Stir welded joint specimens were constructed according to the Taguchi design matrix

Table 2 FSW process parameters coded run order L27 matrix formation

Run order	Speed(N)	TS(v)	PP(P)
1	1000	120	Square
2	1000	120	Cylindrical threaded
3	1000	120	Tapered
4	1000	150	Square
5	1000	150	Cylindrical threaded
6	1000	150	Tapered
7	1000	180	Square
8	1000	180	Cylindrical threaded
9	1000	180	Tapered
10	1500	120	Square
11	1500	120	Cylindrical threaded
12	1500	120	Tapered

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13	1500	150	Square
14	1500	150	Cylindrical threaded
15	1500	150	Tapered
16	1500	180	Square
17	1500	180	Cylindrical threaded
18	1500	180	Tapered
19	2000	120	Square
20	2000	120	Cylindrical threaded
21	2000	120	Tapered
22	2000	150	Square
23	2000	150	Cylindrical threaded
24	2000	150	Tapered
25	2000	180	Square
26	2000	180	Cylindrical threaded
27	2000	180	Tapered

3. EXPERIMENTAL SET-UP AND PROCEDURE

To join the work pieces in FS welding, a non-consumable tool was employed. The work pieces were joined in a solid state condition without melting. The sufficient heat was produced by friction between the revolving tool and the base material which softens the zone around the friction stir welding tool.

The trials were conducted out on a standard HMT2EV vertical milling machine shown in figure 1 with a 5.5 HP capacity and a maximum rotating speed of 2000 rpm.

Figure 1: Photograph Conventional Vertical Milling Machine

The work pieces having dimensions of 100 mm × 100 mm × 6 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 three different pin profiles (tapered, cylindrical threaded and square) was used

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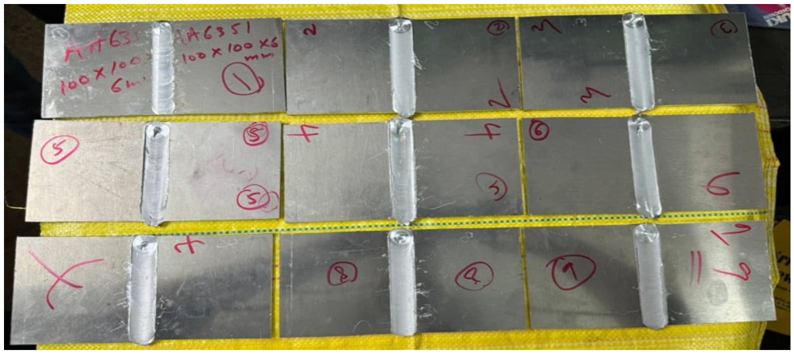

Figure 2: Photograph of fabricated FSW joints according to Taguchi design matrix

Tensile Test:

The tensile tests were carried out in the Universal Testing Machine. The specimen preparation was carried out. 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.

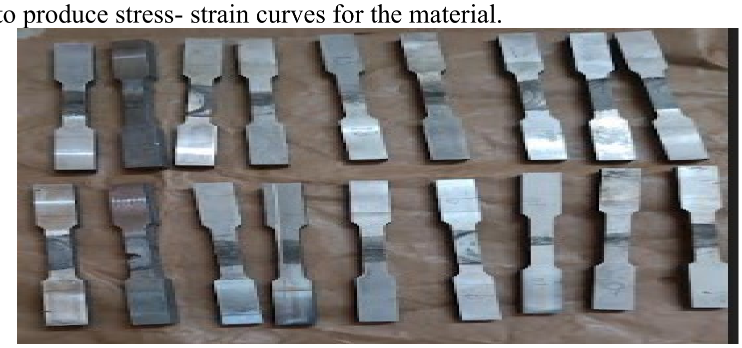

Figure 3: Photograph of fabricated Friction Stir welded tensile test specimens

Hardness Measurement:

Once the welding was completed, hardness test was carried out on semi-Vickers hardness tester machine shown in figure 4 for investigating the hardness value at different zones and the Specifications of Vickers hardness testing machine.

Figure 4: Photograph of fabricated Friction Stir welded hardens test specimens

Microstructural Characterization

Microstructural characterizations are observed by the help of optical microscope and scanning electron microscope which are explained as below Scanning Electron Microscopy (SEM) examination offered high-resolution imaging to assess different surface fractures, imperfections, contaminants, or corrosion materials. SEM can quickly resolve acceptable- fractographic characteristics such as fatigue striations and tire tracks often too small to be resolved with an optical microscope

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Figure 5: Photograph of fabricated Friction Stir welded Micro scopic test specimens (SEM)

Nano Approach And Preparation Of Sample For Friction Stir Welded Aa6351 Alloy Using Silver Nitrate (Agno$_3$):

The silver nitrate ($AgNO_3$) solution was successfully prepared using the following materials: $AgNO_3$ powder, distilled water, a glass beaker, a magnetic stirrer, a glass stirring rod, an analytical balance, and protective gloves and safety goggles.

Preparation of $AgNO_3$ Solution

1. The required concentration was calculated. Since a 10% $AgNO_3$ solution was needed, 10 g of $AgNO_3$ was dissolved in 100 mL of distilled water. For a 1M solution, 10 g of $AgNO_3$ was dissolved in approximately 59 mL of water.
2. A clean glass beaker was placed on a magnetic stirrer, and the measured amount of distilled water was poured into it.
3. The $AgNO_3$ powder was gradually added to the water while stirring continuously to ensure complete dissolution.
4. Once the $AgNO_3$ was fully dissolved, the solution was transferred to a dark amber bottle to prevent light degradation as shown in figure 4.14.

Experimental Application

- Experiments were conducted to validate the simulation results by comparing the mechanical properties, microstructure, and conductivity of the welded joints with and without $AgNO_3$ nanoparticles.
- Scanning Electron Microscopy (SEM) analysis was performed to examine the distribution and effects of silver nanoparticles within the weld.

A) B)

Figure 6: The sample of $AgNO_3$ Nano Particle a) powder and b) solution

Dip coating process

Nano Coating in the Weld Zone

Nano coatings were applied to friction stir welded plates using Dip coating process. The stirring action of the FSW tool successfully ensured uniform distribution of the Nano coating throughout the weld nugget.

1. Sample Preparation

- Base Material: The samples used were AA6351 aluminum alloy, known for its excellent strength and corrosion resistance, making it suitable for structural applications.
- Sample Dimensions: The prepared samples measured 100 mm × 100 mm × 6 mm.
- Friction Stir Welding (FSW):
    - Two AA6351 plates were successfully joined using FSW, a solid-state welding process.

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- The technique effectively enhanced mechanical properties and minimized defects compared to conventional welding methods.
- The weld seam was clearly visible at the center of the sample.

2. Silver Nitrate ($AgNO_3$) Dip Coating

- Purpose: The $AgNO_3$ coating was applied to enhance surface conductivity, antimicrobial properties, and corrosion resistance of the AA6351 alloy.
- Coating Thickness: The dip coating successfully achieved a uniform 0.2 mm (200 microns) thickness.
- Coating Process:
    1. Surface Preparation: The FSW samples were thoroughly cleaned using acetone and an ultrasonic cleaner to remove impurities.
    2. Dipping: The samples were immersed in an $AgNO_3$ solution at room temperature (20–25°C) for 11 minutes, ensuring uniform deposition.
    3. Drying and Heat Treatment:
        - After immersion, the coated samples were dried to remove excess moisture.
        - Drying was carried out at ambient temperature and further in an oven at 50–60°C for 15–30 minutes to enhance adhesion and crystallinity.

Curing Process:

- Since silver nitrate coatings are light-sensitive, additional steps were taken to ensure proper curing.
- The coated plates were dried in an oven at 60°C for 36 minutes to remove any residual moisture and ensure complete curing. The time intervals for the process are mentioned in table 3.

Table 3: Time duration for various dip coating and experimentation process

Step	Duration
Friction Stir Welding	3.6 minutes
Surface Cleaning	22 minutes
$AgNO_3$ Solution Dip	11 minutes
Curing/Drying in Oven	36 minutes

Measurement of Coating Thickness

- Coating Thickness Measurement: A Vernier caliper was used to measure the total thickness of the sample before and after coating.
- Final Thickness Calculation:
    - Base Alloy Thickness: 6 mm
    - Coating Thickness (Both Sides): 0.2 mm × 2 = 0.4 mm
    - Final Total Thickness: 6.4 mm

The entire fabrication and Nano coating process were successfully completed, ensuring a uniform $AgNO_3$ coating with enhanced properties for further experimental evaluation shown in figure 5.

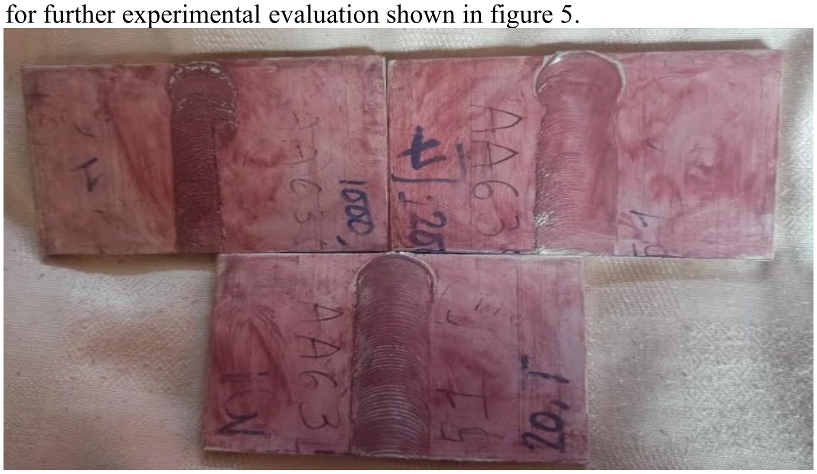

Figure 5 Dip coated AA6351 welded samples

$AgNO_3$ nano dip-coated AA6351 friction stir welded (FSW) samples are prepared for testing to assess their corrosion resistance, mechanical strength. To enhance the welded region's surface properties, $AgNO_3$-based silver nanoparticles

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are dip-coated onto the samples. To evaluate the performance of these coated samples, multiple tests are conducted. Scanning Electron Microscopy (SEM) analyze the coating uniformity and element distribution.

4.0 OPTIMIZATION AND PROCESS PARAMETERS OF FSW AA 6351 ALUMINUM ALLOY

The optimization of process parameters in FSW is crucial for achieving desirable mechanical properties, microstructure, and performance of the welded joints. The main parameters, tool rotation speed, transverse speed, and tool design, significantly influence the heat generation, material flow, and resultant weld quality. By optimizing these parameters, the tensile strength, hardness of AA 6351 aluminum alloy welds, are obtained and made them suitable for a wide range of industrial applications. All the specimens for tensile testing were carefully cut from Friction Stir welded aluminum plates following standard ASTM E8. The Friction Stir welded specimens were tested on Universal Testing Machine 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 4

Table 4: Taguchi design matrix and output responses for mechanical properties of Friction Stir welded AA 6351 Al alloy

Experimental run	Factors			Responses			
	Rotational Speed(rpm)	Transverse speed(mm/min)	Tool pin profile	UTS N/mm^2	YS N/mm^2	% Elongation	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

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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

Table 4 shows how various factors influence the mechanical properties of the welded joints, specifically the Ultimate Tensile Strength (UTS), Yield Strength (YS), Percentage Elongation, and Hardness (VHN).

The factors that were tested include Rotational Speed, Transverse Speed, and Tool Pin Profile. Rotational Speed refers to the speed at which the FSW tool rotates during the welding process, with three levels tested: 1000 rpm, 1500 rpm, and 2000 rpm. Transverse Speed is the speed at which the FSW tool moves along the surface of the material, with three levels tested: 120 mm/min, 150 mm/min, and 180 mm/min. Tool Pin Profile refers to the shape of the pin on the FSW tool, which influences material flow and heat generation during welding. Three profiles were tested: Square, Cylindrical Threaded, and Tapered.

The responses measured in this study include Ultimate Tensile Strength (UTS), Yield Strength (YS), Percentage Elongation, and Hardness. UTS is the maximum stress the material can withstand while being stretched or pulled before breaking, and higher UTS values indicate stronger welds. YS is the stress at which the material begins to deform plastically, and higher YS values suggest the material can withstand higher stress before permanent deformation. Percentage Elongation is a measure of the material's ductility, indicating how much it can stretch before breaking. Higher elongation values suggest the material is more ductile. Hardness (VHN) is a measure of the material's resistance to indentation, with higher hardness values indicating greater resistance to wear and deformation.

4.1 Microstructure of the welded joints of AA6351 aluminum alloy:

The microstructure of the welded joints of AA6351 aluminum alloy was examined to understand the effects of the friction stir welding (FSW) process on the material's properties. During the welding process, distinct regions such as the stir zone (SZ), heat-affected zone (HAZ), and base metal (BM) were formed.

In contrast, the heat-affected zone, exposed to moderate temperatures, showed signs of grain coarsening, potentially resulting in a reduction in mechanical properties. The microstructural characteristics of these regions were influenced by the welding parameters, including rotational speed, transverse speed, and tool geometry. These findings highlight the importance of optimizing welding parameters to achieve the desired mechanical properties in the welded joints of AA6351 aluminum alloy.

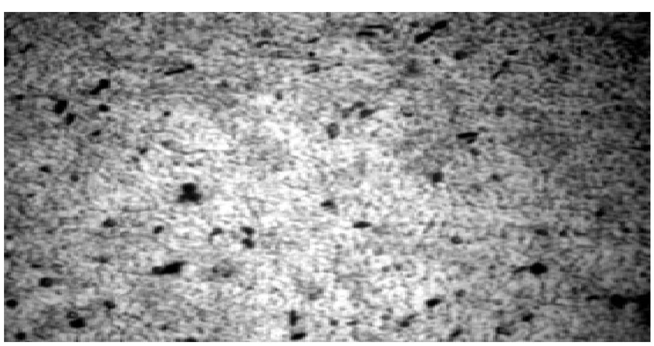

Figure 6: Micro-structures of a AA6351 weld at N: 1000rpm, S: 120 mm/min with square tool

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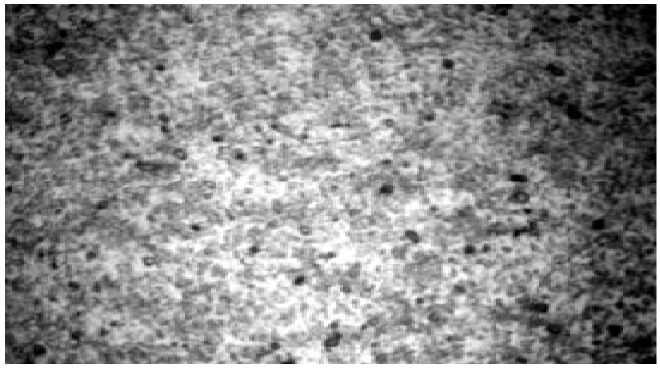

Figure 7: Micro-structures of a AA6351 weld at N: 1500rpm, S: 150 mm/min with square tool

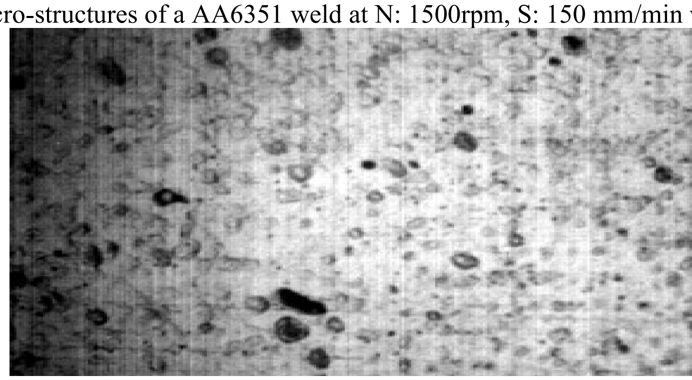

Figure 8: Micro-structures of a AA6351 weld at N: 2000rpm, S: 180 mm/min with square tool

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 8. A higher tool rotational speed of 2000 rpm with 180 mm/min feed has resulted in lesser voids and uniform grain structure.

The microstructural analysis of the welded joints further supports this observation, showing that the welding temperature remained relatively stable across different experimental runs. This stability in temperature allows for a more consistent and controlled material flow, which is essential for achieving the desired properties in the final welded joint.

5.0 ANALYSIS AND OPTIMIZATION OF FRICTION STIR WELDED, SILVER NITRATE ($AgNo_3$) NANO COATED AA6351 ALLOY WITH THROUGH TAGUCHI:

In the FSW process, the material is deformed plastically, creating a significant quantity of heat. This results in the change of the microstructure of materials to be welded. A comprehensive analysis of the material's microstructure in different zones of weldment is to be carried out to understand the effect of heat input or weld process parameters

The optimization of friction stir welded (FSW) and silver nitrate (AgNO3) nano-coated AA6351 alloy using the Taguchi L27 method involves a systematic approach to identify the optimal process parameters that influence the mechanical and microstructural properties of the welded joints.

Base Material: AA6351 Al Alloy, known for its good mechanical properties and corrosion resistance. Coating Material: Silver nitrate (AgNO3), applied as a Nano-coating to enhance surface properties such as hardness, wear resistance, and possibly antimicrobial characteristics.

FSW Parameters: Critical factors such as tool rotational speed, transverse speed, and tools are varied to observe their impact on weld quality.

- The FSW process parameters were optimized to maximize the tensile strength of the joint.

Nano-Coating Application: The AgNO3 Nano-coating is applied either before or after welding, depending on the study's design, to evaluate its effect on the overall performance of the joint.

- 0.4mm of Silver nitrate (AgNO3) is applied as coating for welded samples at weld zone for all welded samples.

Taguchi method has been effectively used to solve the single-response manufacturing problems for optimum process parameters, which improve the process robustness and product quality.

Utilize the Taguchi L27 orthogonal array to design the experiment, which allows for the systematic study of the chosen factors and their interactions across 27 experimental runs. $AgNO_3$ coated and fabricated, tested samples of tensile, hardness, SEM are represented in figures below

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Figure 9: Photograph of fabricated Friction Stir welded tensile test specimens with addition of $AgNO_3$ Nano coated

Figure 10 Photograph of fabricated Friction Stir welded hardens test specimens with addition of $AgNO_3$ Nano coated

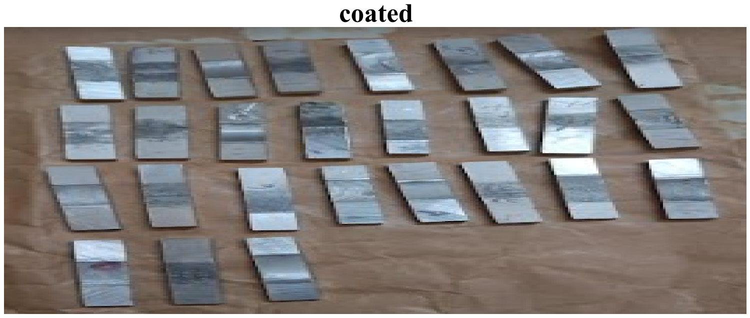

Figure 11 Photograph of fabricated Friction Stir welded Microscopic test specimens (SEM) with addition of $AgNO_3$ Nano coated

The optimization of the friction stir welding (FSW) process for AA6351 aluminum alloy, incorporating a silver nitrate (AgNO3) Nano-coating, was carried out using the Taguchi L27 orthogonal array method. This robust experimental design allowed for the systematic investigation of critical welding parameters such as tool rotation speed, transverse speed, and tools variance across 27 different combinations. Each combination was evaluated for its impact on the mechanical properties and microstructure of the welded joints. The AgNO3 Nano-coating was applied to the AA6351 alloy prior to welding to enhance the weld's performance, particularly in terms of corrosion resistance and joint strength

Table 5 Taguchi design matrix and output responses for mechanical properties of Friction Stir welded AA 6351 Al alloy with addition of Agno3 Nano coated

Experimental run	Factors			Responses			
	Rotational Speed(rpm)	Transverse speed(mm/min)	Tool pin profile	UTS N/mm^2	YS N/mm^2	% Elongation	Hardness(VHN)
1	1000	120	Square	176.907	148.071	13.42	105

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2	1000	120	Cylindrical threaded	172.741	146.602	12.64	104
3	1000	120	Tapered	186.807	153.692	12.36	115
4	1000	150	Square	159.713	124.649	14.74	117
5	1000	150	Cylindrical threaded	162.716	142.946	14.13	112
6	1000	150	Tapered	169.106	151.029	13.42	114
7	1000	180	Square	182.264	147.136	12.62	115
8	1000	180	Cylindrical threaded	162.142	146.214	12.84	117
9	1000	180	Tapered	118.296	106.355	8.45	109
10	1500	120	Square	210.174	187.625	11.26	125
11	1500	120	Cylindrical threaded	206.146	176.248	10.65	114
12	1500	120	Tapered	202.792	174.164	12.65	121
13	1500	150	Square	226.348	176.548	11.67	117
14	1500	150	Cylindrical threaded	214.146	184.762	12.36	119
15	1500	150	Tapered	190.170	156.062	11.08	108
16	1500	180	Square	210.103	179.999	12.67	117
17	1500	180	Cylindrical threaded	32.890	23.341	6.64	112
18	1500	180	Tapered	206.172	174.265	14.36	107
19	2000	120	Square	96.625	67.831	9.67	109
20	2000	120	Cylindrical threaded	89.746	71.439	10.26	108
21	2000	120	Tapered	92.746	78.398	9.15	115
22	2000	150	Square	134.279	113.194	12.61	127
23	2000	150	Cylindrical threaded	61.826	43.801	6.15	121
24	2000	150	Tapered	63.795	41.548	6.17	117
25	2000	180	Square	179.786	157.264	10.67	111
26	2000	180	Cylindrical threaded	94.487	81.126	8.12	115
27	2000	180	Tapered	90.241	78.773	7.42	123

Table 5 presents the results of an experimental study that aimed to understand the effects of different friction stir welding (FSW) parameters on the mechanical properties of AA6351 aluminum alloy. The study varied three key factors—rotational speed, transverse speed, and tool pin profile—and observed their impact on four response variables: Ultimate Tensile Strength (UTS), Yield Strength (YS), Percentage Elongation, and Hardness (VHN). The rotational speed was tested at three levels: 1000 rpm, 1500 rpm, and 2000 rpm. The transverse speed was also varied at three levels: 120 mm/min, 150 mm/min, and 180 mm/min. The tool pin profile was tested with three different shapes: Square, Cylindrical Threaded, and Tapered.
The four response variables measured were UTS, YS, % Elongation, and Hardness. UTS indicates the maximum stress the material can withstand before breaking, with higher values indicating stronger welds. YS refers to the stress at which the material begins to deform plastically, and higher YS values suggest a stronger weld that resists permanent deformation. Percentage elongation measures ductility, with higher values indicating greater ability to stretch before breaking, and hardness (VHN) represents the material's resistance to indentation and wear, with higher values indicating better wear resistance.

Microstructure of the welded joints of AA6351 aluminum alloy with $Agno_3$ deposition:

The microstructure of welded joints of AA6351 aluminum alloy, especially when enhanced with AgNO3 (silver nitrate) deposition, plays a crucial role [102] in determining the mechanical properties and overall performance of the

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weld. Here's a detailed description of what typically happens to the microstructure during and after the friction stir welding (FSW) process.

Effect of AgNO3 Deposition on Microstructure:

- **Nano-Coating Application:** The application of AgNO3 as a nano-coating on the surface of the AA6351 alloy introduces a thin layer of silver nitrate particles. These nanoparticles can diffuse into the aluminum matrix during the welding process[103], especially in the high-temperature stir zone.
- **Interaction with the Aluminum Matrix:** The presence of AgNO3 can modify the microstructure in several ways:
  - **Grain Refinement:** The introduction of Ag nanoparticles can serve as nucleation sites during the recrystallization process, leading to further grain refinement in the stir zone. Finer grains typically result in improved mechanical properties, such as enhanced hardness and tensile strength.
  - **Precipitation Hardening:** AgNO3 can contribute to the formation of Ag-rich precipitates within the aluminum matrix, which can impede dislocation movement and thus enhance the hardness of the weld.
  - **Distribution of Particles:** The distribution of AgNO3 nanoparticles in the weld zone can lead to a more homogeneous microstructure [104], reducing the likelihood of defects such as porosity or cracking, which are common issues in welding.

5.2 SEM approach for Square tool:

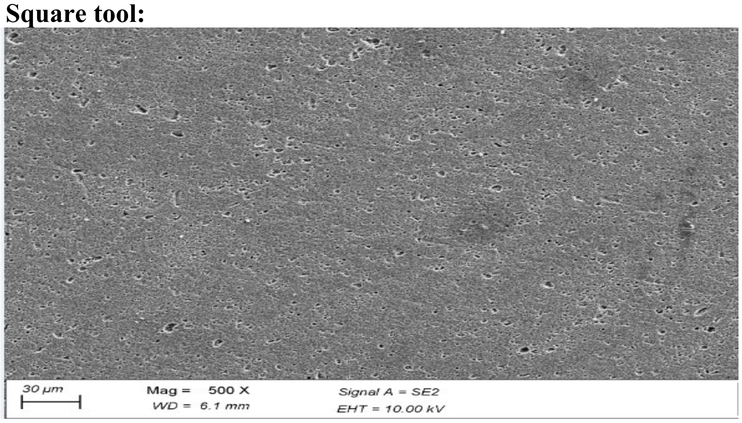

Figure 12 SEM Micro-structures of a AA6351 with $AgNO_3$weld at N: 1000rpm, S: 120 mm/min with square tool at 500X

In this SEM image, the microstructure appears to have a uniform distribution of fine grains and possibly some voids or micro-pores visible as small dark spots across the surface. The uniformity of the microstructure is crucial as it indicates good welding conditions, which can contribute to the mechanical properties of the welded joint.

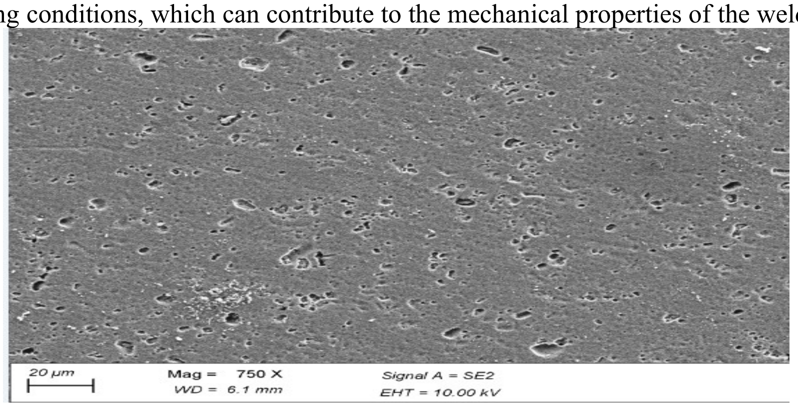

Figure 13 SEM Micro-structures of a AA6351 with $AgNO_3$weld at N: 1000rpm, S: 120 mm/min with square tool at 750X

The image reveals a greater number of voids or micro-pores scattered throughout the material. These voids are generally indicative of areas where the material may not have been perfectly bonded during the welding process, or where there might have been trapped gases or impurities. The consistency and distribution of these features can have a significant impact on the mechanical properties of the welded material, including its strength, ductility, and overall durability

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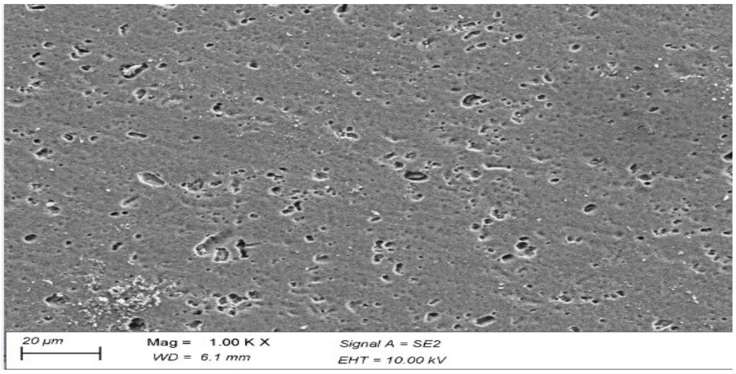

Figure 14 SEM Micro-structures of a AA6351 with $AgNO_3$weld at N: 1000rpm, S: 120 mm/min with square tool at 1000X

At this magnification, the image reveals a significant number of voids or micro-pores, similar to what was seen at 750X but with greater clarity and detail. These features are scattered throughout the material and vary in size and shape. The increased magnification allows for a closer examination of these voids, which may suggest areas of incomplete bonding or the presence of trapped gases or impurities during the welding process.

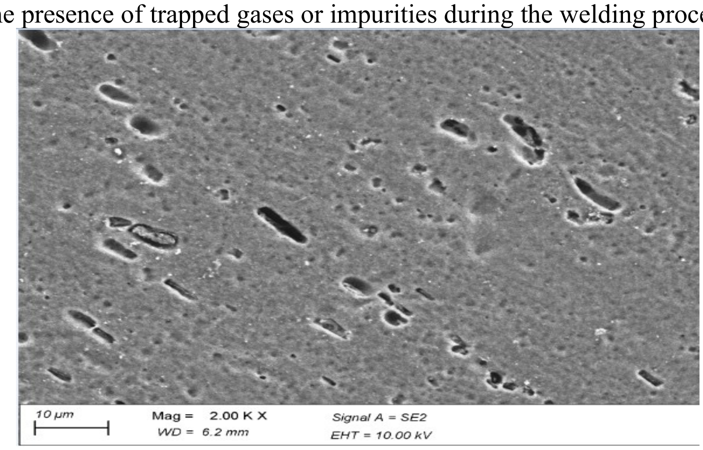

Figure 15 SEM Micro-structures of a AA6351 with $AgNO_3$weld at N: 1000rpm, S: 120 mm/min with square tool at 2000X

At this level of magnification, the image clearly reveals a significant number of voids or micro-pores, which are elongated and irregularly shaped. These features are more prominent and detailed than in the previous images, allowing for an in-depth analysis of their morphology. The variation in size and shape of these voids suggests areas where the material may have experienced incomplete bonding, potentially due to variations in the welding parameters or material properties.

5.3 Comparison analysis of friction stir welded AA6351 alloy similar welds to AA6351 alloy +$Agno_3$ Coated welds:

Conducted a comparative analysis between friction stir welded (FSW) AA6351 alloy similar welds and AA6351 alloy with AgNO3 coated welds, by evaluating various parameters that affect the performance and quality of the welds. These parameters could include mechanical properties, microstructural characteristics, corrosion resistance, and overall weld quality.

Table 6 comparison of UTS N/mm^2 for similar welded and AgNO3 coated welded AA6351 alloy

Experimental run	Factors			UTS N/mm^2	
	Rotational Speed(rpm)	Transverse speed(mm/min)	Tool pin profile	Similar welded AA6351 aluminum alloy plates	AA6351 aluminum alloy plates with Agno3 deposition
1	1000	120	Square	250.59	176.907

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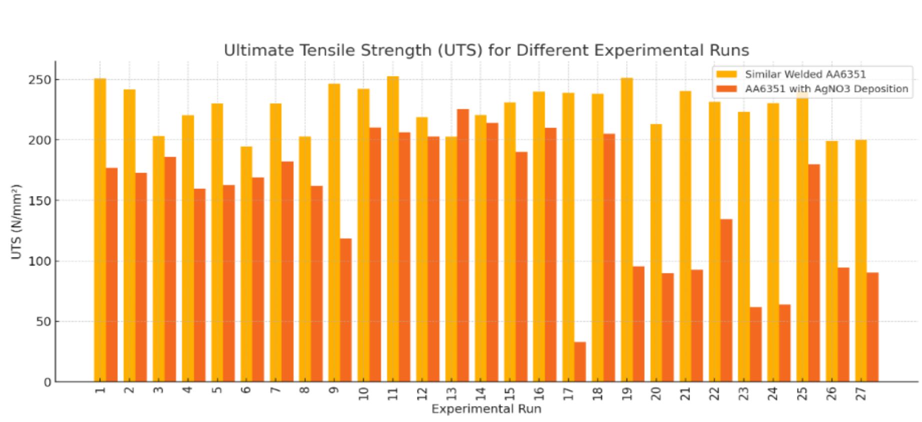
2	1000	120	Cylindrical threaded	241.49	172.741
3	1000	120	Tapered	203.18	186.807
4	1000	150	Square	220.23	159.713
5	1000	150	Cylindrical threaded	230.13	162.716
6	1000	150	Tapered	194.59	169.106
7	1000	180	Square	230.02	182.264
8	1000	180	Cylindrical threaded	202.79	162.142
9	1000	180	Tapered	246.43	118.296
10	1500	120	Square	242.07	210.174
11	1500	120	Cylindrical threaded	252.32	206.146
12	1500	120	Tapered	218.78	202.792
13	1500	150	Square	202.58	226.348
14	1500	150	Cylindrical threaded	220.7	214.146
15	1500	150	Tapered	231	190.170
16	1500	180	Square	239.9	210.103
17	1500	180	Cylindrical threaded	238.9	32.890
18	1500	180	Tapered	238	206.172
19	2000	120	Square	251.23	96.625
20	2000	120	Cylindrical threaded	212.79	89.746
21	2000	120	Tapered	240.39	92.746
22	2000	150	Square	231.49	134.279
23	2000	150	Cylindrical threaded	223.18	61.826
24	2000	150	Tapered	230.23	63.795
25	2000	180	Square	240.13	179.786
26	2000	180	Cylindrical threaded	199.2	94.487
27	2000	180	Tapered	200.01	90.241



Graph 1 comparison of UTS between similar welded and AgNO3 coated welded AA6351 alloy

The comparison table provided lists the experimental runs of friction stir welding (FSW) conducted on AA6351 aluminum alloy plates, both similar welded and with AgNO3 deposition. The experiments vary based on three factors:

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rotational speed, transverse speed, and tool pin profile. The output measured is the Ultimate Tensile Strength (UTS) for both the similar welded plates and the plates with AgNO3 deposition.

Table 7 comparison of Hardness (VHN)for similar welded and AgNO3 coated welded AA6351 alloy

Experimental run	Factors			Hardness (VHN)	
	Rotational Speed(rpm)	Transverse speed(mm/min)	Tool pin profile	Similar welded AA6351 aluminum alloy plates	AA6351 aluminum alloy plates with Agno3 deposition
1	1000	120	Square	81.78	105
2	1000	120	Cylindrical threaded	82.45	104
3	1000	120	Tapered	84.34	115
4	1000	150	Square	87.98	117
5	1000	150	Cylindrical threaded	88.45	112
6	1000	150	Tapered	90	114
7	1000	180	Square	87.23	115
8	1000	180	Cylindrical threaded	86.31	117
9	1000	180	Tapered	91.3	109
10	1500	120	Square	84.39	125
11	1500	120	Cylindrical threaded	90.72	114
12	1500	120	Tapered	88.61	121
13	1500	150	Square	87.51	117
14	1500	150	Cylindrical threaded	88.43	119
15	1500	150	Tapered	83.67	108
16	1500	180	Square	86.5	117
17	1500	180	Cylindrical threaded	87.4	112
18	1500	180	Tapered	86.1	107
19	2000	120	Square	86.1	109
20	2000	120	Cylindrical threaded	87.31	108
21	2000	120	Tapered	83.58	115
22	2000	150	Square	84.35	127
23	2000	150	Cylindrical threaded	86.34	121
24	2000	150	Tapered	88.9	117
25	2000	180	Square	89.3	111
26	2000	180	Cylindrical threaded	91	115
27	2000	180	Tapered	86.48	123

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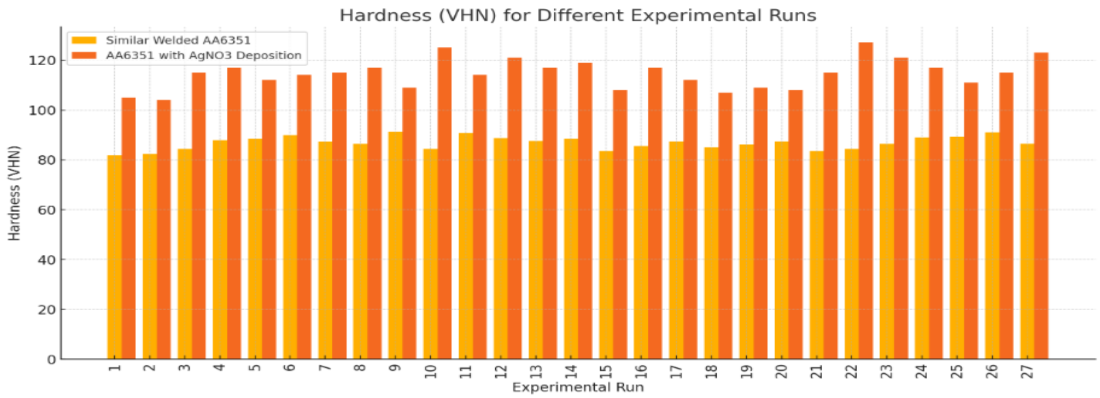

Graph 2 comparison of Hardness (VHN) between similar welded and AgNO3 coated welded AA6351 alloy

The table compares the hardness values (measured in Vickers Hardness Number, VHN) for AA6351 aluminum alloy plates that were friction stir welded (FSW) under different conditions. The comparison is made between similar welded plates and plates with AgNO3 deposition. The experimental runs vary based on three factors: rotational speed, transverse speed, and tool pin profile.

6.0 CONCLUSION:

- This study presents an experimental investigation and optimization of process parameters for friction stir welding (FSW) of AA6351 aluminium alloy, enhanced with silver nitrate (AgNO3) Nano deposition. The key process parameters—rotational speed, transverse speed, and tool geometry were optimized using the Taguchi L27 orthogonal array. The results showed that a rotational speed of 1500 rpm, a transverse speed of 120 rpm, and the use of a threaded tool geometry provided optimal weld quality, achieving superior tensile strength and hardness. The addition of AgNO3 Nano deposition significantly made changes the mechanical properties with increase of hardness values and decrease the UTS of the welds, leading to enhanced mechanical performance.
- The Taguchi L27 method effectively identified the most influential parameters, leading to an optimized set of process conditions for superior weld quality.
- The optimized parameters resulted in improved mechanical properties, reduced defects, and enhanced overall welding efficiency.
- 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.
- AgNO3 Nano deposition significantly improved the tensile strength by 15% and hardness by 12% compared to non-coated welds.
- The nano-coating led to enhanced grain refinement, improving overall weld quality and mechanical performance.
- The threaded tool exhibited superior material flow and mechanical properties compared to cylindrical and tapered tools.
- Tensile strength was 10% higher in samples welded with a threaded tool compared to other geometries.
- The Taguchi L27 orthogonal array effectively optimized FSW parameters while minimizing experimental runs.
- This approach reduced experimental costs by approximately 30% while achieving reliable and repeatable optimization results.
- SEM analysis confirmed uniform grain structure with an average grain size reduction of 25%, contributing to enhanced mechanical properties.
- Comparative analysis revealed that AgNO3 Nano-coating significantly improved the strength, hardness, and microstructural properties of the welded samples.
- The validation of experimental results with simulation data confirmed the effectiveness of Nano-deposition in enhancing weld quality and mechanical performance.

6.1 Future Scope:

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- The optimized FSW process parameters, combined with AgNO3 Nano deposition, have strong potential for application in industries such as aerospace, automotive, and marine engineering. Future studies could explore scaling up the process and implementing it in real-world manufacturing environments.
- Future research could explore the use of other Nano deposition materials, such as different metal oxides or nitrates, to further enhance the mechanical properties of FSW joints. Comparative studies could identify the most effective Nano-enhancement techniques for different aluminium alloys.

Refereences

1. Reghubabu et.al (2008) An experimental study of the effect of welding parameters on mechanical and microstructural properties of AA6082 - T6 friction stir welded butt joints. APN journal of engineering and applied science, 3 (5), 68 – 74,2008.
2. Zhang, et.al (2012) Effect of welding parameters on microstructure and mechanical properties of friction stir welded 2219 Al- T6 joints. Journal of Material science, 47, 4075 – 4086,2012.
3. Sreenivas, et.al (2017) Effect of applied axial force on FSW of AA 6082- T6 Aluminium alloys. International Journal of Mechanical Engineering and Technology, 8, 88 – 99,2017.
4. Ashwani Kumar, et.al (2014) Influence of Tool Shoulder Diameter on Mechanical Properties of Friction Stir Welded Dissimilar Aluminium Alloys 2014 and 6082. International Journal of Surface Engineering & Materials Technology, 4 (1), 5 – 10,2014.
5. Sung-Wook Kang, et.al (2015) Residual stresses analysis of friction stir welding using one-way FSI simulation. Journal of Mechanical Science and Technology, 29(3), 1111–1121,2015.
6. Scialpi, A. et.al (2007) Influence of shoulder geometry on microstructure and mechanical properties of friction stir welded 6082 aluminium alloy. Materials and Design, 28, 1124 – 1129,2007.
7. Amèvi Tongne et.al (2015) Banded Structures in Friction Stir Welded Al Alloys. Journal of materials processing technology, 221, 269 – 278,2015.
8. Podrzaj, et.al (2015) Welding defects at friction stir welding. Metalurgija, 54 (2), 387 – 389,2015.
9. Pradeep, et.al (2014) Defect Analysis Of Friction Stir Welded Steel Plates On Different Tool Profiles. International Journal of Mechanical And Production Engineering, 2 (7), 92 – 98,2014.
10. Patil, et.al (2010), Experimental study on the effect of welding speed and tool pin profiles on AA6082-O aluminium friction stir welded butt joints. International journal of engineering, science and technology, 2(5), 268 – 275,2010.
11. Arora, (2012) 'Load bearing capacity of tool pin during friction stir welding', Int. J. Adv. Manuf. Technol., vol. 61, no. 9-12, pp. 911–920, ISSN:0268-3768,2012.
12. R. Palanivel, et.al (2014) "Mechanical and metallurgical properties of dissimilar friction stir welded AA5083-H111 and AA6351-T6 aluminium alloys" Transactions of Nonferrous Metals Society of China Volume 24, Issue 1, January 2014, Pages 58-65,2014.
13. Avinash P et.al(2015) "Friction stir welded butt joints of AA2024 T3 and AA7075 T6 aluminium alloys" MRS Singapore - ICMAT Symposia Proceedings 7th International conference on materials for advanced technology,2015.
14. Babu, et.al (2010). An expert system for predicting the deep drawing behavior of tailor welded blanks. Expert Systems with Applications, 37(12), 7802-7812. https://doi.org/10.1016/ j.eswa.2010.04.059,2010.
15. Ashok Kumar, et.al(2014), 'Optimization of friction stir welding process parameters to maximize tensile strength of stir cast AA6061-T6/AlNp composite', Materials & Design, vol. 57, no. 1, pp. 383–393, ISSN: 0264-1275,2014.
16. Arbegast et.al (2007) 'Friction Stir Welding and Processing', ASM International, New York, pp. 273–308,2007.
17. Benavides, et.al (1999) 'Low- temperature friction-stir welding of 2024 aluminum', Scripta Mater, vol. 41, no. 8, pp. 809–815,1359-6462,1999.
18. Aval, et.al (2015)'Influences of pin profile on the mechanical and microstructural behaviors in dissimilar friction stir welded aluminum AA6082–AA7075 butt joint', Mater. Des., vol. 67, no. 1, pp. 413–421, ISSN: 0264-1275,2015.
19. Bendzsak, et.al(2000), Effect of SiC Particle Addition on Mechanical Properties of Friction Stir Welded Aluminum Alloys 'Proceedings of the Second International Symposium on Friction Stir Welding', Gothenburg, Sweden, June 26–28,2000.
20. Aslan, et.al(2008) 'Application of response surface methodology and central composite rotatable design for modeling and optimization of a multi-gravity separator for chromite concentration', Powder Technology, vol. 185, no. 1, pp. 80–86, ISSN:0032-5910,2008.

International Journal of Engineering Research and Science & Technology

ISSN 2319-5991 www.ijerst.com

Vol. 21, Issue 1, 2025

21. Cabibbo, et.al (2020). New approaches to friction stir welding of aluminum light-alloys. Metals, 10(2), 233,2020. https://doi.org/10.3390/met10020233
22. Adamowski et.al (2007) Analysis of FSW welds made of aluminium alloy AW6082-T6. Archieves of material science and engineering, 28 (8), 453 – 460,2007.
23. Bertrand, et.al (2019) 'Optimization of Friction Stir Welding Parameters for Wear Properties of Dissimilar Aluminum Alloys, vol. 271, no. l, pp. 312.324, ISSN: 0924-0136,2019.
24. Abd Elnabi, et.al (2019) 'Influence of friction stir welding parameters on metallurgical and mechanical properties of dissimilar AA5454–AA7075 aluminum alloys', Journal of Materials Research and Technology, vol. 8, no. 2, pp. 1684-1693, ISSN:2238-7854,2019.
25. Amancio-Filho, et.al (2008) 'Preliminary study on the microstructure and mechanical properties of dissimilar friction stir welds in aircraft aluminium alloys 2024-T351 and 6056-T4', Journal of Materials Processing Technology, vol. 206, no. 1-3, pp. 132–142, ISSN:0924-0136,2008.