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**Research Article**

# Optimization of Process Parameters for Enhanced Mechanical Properties in FSW of Dissimilar Aluminium Alloys 6061 and 6082

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**ABSTRACT**

This study investigates the optimization of process parameters and mechanical attributes (tensile strength and hardness) of friction stir welded (FSW) joints between different aluminium alloys, namely 6082 and 6061. Four unique process parameters were established utilizing a L4 design of experiments methodology. Each parameter set was applied to join the aluminium grades using the FSW process, resulting in four distinct samples. Following mechanical testing, encompassing hardness and tensile evaluations, the integrity and strength of the welds were tested. The data from these tests were analyzed with Minitab software to conduct ANOVA optimization, with the objective of identifying the ideal process parameters that improve weldment quality and mechanical attributes.

**Keywords:** Friction STIR Welding, Tensile Testing, Hardness Testing.

## INTRODUCTION

Friction Stir Welding (FSW) is an advanced solid-state welding technique that offers superior weld quality by avoiding the melting process, which eliminates defects such as porosity, cracking, and distortion typically seen in fusion welding. This method is especially valuable for joining dissimilar aluminum alloys, such as 6082 and 6061, which have differing thermal and mechanical properties. The study investigates the effects of key process parameters, including tool rotational speed, welding speed, axial force, and tool tilt angle, on the mechanical properties of FSW joints. Using an L4 orthogonal array from the Design of Experiments approach, four distinct samples are created and tested for tensile strength and hardness. Minitab software is employed for statistical analysis, specifically Analysis of Variance (ANOVA), to optimize the process parameters and determine the best settings for achieving high weld strength and quality. The findings aim to improve the mechanical properties of the FSW joints, providing important insights for industries like aerospace, automotive, and marine, where joining dissimilar materials is a critical challenge. Additionally, the research emphasizes the environmental benefits of FSW, including reduced energy consumption and the elimination of filler materials and shielding gases. By addressing issues such as material compatibility, weld zone integrity, and process efficiency, the study contributes to developing reliable welding methods for dissimilar aluminum alloys, advancing the field of FSW for industrial applications and sustainable manufacturing practices.

## OBJECTIVES

Experimental Design: Develop a set of four process parameters using the L4 orthogonal array method in the design of experiments to systematically study their effects on the weld quality.Sample Preparation: Produce four samples by welding aluminum alloys 6082 and 6061 using the FSW process with the designed parameters.Mechanical Testing: Conduct tensile strength and hardness tests on the welded samples to evaluate their mechanical performance.Data Analysis: Use Minitab software to perform ANOVA optimization and identify the most significant process parameters influencing weld strength and hardness.Optimization: Determine the optimal combination of process parameters for achievingmaximum strength and enhanced weld quality.Contributions: Provide recommendations for the industrial

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application of optimized FSW parameters for dissimilar aluminum alloys in aerospace, marine, and automotive sectors.

## METHODOLOGY

The study methodology involves selecting dissimilar aluminum alloys, 6082 and 6061, as base materials for welding due to their distinct properties and industrial relevance. The experimental design utilizes an L4 orthogonal array from the Design of Experiments (DOE) approach to systematically vary welding parameters. Friction Stir Welding (FSW) is employed to join these alloys, producing four distinct weld samples. Mechanical testing includes tensile strength and hardness tests to evaluate the welds' performance. Minitab software is used for data analysis, with Analysis of Variance (ANOVA) identifying key factors affecting tensile strength and hardness. The results are interpreted to recommend optimal welding parameters for superior joint performance in industrial application.

### Scope of this Project Work

The study aims to identify optimal FSW parameters (tool rotational speed, welding speed, axial force, and tool tilt angle) for joining dissimilar aluminum alloys (6082 and 6061). It evaluates the mechanical properties of the welds, focusing on tensile strength and hardness, to assess joint quality. Minitab software and ANOVA are used to analyze experimental data for process optimization. The research addresses challenges in joining dissimilar alloys, such as variations in thermal and mechanical properties, and provides valuable insights for industries like aerospace, marine, and automotive. Additionally, it contributes to sustainable manufacturing by promoting energy-efficient FSW without the need for filler materials or shielding gases and advances the body of knowledge in FSW for future research and industrial use.

## FRICTION STIR WELDING

### Overview of Friction Stir Welding

In 1991, the UK's The Welding Institute (TWI) developed a solid-state welding technology called friction stir welding (FSW). The material is heated and plasticized by a rotating tool, which is then used to create a weld by consolidating the melted metal. Traditional welding methods entail melting the components to fuse them together; FSW does not.

To perform FSW, a spinning tool is placed into the weld joint from both sides. Material is pliable without melting due to the tool's frictional heat. The tool is then moved down the joint line, compressing the pliable material as it goes to create a firm weld.

Compared to conventional welding methods, FSW has a number of benefits, including less heat generation, less distortion, and no requirement for filler material. The procedure does not release any emissions or gases that could be hazardous to people or the environment.

Aluminium alloys with a high strength-to-weight ratio and corrosion resistance are frequently welded using FSW in the aerospace and automotive industries. The FSW process can be used to weld together materials that are incompatible with standard welding methods. As a result, FSW is a promising method for joining lightweight materials in the transportation sector.

A revolving tool generates frictional heat and consolidates the material to form a weld in FSW, which is a solid-state welding method. This method is widely utilised in the aerospace and automotive industries to combine aluminium alloys because of the many benefits it offers over more conventional welding methods.

FSW can be used on a variety of joints, including butt joints, lap joints, T butt joints, and fillet joints, in contrast to the traditional method of friction welding, which is typically carried out on small ax-symmetric parts that can be rotated and pushed against each other to form a joint. This is because traditional friction welding is performed on these kinds of joints.

### Friction Stir Welding (FSW) Process Principles

Friction Stir Welding (FSW) is a solid-state joining process where a rotating, non-consumable tool generates heat through friction and plastic deformation, avoiding melting and related issues like gas solubility changes. This results in less distortion, reduced residual stresses, and improved fatigue performance, enabling the welding of both thin and thick materials. FSW also minimizes harmful fumes, reduces energy consumption, and can be performed in any orientation, making it a versatile and environmentally friendly method. Initially used for light alloys, FSW has expanded to weld high-melting materials like titanium, nickel, and steels.

### Tool Geometry

The development of welding tool geometry has greatly improved weld quality in aluminum alloys, enhancing production speeds, workpiece thickness, and joint properties. According to Mishap and Ma (2005), tool geometry is crucial in determining material flow and maximum traverse speed in Friction Stir Welding (FSW). The tool consists of a shoulder, responsible for heating through friction, and a pin that aids material flow. The relative size of the pin and shoulder is key to effective heating, while the tool design influences microstructure uniformity and applied loads. Typically, concave shoulders and threaded cylindrical pins are used.

### Tool Types

FSW tools are categorized into three types: the fixed probe tool, the adjustable tool, and the bobbin type tool. The fixed probe tool has a combined shoulder and probe with a fixed probe length, suitable for welding workpieces of consistent thickness; however, if the probe wears out, the entire tool must be replaced. The adjustable tool allows for probe length adjustment, making it versatile for varying thicknesses, and the probe can be replaced if damaged. Both fixed and adjustable tools may require a back in ganvil. The bobbin type tool, consisting of a top shoulder, probe, and bottom shoulder, features an adjustable probe length to accommodate different thicknesses and operates perpendicular to the workpiece surface, without needing a back in ganvil. Unlike the other two, it cannot tilt in multiple directions.

## MATERIALS AND METHODS

### Aluminum 6061 Alloy Overview

Aluminum 6061 is a widely used aluminum alloy known for its excellent mechanical properties, corrosion resistance, and versatility. It is a precipitation-hardened alloy that contains magnesium and silicon as its primary alloying elements. This alloy is known for its good strength-to-weight ratio, machinability, and weldability, making it one of the most popular aluminum grades for structural applications.

### Chemical Composition (Approximate)

- Aluminuim (Al) : 95.85–98.56%
- Magnesium (Mg) : 0.8–1.2%
- Silicon (Si) : 0.4–0.8%
- Iron (Fe) : ≤ 0.7%
- Copper (Cu) : 0.15–0.4%
- Chromium (Cr) : 0.04–0.35%
- Zinc (Zn) : ≤ 0.25%
- Titanium (Ti) : ≤ 0.15%
- Manganese (Mn) : ≤ 0.15%
- Others : ≤ 0.05% each

### Aluminum 6082 Alloy Overview

Aluminum 6082 is a medium-strength aluminum alloy with excellent corrosion resistance, making it ideal for structural applications. It belongs to the 6000 series of aluminum alloys, primarily composed of magnesium and silicon. Known as a structural alloy, it is commonly used in highly stressed applications due to its high strength and good weldability. It is particularly popular in Europe and is often compared to Aluminum 6061.

### Chemical Composition (Approximate %)

- Element Percentage (%)
- Aluminium (Al) Balance
- Magnesium (Mg) 0.6 – 1.2
- Silicon (Si) 0.7 – 1.3
- Manganese (Mn) 0.4 – 1.0
- Iron (Fe) ≤ 0.5

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- Element — Percentage (%)
- Zinc (Zn) — ≤ 0.2
- Copper (Cu) — ≤ 0.1
- Chromium (Cr) — ≤ 0.25
- Titanium (Ti) — ≤ 0.1
- Other (Each) — ≤ 0.05

**Comparison: Aluminium 6082 vs. 6061**

| **Property** | **6082** | **6061** |
|---|---|---|
| **Strength** | **Higher** | **Moderate** |
| **Corrosion Resistance** | **Excellent** | **Good** |
| **Weldability** | **Good** | **Very Good** |
| **Machinability** | **Moderate** | **High** |
| **Common Uses** | **Structural applications** | **Aerospace, automotive** |

## EXPERIMENTAL WORKS

Experimental design methods, developed by Fisher, are complex and require many experiments as process parameters increase. The Taguchi method simplifies this by using orthogonal arrays to study the entire parameter space with fewer experiments. The results are analyzed using a signal-to-noise (S/N) ratio to assess the deviation from desired values. The S/N ratio has three categories: smaller-the-better, larger-the-better, and nominal-is-best. Each category has its own formula for calculating the S/N ratio, with the goal of finding the optimal process parameters that maximize the S/N ratio, ensuring better quality characteristics.

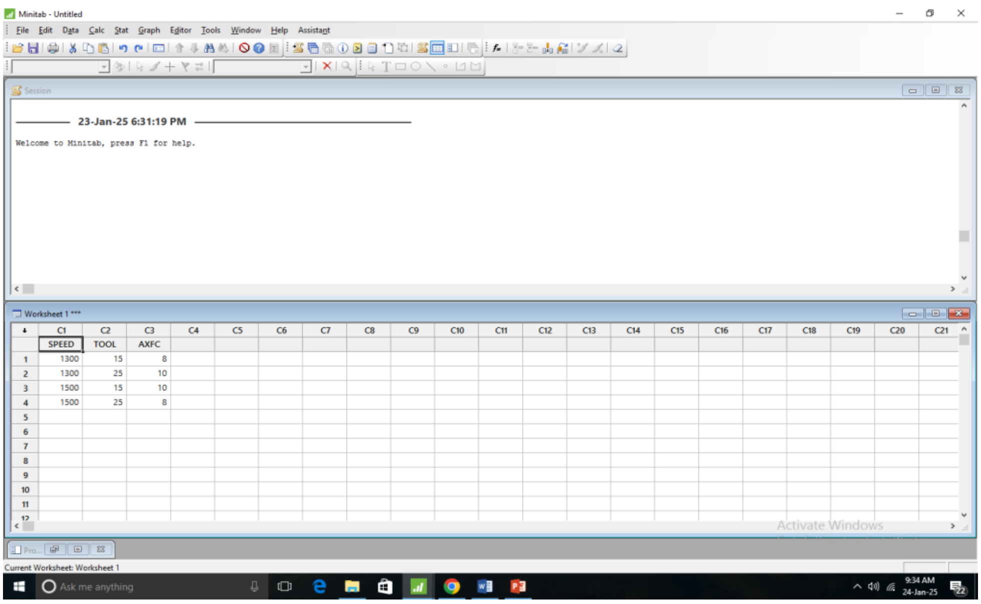
**Design of Experiment**

**Process parameters and their levels**

| S.NO | PROCESS PARAMETERS | | |
|---|---|---|---|
| LEVELS | SPEED RPM | FEED Mm/min | AXIAL FORCE KN |
| 1 | 1300 | 15 | 8 |
| 2 | 1500 | 25 | 10 |

**Design of Orthogonal Array**

**A window is opened in computer as shown in Figure,**



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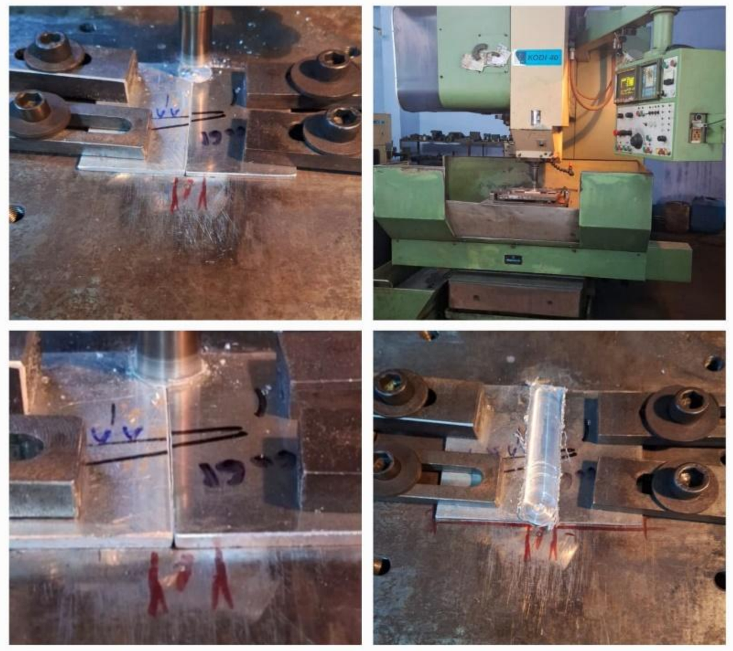
**FSW Welding Process**



**Mechanical Testing**

**Tensile Test**

A tensile test, conducted using a universal testing machine (UTM), is used to determine a material's mechanical properties such as tensile strength, yield strength, and elongation. The process involves preparing specimens with specified dimensions, ensuring they are free of defects. The specimen is then mounted in the UTM, which applies a controlled axial load. Before testing, the UTM is calibrated to zero the force and displacement readings. During the test, data on force, displacement, and time are recorded, and mechanical parameters like stress, strain, yield strength, and ultimate tensile strength are calculated. The results are analyzed through stress-strain curves and summarized in a report. Proper adherence to testing standards, calibration, and operation by trained staff is essential for accurate result.

**Test Results of Tensile**

**Tensile testing sample 1**

**Tensile testing sample 2**

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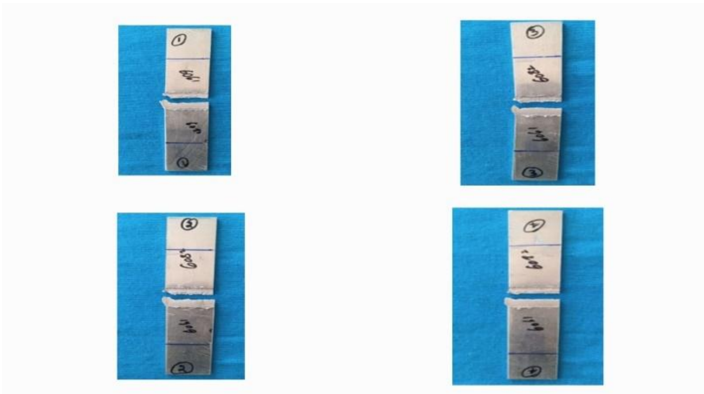
**Tensile testing sample 3** **Tensile testing sample 4**

**After Tensile test of FSW welded samples**



**Tensile strength test of FSW welded samples**

**Test Result of Tensile strength**

| S.NO | SAMPLE ID | TENSILE STRENGTH(N/MM^2) |
|---|---|---|
| 1 | 1 | 22.52 |
| 2 | 2 | 41.07 |
| 3 | 3 | 53.04 |
| 4 | 4 | 32.53 |

**Tensile Result Using Taguchi Method**

**An Orthogonal Array L4 Formation**

| S.NO | SPEED RPM | FEED MM/MIN | AXIAL FORCE |
|---|---|---|---|
| 1 | 1300 | 8 | 22.52 |
| 2 | 1300 | 10 | 41.07 |
| 3 | 1500 | 10 | 53.04 |
| 4 | 1500 | 8 | 32.53 |

**Test of Tensile Strength**

| SPEED | FEED | AXIAL FORCE | TENSILE STRENGTH | SNRA4 |
|---|---|---|---|---|
| 1300 | 15 | 8 | 22.52 | -27.0514 |
| 1300 | 25 | 10 | 41.07 | -32.2705 |
| 1500 | 15 | 10 | 53.04 | -34.4921 |
| 1500 | 25 | 8 | 32.53 | -30.2457 |

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**Response Table for Signal to Noise Ratios- Smaller is better**

| LEVEL | SPEED RPM | TOOL-TR MM/MIN | AXFC KN |
|---|---|---|---|
| 1 | -29.66 | -35.81 | -35.84 |
| 2 | -32.37 | -35.49 | -36.39 |
| DELTA | 2.71 | 0.49 | 4.73 |
| RANK | 2 | 3 | 1 |

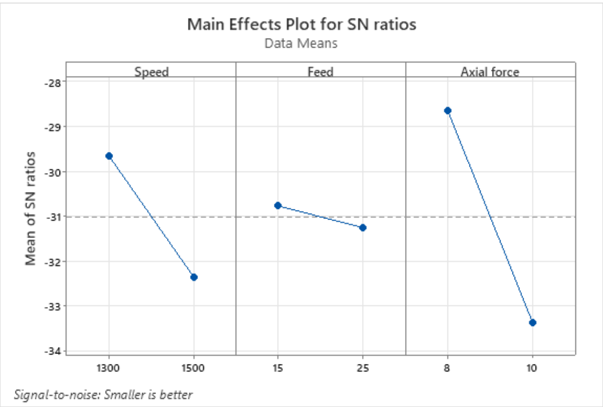
**Response Table for Means**

| LEVEL | SPEED RPM | TOOL-TR MM/MIN | AXFC KN |
|---|---|---|---|
| 1 | 31.80 | 37.78 | 27.52 |
| 2 | 42.78 | 36.80 | 47.05 |
| DELTA | 10.99 | 0.98 | 19.53 |
| RANK | 2 | 3 | 1 |

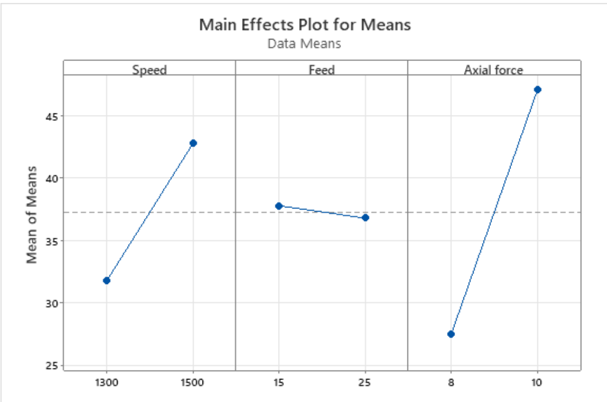
**Analysis of Variance Tensile**

| SOURCE | DF | SEQ SS | ADJ MS | F | P | %OF CONTRIBUTION |
|---|---|---|---|---|---|---|
| SPEED | 1 | 120.780 | 120.780 | 0 | 0 | 24.00% |
| FEED | 1 | 0.960 | 0.960 | 0 | 0 | 0.19% |
| AXIAL FORCE | 1 | 381.421 | 381.421 | 0 | 0 | 75.80% |
| ERROR | 0 | 0 | 0 | | | 0 |
| TOTAL | 1 | 503.161 | | | | 100.00% |

**Main Effects Plot for SN ratios**




**Main Effects Plot for Means**




**Main effects plot for SN ratios**

**WORKSHEET 1**

**Taguchi Analysis: Tensile Strenght versus Speed, Feed, Axial force**

**Response Table for Signal to Noise Ratios**

**Smaller is better**

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| Level | Speed | Feed | Axial force |
|---|---|---|---|
| 1 | -29.66 | -30.77 | -28.65 |
| 2 | -32.37 | -31.26 | -33.38 |
| Delta | 2.71 | 0.49 | 4.73 |
| Rank | 2 | 3 | 1 |

**Response Table for Means**

| Level | Speed | Feed | Axial force |
|---|---|---|---|
| 1 | 31.80 | 37.78 | 27.52 |
| 2 | 42.78 | 36.80 | 47.05 |
| Delta | 10.99 | 0.98 | 19.53 |
| Rank | 2 | 3 | 1 |

**Test Results of Hardness**

**Hardness test of FSW welded sample**

**Hardness strength test of FSW welded samples**

| S.NO | SAMPLE ID | HARDNESS STRENGTH(N/MM^2) |
|---|---|---|
| 1 | 1 | 6.43 |
| 2 | 2 | 11.74 |
| 3 | 3 | 15.15 |
| 4 | 4 | 9.29 |

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**Hardness Using Taguchi Method**

**An Orthogonal Array L4 Formation**

| S.NO | SPEED RPM | FEED MM/MIN | AXIAL FORCE KN |
|---|---|---|---|
| 1 | 1300 | 15 | 8 |
| 2 | 1300 | 25 | 10 |
| 3 | 1500 | 15 | 10 |
| 4 | 1500 | 25 | 8 |

**Test of Hardness Strength, Hardness value -HRB value**

| SPEED | FEED | AXIAL FORCE | HARDNESSSTRENGTH | SNRA 4 |
|---|---|---|---|---|
| 1300 | 15 | 8 | 6.43 | -16.1642 |
| 1300 | 25 | 10 | 11.74 | -21.3934 |
| 1500 | 15 | 10 | 15.15 | -23.6083 |
| 1500 | 25 | 8 | 9.29 | -19.3603 |

**Response Table for Signal to Noise Ratios- Smaller is better**

| LEVEL | SPEED RPM | TOOL MM/MIN | AXFC KN |
|---|---|---|---|
| 1 | -18.78 | -19.89 | -17.76 |
| 2 | -21.48 | -20.38 | -22.50 |
| DELTA | 2.71 | 0.49 | 4.74 |
| RANK | 2 | 3 | 1 |

**Response Table for Means**

| LEVEL | SPEED RPM | TOOL-TR MM/MIN | AXFC KN |
|---|---|---|---|
| 1 | 9.085 | 10.790 | 7.86 |
| 2 | 12.220 | 10.515 | 13.445 |
| DELTA | 3.135 | 0.275 | 5.585 |
| RANK | 2 | 3 | 1 |

**Analysis of Variance Tensile**

| SOURCE | DF | SEQ SS | ADJ MS | F | P | %OF CONTRIBUTION |
|---|---|---|---|---|---|---|
| SPEED | 1 | 9.8282 | 9.8282 | 0 | 0 | 23.00% |
| FEED | 1 | 0.0756 | 0.0756 | 0 | 0 | 0.18% |
| AXIAL FORCE | 1 | 31.1922 | 31.1922 | 0 | 0 | 75.90% |
| ERROR | 0 | 0 | 0 | | | 0 |
| TOTAL | 3 | 41.0961 | | | | 100.00% |

**Main Effects Plot for SN ratios** **Main Effects Plot for Means**

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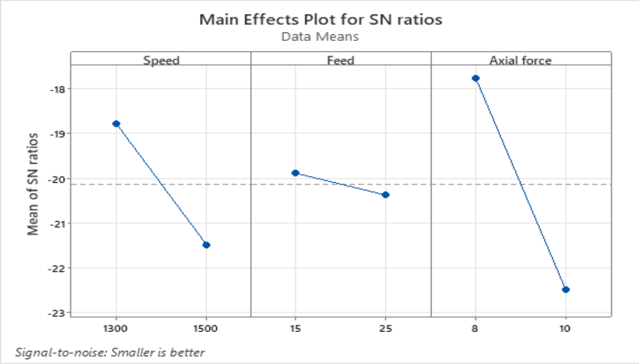



**3.Taguchi Analysis: Hardness versus Speed, Feed, Axial force**

**Response Table for Signal to Noise Ratios**

**Smaller is better**

| Level | Speed | Feed | Axial force |
|---|---|---|---|
| 1 | -18.78 | -19.89 | -17.76 |
| 2 | -21.48 | -20.38 | -22.50 |
| Delta | 2.71 | 0.49 | 4.74 |
| Rank | 2 | 3 | 1 |

**Response Table for Means**

| Level | Speed | Feed | Axial force |
|---|---|---|---|
| 1 | 9.085 | 10.790 | 7.860 |
| 2 | 12.220 | 10.515 | 13.445 |
| Delta | 3.135 | 0.275 | 5.585 |
| Rank | 2 | 3 | 1 |

## RESULTS AND DISCUSSION

**Tensile Strength Test Results**

The tensile strength of the friction stir welded (FSW) joints for the dissimilar aluminum alloys 6061 and 6082 was evaluated for all four samples. The results, as summarized in Table show significant variations in the tensile strength across different samples.

The tensile strength results reveal that the sample with the highest tensile strength was AA-3, which achieved a tensile strength of 53.04 N/mm². This sample was processed with the highest axial force and moderate feed rate, leading to the best material bonding and strength. On the other hand, sample AA-1 displayed the lowest tensile strength (22.52 N/mm²), which can be attributed to a lower axial force and feed rate, resulting in inadequate material flow and insufficient welding heat generation. The comparison graph clearly highlights the difference in tensile strength across the four samples, with sample AA-3 significantly outperforming the others.

**Hardness Strength Test Results**

The hardness of the FSW joints was measured using the Vickers hardness test. The results, as shown in Table 6.10, indicate that the hardness strength varied between the samples.

The hardness of the FSW joints is crucial for determining the weld's resistance to wear and deformation. Sample AA-3, which had the highest tensile strength, also exhibited the highest hardness (15.15 N/mm²). This can be attributed

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to the optimal process parameters used during welding, such as the feed rate and axial force, which led to a refined microstructure and improved hardness. Conversely, AA-1 had the lowest hardness (6.43 N/mm²), which aligns with its lower tensile strength, suggesting that insufficient heat generation during the welding process resulted in lower hardness and strength.

The comparison graph further emphasizes these variations, with sample AA-3 again showing superior performance in terms of both tensile strength and hardness.

**Taguchi Method Analysis**

The optimization of process parameters was conducted using the Taguchi method, specifically analyzing the effect of parameters such as speed, feed, and axial force on the tensile and hardness properties of the FSW joints.

**Tensile Strength**

Based on the Signal-to-Noise (S/N) ratio analysis for tensile strength (Table 6.5), the optimal process parameters for maximum tensile strength were found to be a speed of 1500 RPM, a feed rate of 15 mm/min, and an axial force of 10 kN. This combination resulted in a high S/N ratio of -34.4921, indicating optimal welding conditions for improved tensile strength.

**Hardness Strength**

For hardness strength, the S/N ratio analysis (Table 6.13) suggested that the optimal process parameters were a speed of 1500 RPM, a feed rate of 15 mm/min, and an axial force of 10 kN. This combination yielded an S/N ratio of -23.6083, indicating optimal hardness results.

**4. Analysis of Variance (ANOVA)**

ANOVA analysis was conducted to determine the contribution of each process parameter to the tensile and hardness strength of the welds.

**Tensile Strength**

From Table 6.9, it is evident that axial force was the most influential factor, contributing 75.80% to the variation in tensile strength, followed by speed at 24.00%. Feed had the least impact on tensile strength (0.19%).

**Hardness Strength**

In Table 6.17, axial force was again the dominant factor, contributing 75.90% to the variation in hardness strength. Speed contributed 23.00%, while feed had a minimal impact (0.18%).

**5. Main Effects Plot Analysis**

The main effects plots for both tensile strength and hardness strength (Figures 6.28 and 6.36) show that increasing the speed and axial force results in improved mechanical properties. The feed rate, however, had a lesser impact on both tensile and hardness strength.

**Tensile Strength**

The main effects plot for tensile strength (Figure 6.28) reveals that the highest tensile strength is achieved at the highest speed (1500 RPM) and axial force (10 kN), with moderate feed rates.

**Hardness Strength**

Similarly, the main effects plot for hardness (Figure 6.36) indicates that the highest hardness strength is achieved under the same optimal conditions (1500 RPM speed and 10 kN axial force).

The optimization of process parameters through the Taguchi method has provided valuable insights into the effect of speed, feed rate, and axial force on the mechanical properties of friction stir welded dissimilar aluminum alloys 6061 and 6082. The results indicate that higher axial forces and speeds, combined with moderate feed rates, significantly improve both the tensile strength and hardness of the welded joints. These findings will serve as a guideline for achieving optimal weld quality in industrial applications where these materials are used.

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## CONCLUSION

This project focused on optimizing the process parameters for friction stir welding (FSW) of dissimilar aluminum alloys 6061 and 6082, aiming to enhance the mechanical properties, specifically tensile strength and hardness, of the weld joints. Using a L4 orthogonal array design of experiments, four distinct parameter sets were tested, and the resulting welds were evaluated through tensile and hardness strength tests.

The analysis revealed that axial force and welding speed were the most influential factors affecting both tensile strength and hardness of the FSW joints. Higher axial force and speed, combined with moderate feed rates, led to enhanced mechanical properties.

The optimal process parameters for achieving the best mechanical properties (both tensile strength and hardness) were found to be a welding speed of 1500 RPM, a feed rate of 15 mm/min, and an axial force of 10 kN. These conditions led to the highest tensile strength (53.04 N/mm²) and hardness strength (15.15 N/mm²).

The Taguchi method was successfully employed to optimize the process parameters, with the Signal-to-Noise ratio analysis confirming that axial force had the highest impact on the quality of the welds, followed by speed and feed.

ANOVA results showed that axial force contributed the most to the variation in both tensile strength (75.80%) and hardness strength (75.90%), highlighting the critical role of this parameter in achieving high-quality welds.

The tensile strength and hardness results demonstrated a direct correlation with the process parameters. The best welds, in terms of both strength and hardness, were obtained under conditions of higher speed and axial force, with moderate feed rate.

The optimization of the FSW process parameters for welding dissimilar aluminum alloys 6061 and 6082 has led to a significant improvement in the mechanical properties of the welds. The findings of this study provide a reliable framework for achieving high-quality welds in industrial applications involving these materials. This research contributes to a better understanding of the relationships between process parameters and the mechanical performance of friction stir welded joints, paving the way for more efficient and reliable FSW processes in the manufacturing sector.

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