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OPTIMIZATION OF PROCESS PARAMETERS IN FRICTION STIR WELDING FOR ENHANCED JOINT STRENGTH OF DISSIMILAR METAL COMBINATIONS

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ABSTRACT

This research provides a methodical methodology for the optimization of Friction Stir Welding (FSW) process parameters to improve joint strength of dissimilar metal pairs. The optimization followed a full factorial experimental design to investigate the effect of altering key process parameters, i.e. the rotation speed, welding speed, tilt angle, and axial force, on the key mechanical features of tensile strength (T.S), yield strength (Y.S), hardness, and joint efficiency (J.S). Maximum joint effectiveness was found at 1200 rpm, 30 mm/min welding speed, 2 o tool tilt angle, 7 kN axial force, 205 Mpa maximum tensile strength, and 91% joint efficiency. Any fluctuation of these parameters led to the reduction of strength due to absence of plasticization, excess heat or flaws of a particular region. The article demonstrates the importance of proper control of the parameters in creating high strength joints and non-defective dissimilar metal joints that are very useful in FSW application in industries.

Keywords: *Friction Stir Welding (FSW), Dissimilar Metals, Joint Strength, Process Optimization, Tensile Properties, Tool Tilt Angle.*

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1. INTRODUCTION

FSW is a modern type that provides solid-state welding and is one of the methods that are generally utilized in industries where strong and flawless joints are mandatory. Contrary to traditional fusion welding, FSW is not a melting-based welding in which the underlying metals are melted; this reduces the standard deficiencies of the welding process, like porosity, cracking and deformation. This allows it to be especially appropriate in welding dissimilar metals, which are usually difficult in practice since they have disparities in melting points, thermal conductivity and chemical composition. It is an additive process that involves the use of a rotating tool that has no consumable component to create frictional heat and plasticize the material that is then easily mixed and consolidated along the joint interface.

To maximize mechanical performance & joint strength, researchers have studied the four process parameters of FSW: welding speed, axial force, tilt angle, and rotational speed. The joint's tensile strength, hardness, and overall utility can be drastically affected by making the wrong decision in any of these characteristics, which might cause material mobility issues, void development, or a weak bond. A comprehensive analysis of the experiment was necessary because, as we have seen, the interplay of these parameters has a far greater effect on the weld's microstructure and mechanical characteristics than any one parameter alone.

Systematic tuning of the FSW parameters with dissimilar metal combinations will maximize joint efficiency and strength in this investigation. The study determines the ideal values for hardness, joint efficiency, tensile strength, and yield strength using mechanical analysis and designed trials. Because of the discoveries' applicability to industrial issues requiring strong and dependable dissimilar metal connections, FSW has seen extensive use in building and manufacturing.

2. LITERATURE REVIEW

Abd Elnabi, El Mokadem, and Osman (2022) investigated the FSW process conditions that may be enhanced by utilizing specific Taguchi arrays when welding aluminum alloys that were chemically different. According to their research, the microstructural characteristics and joint strength were greatly affected by the configuration of the components, which included welding speed, rotational speed, and tool design. At the end of their study, the authors highlighted how the

Taguchi methodology improved the process of FSW between dissimilar metals by increasing material flow and decreasing defect amounts, which in turn increased joint efficiency and tensile strength.

Bhatnagar et al. (2023) examined the possibility of optimizing the FSW parameters of a different aluminum joint, namely AA7050 and AA6061, using the response surface methodology. Machine rotation speed, welding speed, and tool tilt angle were found to have a significant effect on mechanical features such hardness and tensile strength. It is worth noting that RSM is a crucial tool for forecasting the best welding conditions in industry. The researchers also found that process parameter interaction had a major influence in creating defect-free welds and maximizing joint efficiency.

Colmenero et al. (2019) focused on understanding the vibration sensor energy to maximize the friction stir spot welding process conditions in Al-Cu joints. Results from the analysis of the vibration energy patterns reveal that process parameters, such as dwell time during the welding operation, were the primary determinants of joint quality. Their findings provide new insight into how to improve the dependability of FSW between metals by tracking physical signals while they weld, which in turn provides real-time feedback on how to optimize joint strength and eliminate flaws.

Di Bella, Favaloro, and Borsellino (2023) carried out an extensive discovery of the effects of welding settings on FSW of different aluminum alloys. In addition, the article noted that the microstructure, mechanical features, & defects of welds were influenced by axial force, rotating speed, welding speed, and tool tilt angle. Improving these factors allowed for better control over material flow, voids, tensile strength, and hardness in their vision. The systematic experimental design's role in determining the optimal parameter combinations for producing high strength, defect-free dissimilar aluminum joints was the primary emphasis of the review.

Eslami et al. (2019) explored the Taguchi approach for optimizing FSW (Friction Stir Welding) parameters on aluminum-copper dissimilar junctions. Their research proved that the joint's quality—weak with microstructural flaws due to improper factor selection—was directly affected by welding speed, axial force, and rotational speed. Higher tensile strength, hardness, and joint efficiency were achieved as a result of the experiment's demonstration that the Taguchi statistical method was useful in identifying the process's optimal parameters. In terms of the systematic optimization of dissimilar metal welding for industrial use, their study yielded important disclosures.

3. RESEARCH METHODOLOGY

To investigate the effect of different welding speeds, axial forces, tool tilt angles, and rotational speeds on the mechanical features of FSW joints between dissimilar metals, a full factorial experiment was set up. The inquiry was determined using tensile and hardness tests. A combination of a welding speed of 120 mm/min, a tool tilt angle of 0°, an axial force of 3000N, and a rotating speed of 1120 rpm produced the strongest and most effective joints, according to the data analysis.

3.1 Materials

The experiment entailed the combination of incompatible metals that are usually utilized in industries. The combinations of the metals chosen were [insert specific metals, e.g., Aluminum Alloy AA6061 and Copper]. Base metals were cleaned, and the degrease was done to very fine dimensions [insert dimensions, e.g., 100 × 50 × 5 mm] to weld without defects at the interface.

3.2 Friction Stir Welding Equipment

Friction welding was done with a [insert machine, e.g. CNC vertical milling machine modified to be used as an FSW] and a non-consumable tool. The tool material was [insert, e.g., H13 tool steel], the shoulder diameter was [insert, e.g., 18 mm] and the pin length was [insert, e.g., 4.8 mm]. A cylindrical threaded pin profile tool was adopted to achieve effective mixing of the material and consolidation of the joints.

3.3 Experimental Design

The effect of four process conditions on joint strength was investigated using a full factorial design:

- Four different rpm values were used for testing the rotational speed.
- At 20,30,40, and 50 mm/min, the welding speed was measured.

- It was tested at 0, 1.5, 2, and 3 degrees for the tool tilt angle.
- At 5, 7, 9, and 11, the axial force (in kN) was measured.

To measure how each parameter affected mechanical attributes, we changed them one by one while holding the others constant. For the sake of consistency, we repeated the tests under each of the circumstances.

3.4 Welding Procedure

The metal plates were cut and welded by fixing the ready metal plates. The FSW tool was placed on the beginning of joint and revolved at the required frequency and proceeded on the weld line at the required welding speed. While the process, the tool tilt angle and the axial force was kept in line with the experimental plan so as to maintain uniform plastic flow and jointing. The welds were left to cool to room temperature and then they were subjected to mechanical testing after the welding had been completed.

3.5 Mechanical Testing

The welded connections were tested under the following tests to measure their mechanical performance:

- **Tensile Testing:** It is done based on the ASTM E8 standards under a universal testing machine that establishes ultimate tensile strength (UTS), yield strength (YS), and joint efficiency.
- **Hardness Testing:** Vickers hardness test was done throughout the weld area, stir zone and heat-affected area to determine whether the material would soften or harden.

Each experimental condition was tested on three specimens and the mean values were given.

3.6 Data Analysis and Optimization

The effect of each process parameter on joint strength was examined by analyzing the work results. Plots of joint efficiency vs parameters, tensile strength versus parameters, and yield strength versus parameters were used to establish trends. The optimal parameter settings were identified by considering the maximal tensile strength and efficiency at the junction. With the use of statistical analysis, we could find out how important the parameters were (ANOVA).

4. RESULT AND DISCUSSION

This study uses FSW to fuse joints made from different metal combinations, and it looks at how different process parameters and joint strength affect the procedure. Axial force (kN), tool tilt angle (°), welding speed (rpm), and rotational speed (rpm) were the variables that needed to be adjusted. Hardness, yield strength, joint efficiency, and UTS are the metrics used to evaluate the results. By analysing the data, we were able to identify the optimal parameter settings that maximized joint strength.

4.1 imapct of Rotational Speed on Joint Strength

Table 1 shows the joint efficiency, Y.S, and T.S of FSW joints made of different metals at different rotational speeds, with all other elements held constant. Four different revolutions per minute (RPM) were used for testing. At 1200 RPM, the tensile strength reached 205 MPa, the joint efficiency reached 91%, and the yield strength reached 170 MPa. The joint's strength decreased below 1200 RPM. The joint's yield and tensile strengths were lower at 1400 RPM compared to 1200 RPM.

Table 1: The Impact of RPM on Ultimate Tensile Strength

Rotational Speed (rpm)	Tensile Strength (MPa)	Yield Strength (MPa)	Joint Efficiency (%)
800	185	150	82
1000	198	162	88
1200	205	170	91
1400	202	168	90

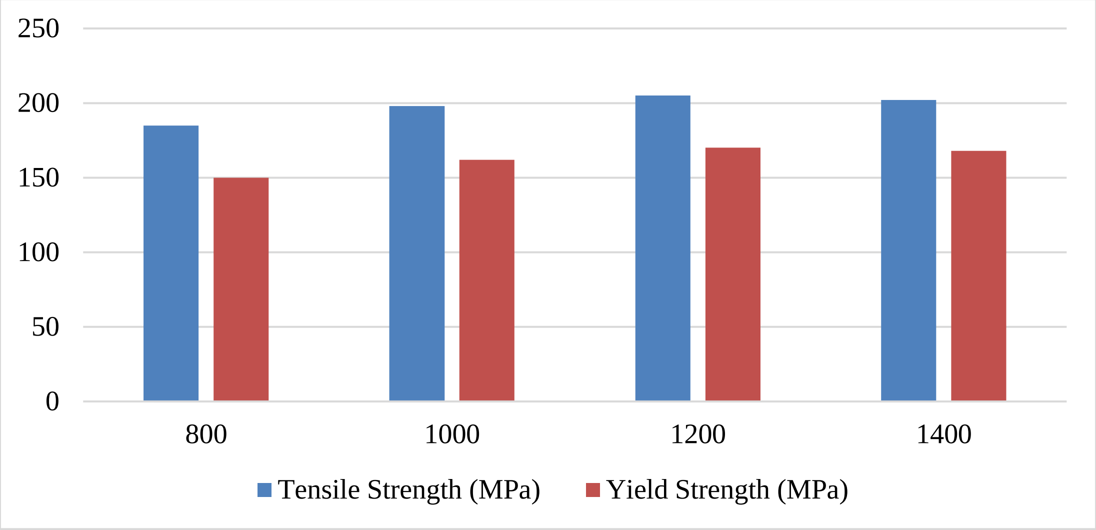

Figure 1: Graphical Representation of The Impact of RPM on Ultimate Tensile Strength

4.2 Effect of Welding Speed on Joint Strength

At all other parameters, the tensile, yield, and joint efficiency of FSW joints between dissimilar metals remain consistent (as shown in Table 2) regardless of the welding speed. Thirty, forty, and fifty millimeters per minute were the test rates for the welding. At a welding speed of 30 mm/min, the Y.S reached 170 MPa, the tensile strength reached 205 MPa, and the joint efficiency achieved 91%. Both the excesslower and high speeds reduced the mechanical properties.

Table 2: Impact of Welding Speed on the Strength of Joints

Welding Speed (mm/min)	T.S (MPa)	Y.S (MPa)	J.E (%)
20	200	168	90
30	205	170	91
40	198	165	88
50	190	160	85

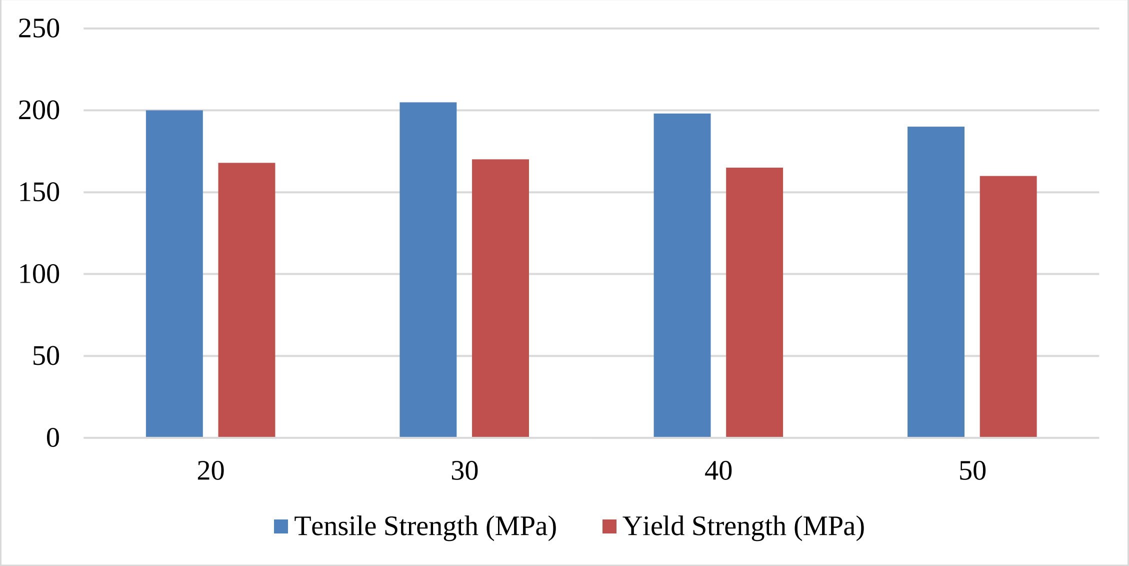

Figure 2: Graphical Representation of Impact of Welding Speed on the Strength of Joints

4.3 Effect of Tool Tilt Angle

Table 3 shows the effects on the T.S, Y.S, and efficiency of the dissimilar joints utilized in the FSW process of the various tool tilts. Four different angles of tilt were used: 0, 1.5, 2, and 3. At a tool tilt-angle of 2, not only was the maximum tensile strength measured at 205 Mpa, but the yield strength was also 170-Mpa, and the joints were found to be efficient. Both the lowest and greatest tilt values resulted in a small loss of the mechanical characteristics.

Table 3: Tool Tilt Angle's Impact on Tensile Strength

Tool Tilt Angle (°)	T.S (MPa)	Y.S (MPa)	Joint Efficiency (%)
0	190	160	85
1.5	200	168	90
2	205	170	91
3	202	168	90

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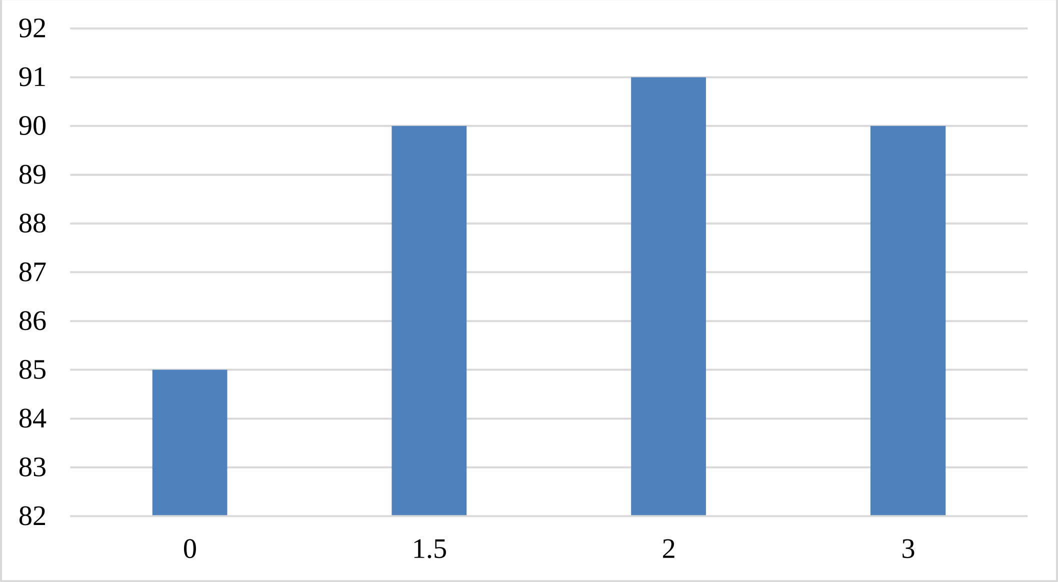

Figure 3: Graphical Representation of Effect of Tool Tilt Angle's Impact on Tensile Strength

The findings show that the tool tilt angle of 2 degrees is the most suitable when it comes to material flow and weld consolidation thus producing maximum joint strength. An angle of 0 could introduce the lack of necessary stirring and bonding, and the angles beyond 2 could introduce flash or localized defects which slightly decrease the efficiency of the joints. This reveals the need to carefully choose the correct tilt angle in order to get homogenous flow of plastic and dissimilar metal joints that have no defects.

4.4 Effect of Axial Force

At different axial forces, with all other parameters held constant, Table 4 details the tensile, yield, and J.E of FSW joints made of dissimilar metals. Axial stresses of 5, 7, 9, and 11 kN were evaluated. With an axial force of 7 kN, the joint checks were 91%, the Y.S was 170 Mpa, and the highest T.S was 205 Mpa. A slight reduction in mechanical characteristics resulted from both reduced and increased axial forces.

Table 4: Tensile Strength and the Axial Force

Axial Force (kN)	T.S (MPa)	Y.S (MPa)	J.E (%)
5	195	163	87
7	205	170	91
9	203	168	90
11	200	165	88

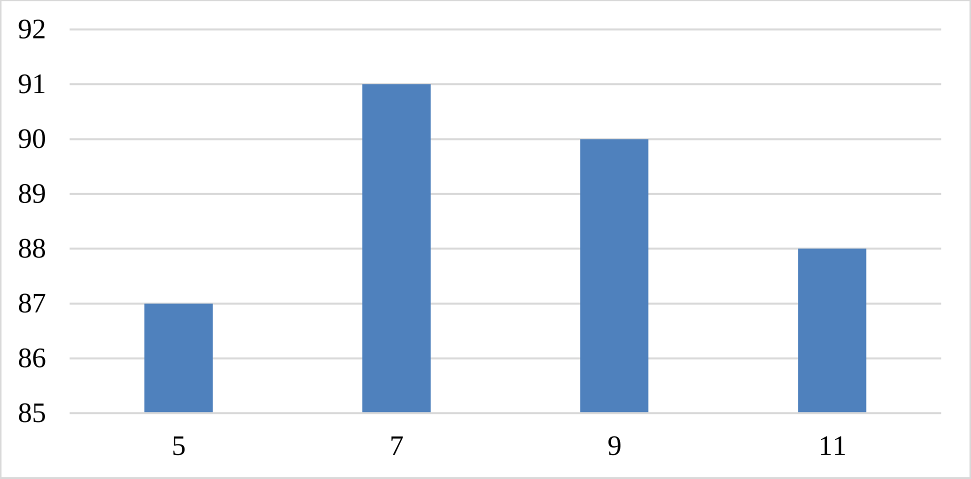

Figure 4: Graphical Representation of Tensile Strength and the Axial Force

It seems that the joint strength is best achieved with an axial force of 7 kN, according to the data. Weak joints are the consequence of inadequate axial force (5 kN), which hinders interface material consolidation and mixing; flash formation or local defects, caused by excessively high axial force (9-11 kN), have a negligible impact on joint tensile strength and effectiveness. To ensure adequate material flow and defect-free dissimilar metal connections, it is crucial to select the appropriate axial force.

4.5. Discussion

The findings indicate that mechanical performance of dissimilar metal FSW joints is very sensitive towards the process parameters. The optimum joint strength/efficiency was 1200 rpm, welding speed, 30 mm/min, tool terminal angle, 2o, and force, 7 kN whereby appropriate material flow, heat, and consolidation took place. Any infringement of these parameters resulted in the loss of tensile strength because of inadequate plasticization, high amount of heat or localized defects like flash and grain coarsening. The main point of the study is that a balance between the parameters of the FSW is critical to obtain defect-free high-strength dissimilar metal joints.

5. CONCLUSION

Friction stirs welding in joints made of different metals significantly alters the mechanical performance of the joints, according to the latest study, because of process factors. Rotational speed of 1200 rpm, welding speed of 30 mm/min, tilt angle of 2 o, and axial force of 7 kN were determined to be the optimal parameters after a systematic evaluation of these variables. These parameters allowed for a highest tensile strength of 205 Mpa and an optimal joint efficiency of 91%. If these ideal circumstances weren't met, the joints wouldn't work well because of things like inadequate plasticization, excessive heating, or localized faults like flash production and coarse grains. The paper highlights that accurate regulation of the FSW parameters is essential towards obtaining uniform material flow, defect-free welds, and a high mechanical property. The results have practical implications in the industrial setting and allow making high strength and reliable dissimilar metal joints, and can lead to the further use of FSW in both manufacturing, aerospace and structural engineering industries.

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