

OPTIMIZATION OF FRICTION STIR WELDING PROCESSING PARAMETERS BY SKH-57 TOOLS STEEL OF SS400-AL6063

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Abstract

The objective of this study's research was to determine the optimal tools and friction stir welding process parameters of dissimilar material between carbon steel SS400. Which is a material widely used in various industries, including shipbuilding and automotive assembly, and aluminum alloy 6063. Which is a lightweight material. These two materials differ physically and in their mechanical properties with significantly different hardness levels. The maximum tensile strength using the design of experiment technique. This study's research in four welding parameters consisted of two shapes of shoulder and pin (spiral shape pin with curved surface shoulder and spiral shape pin with flat surface shoulder), Tools rotational speed (500, 550, 600, and 650 rpm), Traverse speed (20, 30, 40, and 50 mm/min), and Tilt angle (0, 1, 2, and 3 degrees). From the experimental results, the welding conditions of the average maximum tensile strength of 189.33 MPa were a spiral-shaped pin with a curved surface shoulder, a rotational speed of 600 rpm, a traverse speed of 50 mm/min, and a Tilt angle of 3 degrees. In addition, the statistical analytical result indicated that the tool's rotational speed was the most significant factor, and the predicted optimal conditions were a spiral-shaped pin with a curved surface shoulder, a rotational speed of 590 rpm, a traverse speed of 40 mm/min, and a tool tilt angle of 3 degrees. Optimal results had been verified through confirmation experiments with a tensile strength of 191 MPa.

Keywords: Curved Surface Shoulder; Flat Surface Shoulder; Friction Stir Welding; Taguchi Techniques

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Introduction

The northeastern region of Thailand shares borders with neighboring countries. International travel, tourism, transportation, communication and trade necessitate the use of boats as a means of transport. The boats used in the river basins of these border areas are small and made with aluminum components. In contrast, larger boats are constructed using steel, a metal known for its high strength but also its significant weight. Boats that are heavy during travel or when transporting large loads must bear substantial burdens, leading to a high waterline. This results in frequent collisions with underwater debris such as stones, soil, and sand, which affects the boat's lifespan due to wear and corrosion. Therefore, efforts are being made to replace the original steel materials with lighter alternatives while maintaining comparable strength. Lightweight materials like aluminum have garnered interest for addressing these issues. However, replacing steel with aluminum requires the integration of these two materials, which must be strong, durable, and free from breakage. Currently, metal welding involves heating the materials until they melt, which can affect the weld structure. Combined without melting (Gebreamlak *et al.*, 2022). It is well known that welding materials with different mechanical properties requires high-quality welding techniques. One such technique is friction stir welding (FSW), which was developed by The Welding Institute (TWI) in the United Kingdom (Elatharasan and Kumar, 2013). FSW is a solid-state joining process that utilizes a non-consumable tool to join two facing workpieces without melting the base materials (Milicic *et al.*, 2016). Since the heat generated during FSW remains below the melting points of the materials being joined, the process is especially suitable for welding materials that are traditionally difficult to weld, such as aluminum (Gibson *et al.*, 2014). FSW enables the effective joining of both hard and soft materials, including aluminum alloys, while avoiding many common problems associated with conventional fusion welding techniques (Bull *et al.*, 1998). In shipbuilding applications, welding aluminum to steel components using FSW can significantly reduce the ship's overall weight while preserving mechanical properties comparable to those of traditional steel structures. This approach has also found increasing relevance in other industries, including automotive, aerospace, railway, and maritime engineering (Tarnag and Yang, 1998).

The reduction in the weight of the ship will lead to lower fuel consumption (Celik and Cakir, 2016). The submersion depth of the ship has

decreased, which may also result in the ship experiencing less wear and tear. However, friction welding requires the study of material properties and the feasibility of welding. Advance methods of joining technology have been developed (Samson *et al.*, 2023). Additionally, it is necessary to find the appropriate factors for welding to determine the suitable relationship for stir friction welding (Karwande and Rao, 2016).

Materials and Methods

Experimental Materials

This research uses SS400 carbon steel on the AS (Advancing Side) and 6063 grade aluminum alloy on the RS (Retreating Side). These two materials differ physically, chemically, and in their mechanical properties, with significantly different hardness levels. The workpieces, measuring 50 mm in width, 150 mm in length, and 6 mm in thickness, were used in the friction stir welding process.

Tools and Equipment for the Experiment

Welding tools used in this study are made from SKH 57 tool steel, a high-hardness material with a hardness value exceeding that of the materials being welded. This type of steel is commonly utilized for machining operations such as turning and drilling hard materials shown in Figure 1. Two tool shapes made from SKH 57 were employed, as illustrated in Figure 2. The first tool, shown in Figure 2(a), features a spiral-shaped pin with a curved shoulder surface. This design provides a flat contact surface, which promotes strong

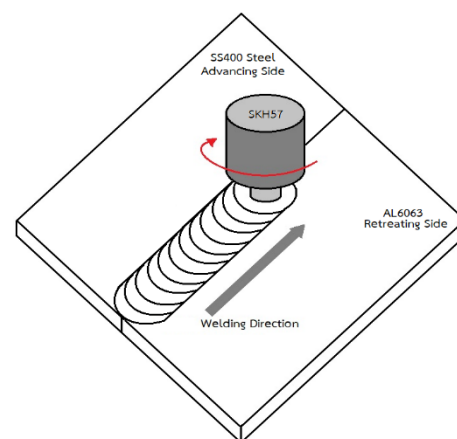


Figure 1. Shows Friction stir welding between carbon steel and aluminum

bonding along the weld seam when pressed against the workpiece. The second tool, shown in Figure 2(b), has a spiral-shaped pin with a flat shoulder surface. This configuration includes surface gaps that influence the material flow and mixing between the two workpieces, contributing to improved weld bonding. The tool has a shoulder diameter of 20 mm, a pin diameter of 7 mm, and a pin length of 5.8 mm. Welding is carried out using an automatic Computerized Numerical Control (CNC) machine, model Litz CV-1200a.

Experimental Variables

Friction stir welding (FSW) between SS400 carbon steel and aluminum 6063 was performed by setting the tool insertion offset from the retreating side (RS) to the advancing side (AS) at 0.1 mm. This slight offset facilitates effective mixing and bonding between the dissimilar materials. The experimental conditions and parameters used in the welding process are summarized in Table 1.

Experimental Design

Designing experiments based on specified variables using the Taguchi Method with a total of 16 experiments conducted, each repeated with 3 welds. The design results are shown in Table 2.

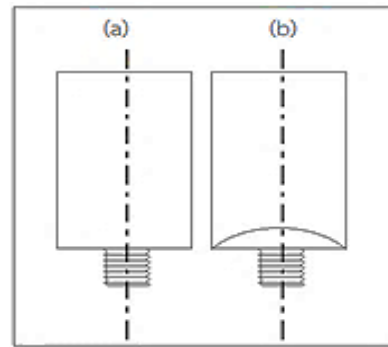


Figure 2. Shows Tools Geometry

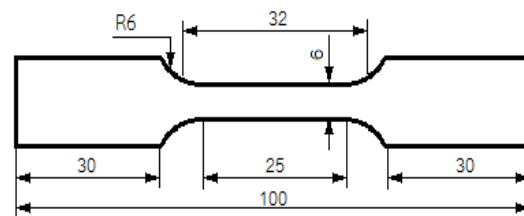


Figure 3. Shows the tensile test specimen according to standards ASTM-E8 (unit: mm)

Table 1. Shows Variables and levels in the experiment

Variable of weld	Unit	Level			
		1	2	3	4
Rotating Speed	RPM	500	550	600	650
Travelling Speed	mm/min	20	30	40	50
Tools Geometry	-	spiral shape pin with flat surface shoulder		spiral shape pin with curve surface shoulder	
Tilt Angle	Degree	0	1	2	3

Table 2. Shows Designing experiments using the Taguchi method with 16 experiments (Taguchi Array L16)

Number of Test	Rotating Speed (RPM)	Travelling Speed (mm/min)	Tools Geometry	Tilt Angle (Degree)
1	500	20	a	0
2	500	30	b	1
3	500	40	a	2
4	500	50	b	3
5	550	20	a	2
6	550	30	b	3
7	550	40	a	0
8	550	50	b	1
9	600	20	a	0
10	600	30	b	2
11	600	40	a	1
12	600	50	b	3
13	650	20	a	1
14	650	30	b	0
15	650	40	a	3
16	650	50	b	2

Testing Mechanical Properties Through Tensile Strength Testing

SS400 carbon steel and 6063 aluminum alloy, which have undergone friction stir welding according to the conditions shown in Table 2, are cut into shapes according to the ASTM-E8 tensile test standard as shown in Figure 3 and then subjected to tensile testing using the GOTECH GT-7001 testing machine.

Statistical analysis

This research studies the influence of variables in friction stir welding of SS400 carbon steel and

6063 aluminum alloy by designing experiments using the Taguchi method and systematically analyzing the results. The analysis was conducted using the Minitab version 19 statistical software to evaluate the results and welding variable conditions in order to obtain appropriate tensile test values. (Response Parameter).

Results and Discussion

Results from the Tensile Strength Test

After welding according to the variables from the experimental design, the workpieces were subjected to mechanical property testing through tensile tests in 16 experimental sets. Each experimental set involved testing 3 pieces, and the results were then averaged along with the standard deviation, as shown in Table 3.

Results of the Weld Surface Analysis

Analysis of the weld surface by observing the macro surface to identify defects or characteristics of the surface found that Welding using a spiral-shaped pin with a flat surface shoulder with a welding rotation speed of 500 RPM, a welding travel speed of 20 mm/min, and an inclination tilt angle of 0 degrees, as shown in Figure 4, is a welding variable that resulted in the lowest average tensile strength test at an average value of 158 MPa. Defects were found to be small

voids, uneven surface smoothing, slight burrs at the weld edge, and the aluminum alloy grade 6063 being inconsistently smoothed onto the carbon steel SS400. This inconsistency may be due to the mismatch between the welding rotation speed and the welding travel speed. Meanwhile, welding using a spiral-shaped pin with a curved surface shoulder. The rotational welding speed is 600 RPM, the travel speed is 50 mm/min, and the tilt angle is 3 degrees, as shown in Figure 5. These welding conditions resulted in the highest average tensile strength test at 189 MPa. The surface of the weld bead is uniformly smooth, with no defects observed. There are slight burrs at the edges of the weld bead. The aluminum alloy grade 6063 was fully blended into the carbon steel SS400, possibly due to the correlation between the rotational welding speed and the travel speed. Additionally, the screw of the tools can effectively pull aluminum scraps towards the steel side. This screw of the tools is suitable for friction welding of different materials. (Dissimilar) of aluminum and steel (Li *et al.*, 2017). While the concave shoulder of the stirrup allows for



Figure 4. Shows welding using a spiral-shaped pin with a flat surface shoulder with a welding rotation speed of 500 RPM, a welding travel speed of 20 mm/min, and an inclination tilt angle of 0 degrees



Figure 5. Shows welding using a spiral-shaped pin with a curved surface shoulder with a welding rotation speed of 600 RPM, a welding travel speed of 50 mm/min, and an inclination tilt angle of 3 degrees

Table 3. Shows results from the tensile strength test

No. of test	Everage of Strength (MPa)	Standard deviation	No. of test	Everage of Strength (MPa)	Standard deviation
1	158	4.23	9	177	4.66
2	159	2.17	10	179	2.26
3	142	3.91	11	180	3.12
4	160	3.89	12	189	3.52
5	179	4.02	13	177	4.27
6	180	3.59	14	178	3.15
7	184	4.19	15	175	3.65
8	168	3.91	16	180	2.91

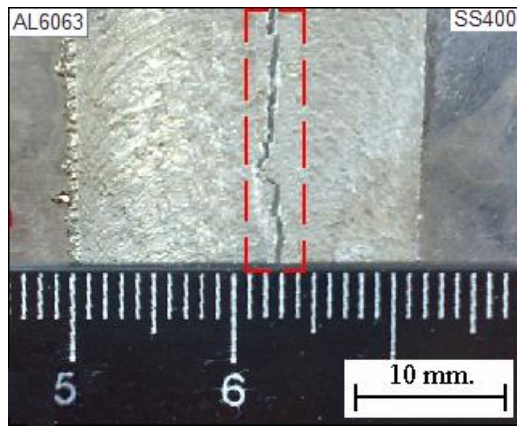


Figure 6. Shows the weld surface obtained from the lowest tensile strength test

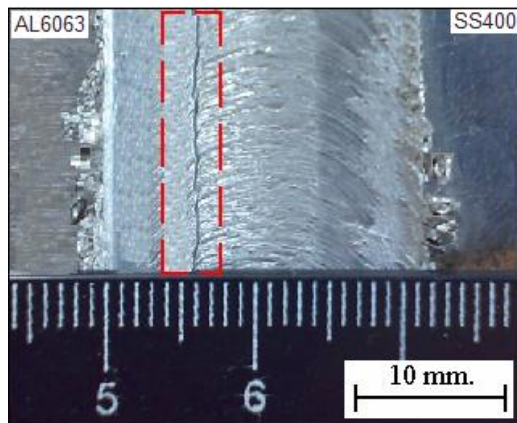


Figure 7. Shows the weld surface obtained from the tensile strength test is the highest

good movement of aluminum particles, aluminum, being more ductile than steel, moves well through the concave channel to the steel side, resulting in good bonding and integration of both materials (Bozorgzadeh and Idris, 2015).

Structural Analysis and Fracture

From Figure 6, the tensile test shows that the fracture occurred at the center of the weld joint between the carbon steel SS400 and aluminum 6063. This may be due to improper welding or welding conditions, causing the weld to fracture at the center, resulting in a lower tensile test value. Meanwhile, from Figure 7, the tensile test shows that the fracture occurred on the left side of the joint, which is the aluminum side. This indicates that the weld is strong enough not to cause a fracture at the weld joint, resulting in a higher tensile test value. The middle section of the workpiece is the area most

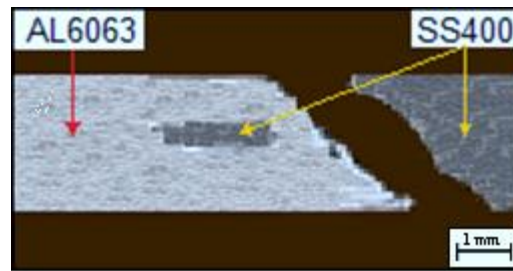


Figure 8. Shows a side view image of the weld line obtained from the lowest tensile test

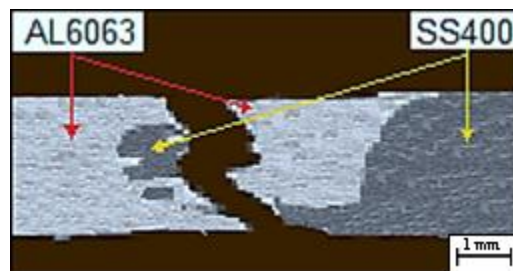


Figure 9. Shows a side view image of the weld line obtained from the highest tensile strength test

affected by heat. It will be found that if a tensile test causes the workpiece to break in the middle, it may indicate incomplete bonding. If the workpiece breaks in the aluminum area during the tensile test, it indicates complete bonding because the materials on both sides have fused well. The fracture of the workpiece is brittle, possibly due to incomplete material flow mechanisms on each side. There is no bonding through temperature, but they may bond due to physical characteristics.

From Figure 8, the side view under the welding conditions that yielded the lowest tensile test values shows that the weld seam failed at the joint between the SS400 carbon steel and the 6063 aluminum. Although the weld seam involved the movement of SS400 carbon steel towards the 6063 aluminum, indicating that the materials on both sides moved towards each other, it did not result in a strong weld seam. In contrast, Figure 9 shows that the weld seam involved the movement of both types of materials towards each other. The bonding of the materials shows a clear phase separation when observed under low magnification. The steel moves towards the aluminum, and the aluminum also moves towards the steel. This resulted in higher tensile test values. The tensile test did not fail at the weld seam but at the interface of the two materials internally. Previous research on welding, specifically the welding of aluminum 6061 to AISI 316 stainless

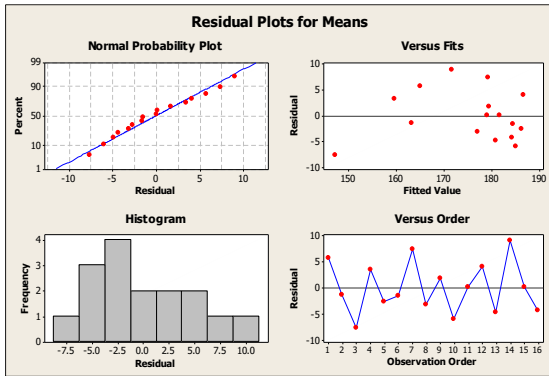


Figure 10. Shows accuracy verification

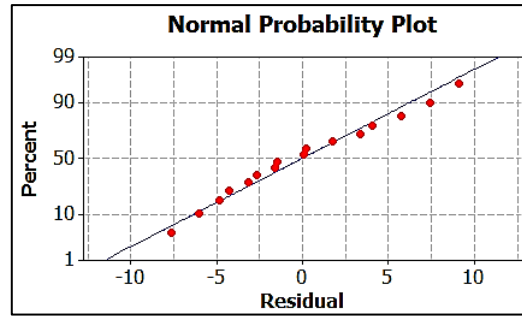


Figure 12. Shows the normal probability plot

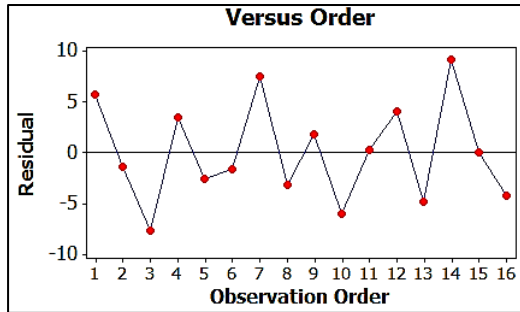


Figure 11. Shows the graph shows the distribution of the data

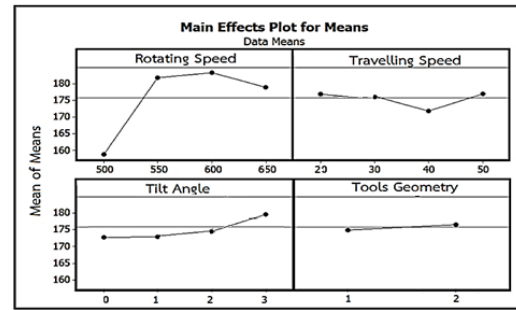


Figure 13. Shows Influence of the main factors of the experiment

Table 4. Shows the results of the variance analysis

Source	DF	Seg SS	Adj SS	Adj MS	F	P
Rotating Speed	3	1575.28	1575.28	525.09	7.28	0.02
Travelling Speed	3	87.24	87.24	29.08	0.40	0.75
Tools Geometry	3	271.65	271.65	90.55	1.25	0.38
Tilt Angle	1	12.29	12.29	12.29	0.17	0.69
Error	5	360.88	360.88	72.18		
Total	15	2307.34				

S = 8.496 R-Sq = 84.4% R-Sq (adj) = 73.1%

steel, found that welding using heat from a tool rotation that is too slow may result in poor bonding or movement of the steel (Newishy *et al.*, 2023). The movement between the two materials, if one side moves, will affect the mechanical properties positively. However, if both sides move simultaneously, it will enhance the mechanical properties even more because the materials will bond together.

Model Verification

Model verification is very important to ensure the accuracy and appropriateness of experimental data before conducting result analysis. After verifying the model, it is then used to analyze the resulting variance (Sedmak *et al.*, 2016) as shown in Figure 10.

Data Independence Verification

Based on the analysis of the generated graph, it was observed that the data points are distributed in a manner that prevents the identification of any clear trends or patterns. The distribution appears random, indicating that the data are independent of one another, as shown in Figure 11.

Checking the normality of the data by examining the Normal Probability Plot. The graph appears as a straight line, as shown in Figure 12, indicating that the data from the analysis is normal.

Regression equation (Equation 1) Obtained from experiments that are accurate and can be considered based on the decision coefficient (determination; R^2). From the data in Table 4, with an R^2 value of 84.4%, it indicates that out of 100 units of the experimental rate, 84.4 units are

variability from the four welding condition variables, and 15.6 units are due to uncontrollable factors. Considering the adjusted R^2 value of 73.1%, which differs from the R^2 value at a certain level, it shows that the 16 experimental data points used have a certain level of correlation. This equation has a scope of experimentation at Rotating Speed (500, 550, 600, and 650 rpm) and Travelling Speed (20, 30, 40, and 50 mm/min). Tools Geometry 2 Shapes (spiral shape pin with flat surface shoulder and spiral shape pin with curve surface shoulder) and Tilt Angle 4 levels (0, 1, 2, and 3 degrees).

$$\text{UTS (MPa)} = 120.602 + 0.123911 (A) - 0.076926 (B) - 0.909244 (C) \dots (1)$$

By
(A) = Rotating Speed (B) =
Travelling Speed and (C) = Tilt
Angle

The analysis of variance from the experiment at a significance level of 0.05, considering the P-value, found that the influence of the main factor, which is the welding rotation speed, significantly affects the tensile strength at the weld line, as shown in Table 4.

From Figure 13, considering the welding rotational speed graph, it is found that at a welding rotational speed of 500 RPM, the tensile strength is low. Increasing the welding rotational speed to 550 RPM results in higher tensile strength. found that welding using heat from a tool rotation that is too slow may result in poor bonding or movement of the steel.

At a welding rotational speed of 600 RPM, the tensile strength is at its highest. It then decreases at a welding rotational speed of 650 RPM, where excessive speed leads to increased heat (Kilic *et al.*, 2025). Meanwhile, at a welding travel speed of 50 mm/min, the tensile strength test value is the best. Increasing the travel speed results in lower tensile strength test values, possibly due to the travel speed not being in sync with the rotational speed. However, the tensile strength slightly decreases at 20 mm/min. Changes in the tools geometry also affect the tensile strength. (Veljic *et al.*, 2014; Liu *et al.*, 2018; Hoyos and Serna, 2021) While the stirring tilt angle of 3 degrees yields good tensile test results. Reducing the welding angle will slightly lower the tensile test values.

Conclusions

SS400 steel and 6063 aluminum are materials with different mechanical, chemical, and physical properties. They have distinct characteristics,

with SS400 steel being a material that is hard, strong, and durable for use, while 6063 aluminum is lightweight and has better flexibility than steel materials.

Friction stir welding between SS400 carbon steel and 6063 aluminum alloy can be successfully bonded and exhibits strong weld strength. The results can be summarized as follows:

1. Welding using a spiral-shaped pin with a curved surface shoulder at a rotation speed of 600 rpm, a welding travel speed of 50 mm., and a tilt angle of 3 degrees achieved an average tensile strength of 189 MPa, which is 78.75 percent of the grade 6063 aluminum alloy, the main material used in the welding process.

2. The rotational speed is a key factor in friction stir welding between SS400 carbon steel and 6063 aluminum alloy. Increasing or decreasing the speed will affect the tensile strength of the weld seam. The next influencing factors are the shape of the welding tool, the welding travel speed, and the tilt angle, respectively.

3. Friction stir welding is essential for determining the appropriate welding parameters and also for finding the relationships of the main factors used in welding. This is because the materials used for friction stir welding come in many types, each with different welding parameters.

4. The use of regression equations in analysis with statistical processing software found that the optimal welding factor levels are a welding rotation speed of 580 RPM, a welding travel speed of 50 mm/min, a spiral shape pin with curve surface shoulder, and a tilt angle of 3 degrees. These factors can provide the most suitable levels, with an expected tensile strength test result of 190 MPa.

5. This research is beneficial for studying important parameters for the research. If researchers want to friction-weld materials between steel and aluminum of different grades, they can use these parameters for preliminary studies.

6. From the analysis, it was found that a spiral-shaped pin with a curved surface shoulder of the welding tool provided better test results. This may be due to the tool's gap having a concave shape, which allows for better bonding of the materials on both sides compared to the flat shoulder type that compresses the workpiece.

7. The mechanical testing indicates that the fracture of the weld seam may be brittle. This could be due to the flow mechanism of the material on the side with lower hardness not being able to bond completely with the material on the other side, while the material on the side with higher hardness does not reach a high enough temperature to cause movement towards the aluminum side. Therefore, it can be predicted that higher temperatures may

result in better bonding of steel materials compared to lower or inappropriate temperatures.

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