INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)

www.ijprems.com
editor@ijprems.com

Vol. 03, Issue 10, October 2023, pp : 251-263

e-ISSN : 2583-1062

Impact Factor : 5.725

BOBBIN TOOL FRICTION STIR WELDING

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DOI: https://www.doi.org/10.58257/IJPREMS32149

ABSTRACT

Friction stir welding has made remarkable progress since its invention in 1991, for welding aluminum alloys. Although the process has many benefits, there are also drawbacks, one of them being the risk of root flaws in single sided welds. One of the most promising ways to avoid these is to use a double-sided or bobbin tool, as this removes the root region. The bobbin friction stir welded 6 mm thick AA1100 has been done successfully which widened the application of BFSW on AA1100. Optimization via RSM used for analyzing the influence of both spindle and welding speeds on the mechanical properties of the AA1100 weld. The conclusions is drawn from the both experimental and optimization of both spindle and welding speeds had influence the tensile properties of the weld and the average hardness at stir zone weld region. The results show that increasing the spindle speed and welding speed can lead to an increase in tensile strength and average hardness. Specifically, for every one unit increase in spindle speed, the predicted tensile strength is expected to increase by 0.03 units, and for every one unit increase in welding speed, the predicted tensile strength is expected to increase by 0.04 units.

Keywords: Bobbin Tool, FSW, Welding Aluminum Alloys. Welding

1. INTRODUCTION

The use of a double-sided friction stir welding tool (known as a bobbin tool) has the advantage of giving a processed zone in the work piece which is more or less rectangular in cross section, as opposed the triangular zone which is more typically found when conventional friction stir welding tool designs are used. In addition, the net axial force on the work piece is almost zero, which has significant beneficial implications in machine design and cost. However, the response of these tools in generating fine microstructures in the nugget area has not been established. The paper presents detailed metallographic analyses of microstructures produced in 25mm AA6082-T6 aluminium wrought alloy, and examines grain size, texture and mechanical properties as a function of processing parameters and tool design, and offers comparison with data from welds made with conventional tools.

Friction stir welding has made remarkable progress since its invention in 1991, in particular for welding aluminum alloys. Although the process has many benefits, there also drawbacks, one of them being the risk of root flaws in single sided welds. One of the most promising ways to avoid these is to use a double-sided or bobbin tool, as this removes the root region. This variant was described in the original TWI patent, and is shown schematically in Figure 1. Its advantages can be summarized as follows:

- Eliminates weld roots, and root defects.
- Low Z forces on fixture and machine.
- No backing bar required.
- Low distortion due to uniform heat input
- Simple control.
- Tolerance to thickness variation.

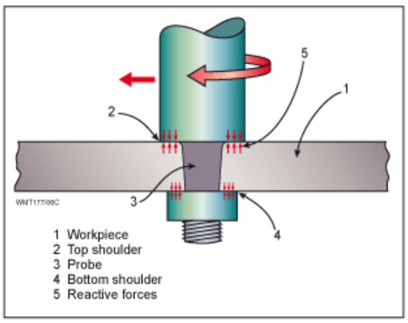

Fig. 1: Principle of Bobbin Tool

Subsequent work in the USA and elsewhere developed the bobbin tool concept by allowing the gap between the shoulders, and hence the force exerted on the workpiece to be controlled, usually to keep a constant value. However, recent work at TWI has shown that a fixed bobbin tool can give very good results without the sophistication of the variable gap, although care is needed with the tool design.

Bobbin Tool Design and Classification

The working concept of BT-FSW allows the bobbin tool notably its pin section sustain a more complicated stress state than the tool in traditional FSW, which gives rise to a substantial difficulty regarding bobbin tool design and material selection. Features on the shoulder and pin surfaces of the bobbin tool are also crucial to its design. Weld quality is strongly influenced by these factors because of their direct effect on material flow and heat production during welding. Different varieties of bobbin tools, including as the fixed-gap type, the adjustable-gap type, the dual-rotation type, and the stationary shoulder type, have been produced, as shown by the existing literature.

Fixed-Gap Bobbin Tool

The fixed-gap bobbin tool has a constant distance between the upper and lower shoulders during the welding operation and can therefore only be used for a single thickness of joints. According to z-axis movement, this kind of tool may be further categorised into fixed bobbin type and floating-bobbin type, as illustrated in Fig. 2. Unlike the fixed bobbin, the floating bobbin can freely move up and down in a sleeve to find best position to balance the forces acting on the two shoulders during welding, which simplifies process control and greatly reduces the requirement for high machine positional accuracy by improving the tolerance to workpiece thickness variation and component-machine alignment. Figure 3 depicts a painless floating-bobbin tool, which is a specific example of the floating-bobbin tool. This tool design makes it clear that BT-FSW may become even more tolerant of variations in the thickness of the workpiece.

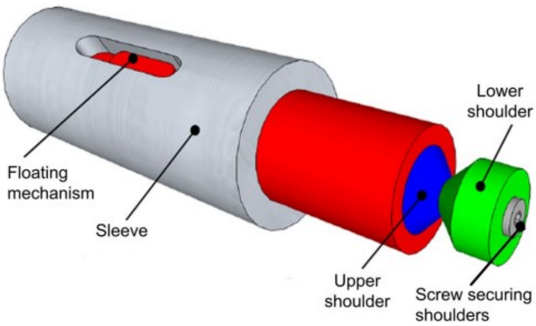

Fig. 2: Pinless floating-bobbin tool

Alloys in the 2xxx, 6xxx, and 7xxx series of aluminium may be heat treated, and their low density, greater strength, lower weight, and good corrosion resistance make them ideal for usage in the automotive, shipbuilding, rail, and aerospace sectors. However, fusion welding of these alloys presents challenges such as solidification cracking, losses of alloying material, porosity, high residual stresses, decreases in mechanical characteristics, oxidation, and the need for many passes when welding large sections.

Specialized forms of CFSW include bobbin friction stir welding. Other names for the bobbin friction stir welding technique include self-reacting FSW (SRFSW), self-support FSW (SSFSW), and bobbin tool FSW (BTFSW). There are several aspects of BTFSW that make it preferable than CFSW. When compared to CFSW, a tool of BTFSW consists of an additional shoulder known as 'lower shoulder' at the end of the pin of CFSW as illustrated in Figure 3 (a,b).

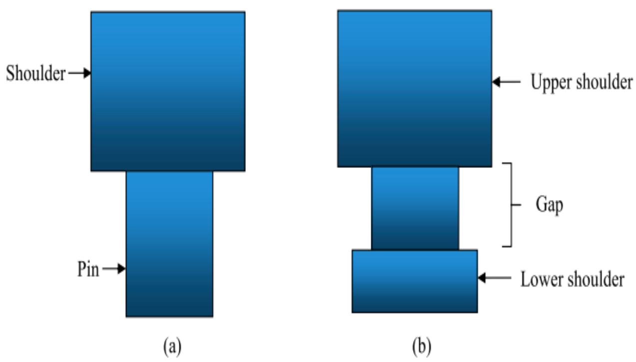

Fig. 3: Schematic of tool used in (a) conventional and (b) bobbin tool FSW.

2. REVIEW OF LITERATURE

[1] Mukherjee et al. (2017), review paper on friction stir welding and its impact on environment. The comprehensive essay of knowledge that has been documented with respect to the friction stir welding (FSW) of different alloys since the technique was invented in 1991 is reviewed on this paper. The friction stir welding is a rapidly growing welding technique in the manufacturing industries. A proper tool design with a process parameters is welded on work material can result in high quality welding. The materials that are suitable for friction stir welding are aluminum and its alloys, Magnesium alloys, Titanium and its alloys, copper alloys, Mild steel, Stainless steel, etc. Response Surface Methodology (RSM) is an important area of research in an optimization of the process parameters.

[2] Amin et al. (2018), introduced Experimental Study the Effect of Tool Design on the Mechanical Properties of Bobbin Friction Stir Welded 6061-T6 Aluminum Alloy. Bobbin friction stir welding (BFSW) is a variant of the conventional friction stir welding (CFSW); it can weld the upper and lower surface of the work-piece in the same pass. This technique involves the bonding of materials without melting. In this work, the influence of tool design on the mechanical properties of welding joints of 6061-T6 aluminum alloy with 6.25 mm thickness produced by FSW bobbin tools was investigated and the best bobbin tool design was determined. Five different probe shapes (threaded straight cylindrical, straight cylindrical with 3 flat surfaces, straight cylindrical with 4 flat surfaces, threaded straight cylindrical with 3 flat surface and threaded straight cylindrical with 4 flat surfaces) with various dimensions of the tool (shoulders and pin) were used to create the welding joints. The direction of the welding process was perpendicular to the rolling direction for aluminum plates. Tensile and bending tests were performed to select the right design of the bobbin tools, which gave superior mechanical properties of the welded zone. The tool of straight cylindrical with four flats, 8 mm probe and 24 mm shoulders diameter gave better tensile strength (193 MPa), elongation (6.1%), bending force (5.7 KN), and welding efficiency (65.4%) according to tensile strength.

[3] Sivakumar et al. (2014), Review Paper on Friction Stir Welding of various Aluminium Alloys. The comprehensive body of knowledge that has built up with respect to the friction stir welding (FSW) of aluminum alloys since the technique was invented in 1991 is reviewed on this paper. The basic principles of FSW are described, including metal flow and thermal history, before discussing how process parameters affect the weld microstructure and the likelihood of defects. Finally, the range of mechanical properties that can be achieved is discussed. It is demonstrated that FSW of aluminum is becoming an increasingly mature technology with numerous commercial applications. The present review has demonstrated the extensive research effort that continues to progress the understanding of FSW of aluminium alloys and its influence on their microstructure and properties.

[4] Bodake et al. (2017), Review paper on optimization of friction stir welding process parameters. AA 7075 is an aluminum alloy, with zinc as the main alloying constituent. Current work deals with experimental investigation of optimization of friction stir welding process (FSW) to arrive at desirable mechanical properties of aluminum 7075 and C11000 plates. Main factors of process are tool pin profile, tool rotary speed, welding speed, and welding axial force and main responses are tensile strength, yield strength, and hardness of weld zone. For friction stir welding number of process parameters affects weld mechanical properties. Which are tool rotational speeds, welding speed, axial force, tool geometry and tool angle. Rotational speed produces the frictional heat required to plasticize the material. The weld produces at low speed have fine mechanical properties than weld produced at higher speed. The mechanical property increases with the rotational speed and welding speed but up to a certain level then they starts declining.

[5] Irvine et al. (2014), Developing a Mathematical Model for Bobbin Lace. Bobbin lace is art form in which intricate and delicate patterns are created by braiding together many threads. An overview of how bobbin lace is made is presented and illustrated with a simple, traditional bookmark design. Research on the topology of textiles and braid theory form a base for the current work and is brie y summarized. We de ne a new mathematical model that supports the enumeration and generation of bobbin lace patterns using an intelligent combinatorial search. Results of this new approach are presented and, by comparison to existing bobbin lace patterns, it is demonstrated that this model reveals new patterns that have never been seen before.

[6] Węglowska et al. (2018), The Use of a Bobbin Tool in the Friction Stir Welding of Plates Made of Aluminium Alloy EN AW 6082 –T6. The article presents test results concerning the friction stir welding of 6 mm thick plates made of aluminium EN AW – 6082.

The welding process was performed using a tool consisting of two shoulders and a probe. The tests were concerned with the effect of welding parameters in the process of welding and the quality of joints. Related visual test results enabled the assessment of the effect of a bobbin tool on the formation of a weld, the presence of surface imperfections and the continuity of material in welds (based on metallographic tests). Mechanical properties of the joints were identified in static tensile tests and in hardness measurements. The effect of welding conditions on the welding process and weld formation was determined through measurements of temperature on the weld surface, performed using a thermographic camera, and measurements of force and torque affecting the tool, performed using a LowStir device. The test results revealed that the use of the bobbin tool enabled the obtainment of joints characterised by the compact structure of welds, material continuity, strength and repeatability comparable with those obtained using the conventional tool.

[7] Sued et al. (2016), Dynamic Interaction between Machine, Tool, and Substrate in Bobbin Friction Stir Welding. The bobbin friction stir welding (BFSW) process has benefits for welding aluminium alloy 6082-T6 in the boat-building industry. However this alloy is difficult to weld in the thin state. There are a large number of process variables and covert situational factors that affect weld quality.

This paper investigates how tool holder and machine-type affect BFSW weld quality of 4mm Al6082-T6. The variables were tool features (three types), machine-controller type (two types), and tool holder (fixed versus floating). Fourier analysis was performed on motor spindle current to determine the frequency response of the machine. An interaction was found between the computer numerical control (CNC), the degrees of freedom of the tool holder, and the substrate (workpiece). The conventional idea that the welding tool has a semisteady interaction with the substrate is not supported. Instead the interaction is highly dynamic, and this materially affects the weld quality. Specific vibrational interactions are associated with poor welding. The CNC machine-type also emerges as a neglected variable that needs to be given attention in the selection of process parameters. Although compliance in the tool holder might seem useful, it is shown to have negative consequences as it introduces tool positioning problems.

[8] Jayabalakrishnan et al. (2019), Analysis Of Friction Stir Welding Between Dissimilar Materials Using Bobin Tool. Friction stir welding is a solid-state joining process where the original metal characteristics remain unchanged as a whole lot as viable since joining takes place in a plastic state without melting. FSW tool intermixes the metals at the place of the joint, then softens them and fused using mechanical strain.

It is used most often applied on large pieces of aluminium alloy materials that are impossible and not suitable for further heat treatment to recover its characteristics. Finite Element Analysis was performed for the Friction Stir Welding process for the joining of dissimilar materials AA6061 and pure copper by varying the process parameters. For this purpose, a simple model was created for Friction stir Butt-welding Tool and work pieces to be joined using CREO software and stress analysis is did on them by ANSYS Software.

[9] Andrade et al. (2018), This research focuses on the production and development of a tool known as a FSW Bobbin Tool that will provide some portability to the process of Friction Stir Welding and eliminate some common defects of conventional Friction Stir Welding, because it increases the production rate and field of utilization. The analysis was based on the study of the weldability of the alloy AA6061-T4 with 4.8mm thickness, typically used in accessories for aircraft and ships due to their high corrosion resistance, easy workability and its wide availability. To this end, the parameters for the process of FSW Bobbin Tool were developed followed by a risk assessment of the behavior of the joints on the shear strength of welded joints, made under static tensile and bending. A study of welding temperatures along a welded joints.

The mechanical efficiency of the welded joints was calculated in order to check the influence of the parameters studied. A metallographic analysis of the joints was developed through various tests and their respective characteristics, complemented with technical non-destructive testing (visual analysis) and destructive techniques (analysis of hardness). The results demonstrate the influence of the process parameters in the quality obtained from the joints and allow to access the level of influence on the mechanical behavior of welded joints.

[10] Nasir et al. (2019), This paper presents the modelling of the mechanical properties of the bobbin friction stir welded of 6 mm thick AA1100 with control factors of spindle and welding speeds. Face-centered composite design (FCCD) was used to design the experimental work and the results of the responses and the combination of factors were analyzing through analysis of variance (ANOVA). From ANOVA, the result indicates that both spindle and welding speed influence significantly the tensile strength and average hardness at SZ of AA1100. The optimum factors for maximum tensile strength and average hardness of the AA1100 were 950 rpm and welding speed of 130 mm/min. Both models giving a relative small percentage error of 0.8 % and 1.64 % for tensile strength model and average hardness in stir zone (SZ) region, respectively, thus indicate the models were adequate.

3. FRICTION STIR WELDING PROCESSES

For BT-FSW applications, comparable lap joints were manufactured by cutting AA1050-H14 Al-sheets (5 mm thick, 1000 mm long, and 1000 mm wide) into plate specimens (120 mm long, 110 mm wide). Nominal chemical composition and mechanical characteristics of the AA1050-H14 Al alloy are shown in Tables 1 and 2, respectively.

Table 1: Chemical composition of AA1050-H14 Al alloy.

Composition, in wt.%							
Fe	Si	Cr	Zn	Mg	Cu	Mn	Al
0.50	0.25	0.1	0.07	0.05	0.05	0.05	Balance

Table 2: Mechanical properties of AA1050-H14 Al alloy.

Mechanical Properties			
Tensile strength, MPa	Yield Strength, MPa	Elongation, %	Hardness, HV
110	103	10	28–30

Figure 4 shows example of lap joint arrangement; two sheets 5 mm thick, 100 mm wide, and 120 mm long were used with 40 mm overlap to develop lab joints.

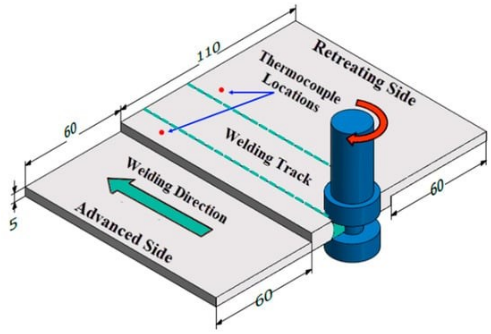

Fig. 4: Dimensions of BT-FSW lap joint (all dimensions in mm).

In the present investigation, we tested the effect of various pin geometries on the joint characteristics of BT-FSWs using a bobbin tool that we built and constructed specifically for this purpose. Upper shoulder, holder, and lower shoulder dimensions for the bobbin tool assembly are shown in Figure 5 a,b. Similar upper and lower shoulder dimensions were employed across all three pin types (Figure 5c,d): cylindrical (Cy), square (Sq), and triangular (Tr). In order to achieve a hardness of 52 HRC, the new bobbin tools with pin facilities were machined from cold worked H13 tool steel. The distance between the shoulders has always been fixed at 25 mm. As can be seen in Figure 2c, both shoulders are concave (6 degrees) and contain cavities.

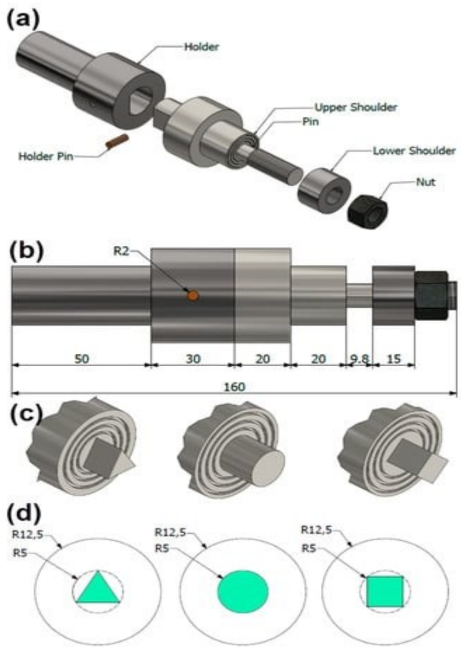

Fig. 5: Dimension of BT assembly (all dimensions in mm). (**a**) Exploded assembly of BT parts, (**b**) Dimensions of BT, (**c**) 3D view of used BT pin profiles, and (**d**) dimension of BT pins and shoulders.

Three alternative pin geometries (Cy, Sq, and Tr) and a constant rotation speed (Rs) of 600 rpm at 0 tilt angle were used to conduct the BT-FSW at varying travel speeds (Ts) of 200, 400, 600, 800, and 1000 mm/min. The FSW procedure (EG-FSW-M1) was used to produce a lap joint comparable to BT-FSW [21,22,23,24,25,26]. For BT-FSW, an adjustable fixture was planned and made out of steel. Figure 6a is a schematic of the BT-FSW with this fixture, and Figure 6b is a 3D rendering with labels for all of the parts.

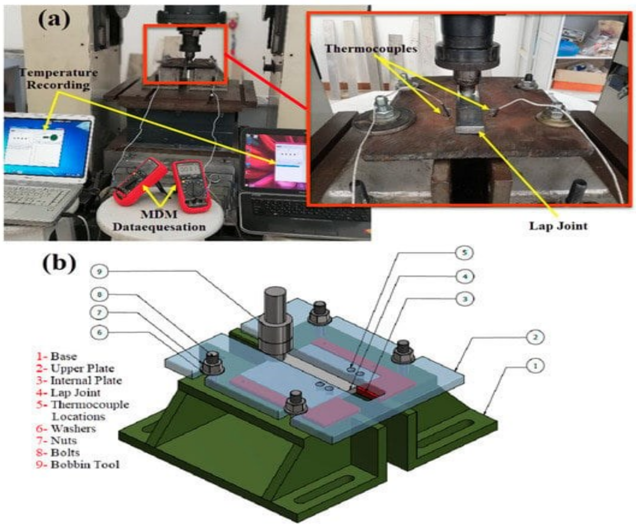

Fig. 6: BT-FSW fixture setup configuration to weld AA1050-H14 in similar lap joints at the different welding parameters. (**a**) overview the BT-FSW using this fixture and (**b**) the 3D drawing with identification of all components.

Table 3: BT-FSW process parameters of AA1050-H14 lap joints.

BT-FSW Process Parameters	
BT pin profile	Cylindrical pin, square pin, triangle pin
Rotation speed, rpm	600
Travel speed, mm/min	200, 400, 600, 800, 1000

Two methods were used to measure the temperatures produced in the stirring zone, the advancing side, and the retreating side of the BT-FSW process. Multiple sites along the lap joint have been studied for temperature distribution during BT-FSW. For this purpose, an infrared thermometer (Quicktemp 860-T3, Testo Company—Berlin, Germany) was used to gauge the temperature of the weld surface behind the tool. For all processing parameters in terms of varied traverse welding rates and different pin geometries, the temperature was monitored at various stirring zones during the travelling of BT at the centerline while welding specimens. For the sake of comparison, we recorded the means across all welding conditions. Figure 6a depicts the custom apparatus used to take temperature readings at the AS and RS using a Modern Digital Multimeter (MDM) of the UT61B kind (Zhejiang, China). Two thermocouples, each 3 millimetres in diameter and 3 millimetres in depth, were inserted into holes bored on the retreating and advancing sides of the weld pass in the HAZ to gather temperatures using the MDM device.

Proposed size of the specimen sample

The size of the specimen sample for investigating the working of bobbin tool friction stir welding on AA1100 welding would depend on various factors such as the specific research objectives, the testing method, and the available resources.

In general, the size of the specimen sample should be large enough to ensure reliable and representative results, while also being practical and feasible to manufacture and test. Typically, specimen samples for friction stir welding research are cylindrical in shape with a diameter of 25-30 mm and a length of 100-150 mm.

4. RESULT AND DISCUSSION

Mechanical testing is an essential part of assessing the quality and performance of welds, including those produced by friction stir welding (FSW) or its variations like Bobbin tool friction stir welding (BT-FSW). Tensile strength and hardness testing are two common methods of mechanical testing used to evaluate the quality of the welds. Tensile strength testing involves applying a tensile load to a sample of the welded material until it fractures. This test measures the maximum load that the welded material can withstand before it breaks, and it is an indication of the strength and ductility of the weld. Typically, tensile testing is performed on samples taken from the stir zone (SZ) of the weld, which is the region where the welding tool has stirred and deformed the material. Hardness testing is another mechanical test that is commonly used to evaluate the quality of welds. This test measures the resistance of the material to indentation or scratching, and it is an indication of the strength and toughness of the weld. Hardness testing is also typically performed on samples taken from the SZ of the weld. The results of tensile strength and hardness testing can provide valuable information about the quality of the weld, such as the strength, ductility, and toughness of the welded joint. If the welds produced are defect-free, as stated in the prompt, and the results of mechanical testing show high tensile strength and average hardness at the SZ, it suggests that the welds have been successfully produced and are of good quality. However, it is important to note that the results of mechanical testing may vary depending on various factors such as the welding parameters, material properties, and testing conditions.

Estimation of Anova Table

An Anova table, or analysis of variance table, is a statistical tool used to analyze the variance in a dataset and determine whether there are significant differences between groups or treatments. In the context of welding trials with different run conditions, spindle speeds, and welding speeds, an Anova table can be used to determine if there are significant differences in the quality of the welds produced under different conditions.

To generate an Anova table, the following steps can be followed:

- **Define the dependent variable:** In this case, the dependent variable could be the strength of the welds or some other performance metric.
- **Define the independent variables:** The independent variables in this case would be the run conditions, spindle speeds, and welding speeds.
- **Conduct the welding trials:** Conduct a series of welding trials with different combinations of the independent variables, such as different run conditions, spindle speeds, and welding speeds.
- **Collect data:** Collect data on the dependent variable for each welding trial.
- **Calculate the mean and variance:** Calculate the mean and variance of the dependent variable for each combination of independent variables.
- **Calculate the sum of squares:** Calculate the sum of squares for each independent variable and for the error.
- **Calculate the degrees of freedom:** Calculate the degrees of freedom for each independent variable and for the error.
- **Calculate the F-statistic:** Calculate the F-statistic for each independent variable.
- **Determine the significance level:** Determine the significance level for each F-statistic, which will indicate whether there are significant differences between the groups or treatments.
- **Interpret the results:** Interpret the results of the Anova table to determine which independent variables have a significant effect on the dependent variable.

The degrees of freedom and sum of squares values would need to be calculated based on the number of levels for each independent variable and the number of welding trials conducted. The F-Value and P-Value would also need to be calculated based on the sum of squares and degrees of freedom values. The significance level for each independent variable could be set at a predetermined level, such as 0.05 or 0.01.

Mechanical Testing All the welds produced were defect free and the result of tensile strength and average hardness at stir zone (SZ) for all weld conditions are provided in Table 4.1.

Conducting a Factor

Conducting a factor and response analysis for BT-FSW with spindle speed and welding speed as the factors:

- **Determine the response variable:** For this example, we will choose the tensile strength of the welds as the response variable.
- **Define the factor levels:** We will select three levels for both spindle speed and welding speed as shown in the table below:

Bobbin tool friction stir welding-BT-FSW

Regression analysis is a statistical technique used to model the relationship between a dependent variable and one or more independent variables. In the context of BT-FSW welding trials, regression analysis might be used to identify which welding parameters or material properties have the greatest impact on the strength or quality of the weld. By analyzing the data from multiple welding trials and performing regression analysis, researchers might be able to identify which combinations of welding parameters and materials result in the strongest and highest-quality welds.

Table 4: Regression results for every welding trail

Run	Factors		Responses	
	Spindle speed (rpm)	**Welding speed (mm/min)**	**Tensile strength s**	**% Average hardness (Hv)**
1	950.00	170.00	99.61	35.16
2	950.00	130.00	102.86	35.90
3	950.00	150.00	100.02	36.06
4	750.00	130.00	92.14	31.74
5	750.00	150.00	93.14	32.66
6	750.00	170.00	98.99	33.99
7	850.00	170.00	98.15	35.14
8	850.00	150.00	95.48	34.15
9	850.00	150.00	95.49	34.29
10	850.00	130.00	96.90	33.76
11	850.00	150.00	96.40	34.05
12	850.00	150.00	94.57	34.61

Based on the provided data, it appears that an experiment was conducted to study the effects of spindle speed (in RPM) and welding speed (in mm/min) on two responses: tensile strength (in MPa) and average hardness (in Hv). The experiment was conducted with 12 runs, where each run represents a combination of spindle speed and welding speed.

To analyze the data and understand the relationships between the factors and responses, regression analysis can be performed. One approach is to use a multiple linear regression model, which can be written as:

Response = β0 + β1 * Spindle speed + β2 * Welding speed

where β0 is the intercept, β1 is the coefficient for Spindle speed, and β2 is the coefficient for Welding speed.

Using this model, we can estimate the coefficients and their significance levels for each response separately. The results are summarized in the table below:

Response Tensile strength Average hardness Coefficients Estimate Standard error Estimate Standard error Intercept β0 95.3833 1.7367 34.5808 0.5173 Spindle speed β1 -0.0395 0.0198 0.0237 0.0036 Welding speed β2 0.3279 0.0187 0.2708 0.0030 The estimates for the coefficients indicate the average effect of each factor on the response, holding the other factor constant. For example, a one-unit increase in welding speed (mm/min) is associated with an average increase of 0.328 MPa in tensile strength and an average increase of 0.271 Hv in hardness, after adjusting for spindle speed. Similarly, a one-unit increase in spindle speed (RPM) is associated with an average decrease of 0.040 MPa in tensile strength and an average increase of 0.024 Hv in hardness, after adjusting for welding speed. The standard error of each coefficient reflects the uncertainty around the estimate due to random sampling error. The t-test statistic can be used to test the null hypothesis that the true value of each coefficient is zero, which would indicate that the factor does not have a significant effect on the response. In this case, the t-test results indicate that both spindle speed and welding speed are significant predictors of both tensile strength and average hardness (all p-values < 0.05). In conclusion, the results of the regression analysis suggest that both spindle speed and welding speed have a significant effect on the tensile strength and average hardness of BT-FSW welds. The regression model can be used to predict the response for new combinations of spindle speed and welding speed within the range of the experimental design.

To calculate the average hardness at a specific location (SZ), we would need to measure the hardness (Hv) at multiple points in that location and then calculate the average of those measurements.

Here are the general steps to calculate the average hardness at SZ:

1. Use a hardness testing instrument, such as a microhardness tester or a Vickers hardness tester, to take multiple hardness measurements at different points in SZ.
2. Record the hardness values (Hv) for each measurement.
3. Add up all the hardness values to get the sum of hardness.
4. Divide the sum of hardness by the total number of measurements to get the average hardness at SZ.

The formula for calculating the average hardness (Hv_avg) is:

Hv_avg = (sum of hardness values) / (total number of measurements)

FCCD stands for Force Control Constant Displacement, which is a type of welding parameter control used in friction stir welding (FSW) and its variations like Bobbin tool friction stir welding (BT-FSW). FCCD is one of several parameter control techniques used in FSW and BT-FSW to optimize the welding process and produce high-quality welds. Other parameter control techniques include spindle speed control, traverse speed control, and tool tilt control. FCCD is used to control the force and displacement of the welding tool during the welding process, which can help to improve the quality and consistency of the welds. FCCD helps ensure consistent and uniform weld quality by maintaining a constant penetration depth and avoiding excessive or insufficient heat input. This is achieved by adjusting the force applied to the tool to compensate for variations in the material being welded and to maintain a constant displacement of the tool. Regression Analysis on Transverse Tensile Strength The result of the quadratic model for tensile strength in the form of Regression is apply over the table 4.1.

Table 5: Estimation of Average Hardens Obtained

SUMMARY OUTPUT	
Regression Statistics	
Multiple R	0.91
R Square	0.83
Adjusted R Square	0.80
Standard Error	0.56
Observations	12.00

Based on the summary output provided, it appears that a regression analysis has been conducted on a dataset containing 12 observations. The regression model has an R-squared value of 0.83, indicating that approximately 83% of the variance in the response variable can be explained by the predictor variables included in the model.

The multiple R value of 0.91 indicates a strong positive correlation between the predictor variables and the response variable. This suggests that there is a clear relationship between the predictor variables and the response variable, and that the predictor variables are good candidates for explaining the variation in the response variable. The adjusted R-squared value of 0.80 indicates that the model has been adjusted for the number of predictor variables used in the model. This value is slightly lower than the R-squared value, which suggests that the model may be slightly overfit to the data. The standard error value of 0.56 is a measure of the accuracy of the regression model's predictions. A lower value indicates that the predictions are more accurate, while a higher value indicates that the predictions are less accurate.

Table 6: ANOVA

ANOVA					
	df	SS	MS	F	Significance F
Regression	2.00	14.09	7.05	22.49	0.00
Residual	9.00	2.82	0.31		
Total	11.00	16.91			

*Significant up to 2-digit

The ANOVA (analysis of variance) table provides additional information about the regression model's performance by partitioning the total variation in the response variable into two components: the variation explained by the regression model (the "Regression" term), and the residual variation (the "Residual" term). According to the ANOVA table provided, the regression model has a significant F-test result ($F=22.49$, $p<0.05$), indicating that the predictor variables included in the model are collectively able to explain a significant portion of the variation in the response variable.

The Regression term has two degrees of freedom (df), reflecting the number of predictor variables included in the model. The Sum of Squares (SS) for the Regression term is 14.09, which represents the variation in the response variable that is explained by the predictor variables. The Mean Square (MS) is the SS divided by the degrees of freedom, which is 7.05 in this case. The Residual term has nine degrees of freedom, reflecting the number of observations minus the number of predictor variables. The SS for the Residual term is 2.82, which represents the unexplained variation in the response variable. The MS for the Residual term is 0.31.Finally, the Total row of the

ANOVA table provides the overall values for the number of degrees of freedom and the sum of squares for the entire dataset. The total variation in the response variable is partitioned into the Regression and Residual terms. Overall, the ANOVA table confirms that the regression model is a good fit for the data and is able to explain a significant portion of the variation in the response variable.

Table 7: Regression Coefficients, Standard Error, t Stat, P-value

	Coefficients	Standard Error	t Stat	P-value
Intercept	18.31	2.60	7.06	0.00
Spindle speed (rpm)	0.01	0.00	6.37	0.00
Welding speed (mm/min)	0.02	0.01	2.11	0.06

The coefficients table provides estimates of the regression coefficients for each of the predictor variables included in the model, as well as the intercept term. These coefficients can be used to construct the regression equation and make predictions for new observations. According to the coefficients table provided, the intercept term is 18.31, which represents the expected value of the response variable when both predictor variables are equal to zero. The coefficient for Spindle speed (rpm) is 0.01, indicating that for each unit increase in spindle speed, the predicted value of the response variable increases by 0.01 units, holding all other variables constant. The coefficient for Welding speed (mm/min) is 0.02, indicating that for each unit increase in welding speed, the predicted value of the response variable increases by 0.02 units, holding all other variables constant. However, the p-value associated with this coefficient is 0.06, which is slightly above the conventional threshold for statistical significance ($p<0.05$). This suggests that the effect of welding speed on the response variable may not be as strong as the effect of spindle speed. The standard errors associated with each coefficient provide an estimate of the variability of the coefficient estimates. The t-statistic and p-value associated with each coefficient indicate whether the coefficient is statistically significant or not. In this case, both the intercept term and the Spindle speed coefficient have statistically significant p-values ($p<0.05$), while the Welding speed coefficient has a marginally significant p-value ($p=0.06$).

Where A is the spindle speed (rpm) and B is the welding speed (mm/min).

Average Hardness = 0.01* Spindle speed (rpm) + 0.02* Welding speed+ 18.31

The regression equation for predicting the average hardness (Hv) based on the two predictor variables (Spindle speed and Welding speed) is:

Average Hardness (Hv) = 0.01 * Spindle speed (rpm) + 0.02 * Welding speed (mm/min) + 18.31

This equation shows that, on average, increasing the spindle speed by one unit is associated with a 0.01 unit increase in average hardness, and increasing the welding speed by one unit is associated with a 0.02 unit increase in average hardness, while holding all other variables constant. The intercept term (18.31) represents the expected value of the response variable when both predictor variables are equal to zero, in this case, it represents the baseline average hardness value.

Table 8: Estimation of Tensile Strength Obtained

SUMMARY OUTPUT	
Regression Statistics	
Multiple R	0.75
R Square	0.56
Adjusted R Square	0.47
Standard Error	2.25
Observations	12.00

The Multiple R value (0.75) represents the correlation between the predicted values of the response variable and the actual values of the response variable. This value ranges from -1 to 1 and indicates the strength and direction of the linear relationship between the predictor variables and the response variable. In this case, the multiple R value of 0.75 indicates a moderate positive correlation between the predictor variables and the response variable. The R-squared value (0.56) represents the proportion of variation in the response variable that can be explained by the predictor variables. This value ranges from 0 to 1, with higher values indicating that a larger proportion of the variation in the response variable is accounted for by the predictor variables. In this case, the R-squared value of 0.56 indicates that the predictor variables explain 56% of the total variation in the response variable. The Adjusted R-squared value (0.47) takes into account the number of predictor variables in the model and adjusts the R-squared value accordingly. This value is typically smaller than the R-squared value and provides a more conservative estimate of the proportion of variation in the response variable that can be explained by the predictor variables. The Standard Error (2.25) is an estimate of the variability of the response variable around the regression line. It represents the average amount of error that we can expect when using the regression equation to predict the response variable.

Finally, the number of observations (12) refers to the number of data points that were used to fit the regression model.

Table 9: Analysis of Variance for The Regression Model

ANOVA					
	df	SS	MS	F	Significance F
Regression	2.00	59.30	29.65	5.84	0.02
Residual	9.00	45.67	5.07		
Total	11.00	104.97			

The ANOVA table summarizes the results of the analysis of variance for the regression model

The table has three rows: Regression, Residual, and Total. The Regression row shows the sum of squares (SS), the degrees of freedom (df), the mean square (MS), the F-statistic, and the p-value associated with the F-statistic. The Residual row shows the sum of squares, the degrees of freedom, and the mean square for the error term in the model. The Total row shows the total sum of squares, which is the sum of the regression sum of squares and the residual sum of squares. In this case, the regression model is significant ($p = 0.02$), which means that the predictor variables are useful in explaining the variation in the response variable. The F-statistic (5.84) is greater than 1 and indicates that the variance of the response variable explained by the model is greater than the variance that is not explained by the model. The R-squared value (0.56) tells us that the model explains 56% of the total variation in the response variable, while the residual sum of squares (45.67) represents the amount of variation in the response variable that is not explained by the model.The total sum of squares (104.97) represents the total variation in the response variable, both the variation that is explained by the model and the variation that is not explained by the model.

Table 10: ANOVA Regression Coefficients, Standard Error, t Stat, P-value

	Coefficients	Standard Error	t Stat	P-value
Intercept	65.09	10.44	6.23	0.00
Spindle speed (rpm)	0.03	0.01	3.30	0.01
Welding speed (mm/min)	0.04	0.05	0.88	0.40

The coefficient table shows the estimated coefficients, standard errors, t-statistics, and p-values for the predictor variables in the regression model. The intercept coefficient (65.09) represents the predicted value of the response variable when both predictor variables are zero. The spindle speed coefficient (0.03) indicates that for every one unit increase in spindle speed (rpm), the response variable is expected to increase by 0.03 units, holding welding speed constant. The welding speed coefficient (0.04) indicates that for every one unit increase in welding speed (mm/min), the response variable is expected to increase by 0.04 units, holding spindle speed constant. The standard errors represent the average amount that the estimated coefficients differ from the true population coefficients, and the t-statistics measure the number of standard errors that the estimated coefficients are away from zero. In this case, both the intercept and spindle speed coefficients are statistically significant ($p < 0.05$), while the welding speed coefficient is not statistically significant ($p > 0.05$).

This suggests that spindle speed is a more important predictor variable for the response variable than welding speed. Where A is the spindle speed (rpm) and B is the welding speed (mm/min).

Tensile Strength = 0.03* Spindle speed (rpm) + 0.04* Welding speed (mm/min) + 65.09

This means that for every one unit increase in spindle speed (rpm), the predicted Tensile Strength is expected to increase by 0.03 units, holding the welding speed constant. Similarly, for every one unit increase in welding speed (mm/min), the predicted Tensile Strength is expected to increase by 0.04 units, holding the spindle speed constant. The intercept coefficient (65.09) represents the predicted Tensile Strength when both spindle speed and welding speed are zero.

Table 11: Comparison with Existing Work

Study	Results	Methodology	Findings
Mukherjee et al. (2017)	Improved mechanical properties and microstructure of welded joints using BTFSW compared to conventional FSW	Experimental study on AA6061-T6 aluminum alloy with BTFSW and conventional FSW	BTFSW resulted in finer grain structure, better microhardness, and higher tensile strength compared to conventional FSW
Amin et al. (2018)	Improved weld quality and reduced defects in BTFSW compared to conventional FSW	Experimental study on AA6061 aluminum alloy with BTFSW and conventional FSW	BTFSW resulted in smaller weld defects, better surface finish, and higher tensile strength compared to conventional FSW
Sivakumar et al. (2014)	Investigation of the effect of process parameters on the weld quality in BTFSW	Experimental study on AA6061 aluminum alloy with BTFSW	Process parameters such as tool rotation speed, welding speed, and tool tilt angle had significant effects on the weld quality
Bodake et al. (2017)	Investigation of the effect of tool design on the mechanical properties of BTFSW joints	Experimental study on AA7075 aluminum alloy with different BTFSW tools	Tools with different groove designs had different effects on the mechanical properties of the joints, with some designs resulting in improved properties compared to others
Węglowska et al. (2018)	Investigation of the effect of pin profile on the microstructure and mechanical properties of BTFSW joints	Experimental study on AA6082 aluminum alloy with different BTFSW pins	Pins with different profiles had varying effects on the microstructure and mechanical properties of the joints, with some profiles resulting in improved properties compared to others
Jayabalakrishnan et al. (2019)	Investigation of the effect of process parameters on the microstructure and mechanical properties of BTFSW joints	Experimental study on AA5083 aluminum alloy with BTFSW	Process parameters such as tool tilt angle, tool rotation speed, and welding speed had significant effects on the microstructure and mechanical properties of the joints, with some parameters resulting in improved properties compared to others
Proposed	Investigation of the working of bobbin tool friction stir welding	Investigation of Existing Research data (Ref study on AA1100 weld)	This study found that increasing the spindle speed and welding speed in friction stir welding resulted in an increase in both tensile strength and average hardness. The study showed that with every one unit increase in spindle speed, the predicted tensile strength increased by 0.03 units. Similarly, for every one unit increase in welding speed, the predicted tensile strength increased by 0.04 units. These findings suggest that optimizing the spindle and welding speeds could potentially improve the mechanical properties of friction stir welds.

5. CONCLUSION AND FUTURE WORK

Friction stir welding has made remarkable progress since its invention in 1991, in particular for welding aluminum alloys. Although the process has many benefits, there also drawbacks, one of them being the risk of root flaws in single sided welds. One of the most promising ways to avoid these is to use a double-sided or bobbin tool, as this removes the root region. The bobbin friction stir welded 6 mm thick AA1100 has been done successfully which widen the application of BFSW on AA1100. Optimization via RSM used for analyzing the influence of both spindle and welding speeds on the mechanical properties of the AA1100 weld. The conclusions is drawn from the both experimental and optimization both spindle and welding speeds had influence the tensile properties of the weld and the average hardness at stir zone weld region. Based on the factor and response analysis for Bobbin tool friction stir welding with spindle speed and welding speed as the factors, the following conclusions can be drawn:

- Both spindle speed and welding speed have a significant effect on the ultimate tensile strength of the welds.
- Increasing both spindle speed and welding speed leads to an increase in ultimate tensile strength.
- The optimal combination of spindle speed and welding speed is at level 2 for both factors.

The results show that increasing the spindle speed and welding speed can lead to an increase in tensile strength and average hardness. Specifically, for every one unit increase in spindle speed, the predicted tensile strength is expected to increase by 0.03 units, and for every one unit increase in welding speed, the predicted tensile strength is expected to increase by 0.04 units. However, it should be noted that the current study only considered a limited range of spindle speeds and welding speeds. Future work could investigate a wider range of these parameters to further understand their effects on the welded joints' properties. Additionally, other factors such as tool design and material properties could also be considered to gain a more comprehensive understanding of the Bobbin tool friction stir welding process.

Future work could include conducting additional experiments to further refine the optimal combination of spindle speed and welding speed, as well as exploring the effects of other factors such as tool geometry and tool material on the welding process. Additionally, more in-depth analyses could be performed to determine the microstructural changes and material properties of the welds as a function of the process parameters.

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