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Modeling and Parametric Optimization of Friction Stir Welding For Magnesium AZ91D Alloys Using Factorial Design

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Abstract

Automatic and robotic welding systems could be used effectively, when optimal process parameters for achieving the desired quality and relative effects of input parameters on output parameters can be obtained. Numerical optimization technique is applied to determine and characterize the cause and effect relationship between true mean responses and input control variables influencing the responses. This paper deals with the application of Factorial design approach for optimizing three frictions stir welding parameters viz. rotation speed, welding speed, and axial force out by developing a mathematical model for sound quality, Tensile strength and hardness on butt joint.

Keywords: Factorial Design approach, Numerical optimization, Friction stir welding, Rotational speed, Welding speed, axial force, Tensile strength and Hardness.

Introduction

Friction stir welding (FSW) is a significant manufacturing process for producing welded structures in solid state [1]. Compared with many of the fusion welding processes that are routinely used for joining structural alloys, FSW is an emerging solid state joining process in which the material that is being welded does not melt and recast [2]. Magnesium alloys represent unique structural materials combining high specific strength with the capability to absorb shock and vibration energy [3]. For instance, cast Mg alloy AZ91 containing 9 mass% Al and 1 mass %Zn has been most widely used in aircraft and engine building industries due to its high castability, low density, and good mechanical properties. Defect free welds with good mechanical properties have been made in a variety of aluminum alloys, even those previously thought to be not weldable. Friction stir welds will not encounter problems like porosity, alloy segregation and hot cracking, and welds are produced with good surface finish and thus no post weld cleaning is required [4]. There have been a lot of efforts to understand the effect of process parameters on material flow behavior, microstructure formation and hence mechanical properties of friction stir welded joints. The effect of some important parameters such as rotational speed, traverse speed and axial force on weld properties is major topics for researchers [5−7].

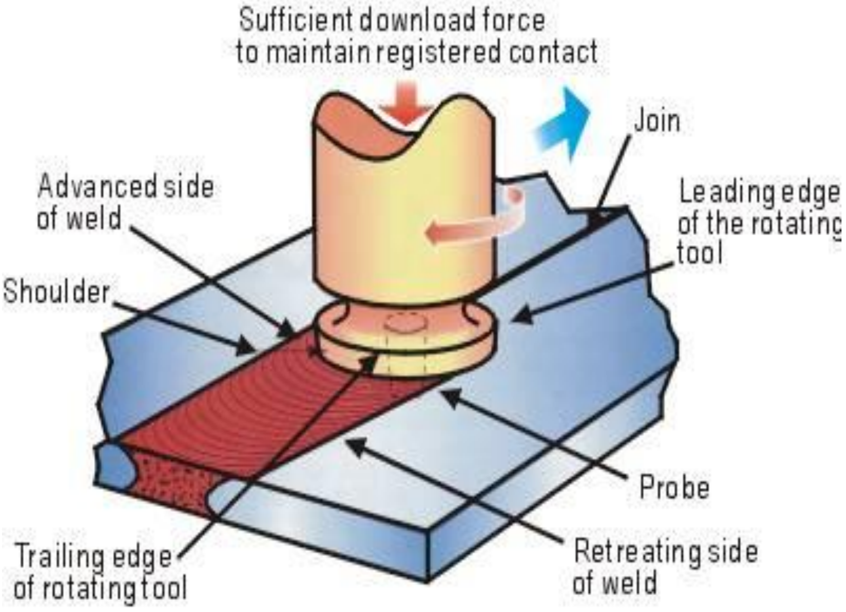

Figure 1: Friction stirs welding

Naiyi Li [8] have studied FSW offers a quality advantage that leads the welds strength and ductility either identical or better than that of the base metal alloy. For automotive applications with FSW techniques, particularly for the 2005 Ford GT, however, further investigations must be conducted to meet the design and performance requirements of light-weight metal construction. DU Xing-hao and WU Bao-lin [9] have investigated Friction stir processing combined with rapid heat sink can produce an ultra-fine grained structure for AZ61 alloy. The mean grains can be refined to less than 300 nm. Friction stir processing drastically increases the microhardness of AZ61 substrate. The mean value of Hv120−130 is almost three times higher than that of the AZ61 substrate. N.Rajamanickam, and V.Balusamy *et al.*,[10] have investigated the real time prediction of tensile strength, percentage of elongation and hardness for various tool rotation speeds and welding speeds without requiring experimental testing. It's observed that the simulations results are 93% accurate, and they can be used for predicting the mechanical properties of weldments fairly accurately. Won-Bae Lee and Jong-Woong Kim *et al.*, [11] have studied the microstructural development and mechanical properties of the friction stir welded

AZ91D 4mm thick plates have been determined AZ91D Mg alloy was successfully joined using friction stir welding under the optimum conditions ranges of 41 to 187 mm/min of welding speed with 115 to 131 $rad.s^{-1}$ of the tool rotation speed. It has been confirmed that the original base metal grain structure became completely eliminated and replaced by very fine and equiaxed grains in the stir zone. β - intermetallic phase which was in the base metal was dissolved by the frictional heat input.

Factorial Design Approach and Terminology

Factorial design planning is simply applied to determine and represent the cause and effect relationship between true mean responses and input control variables influencing the responses. The process of design of experiments involves the following steps,

1. Screening designs are used in beginning of process where more than five factors are involved, to recognize the most critical factors.
2. Characterization deigns narrow the numbers of factors to only a few and permit for some quantitative understanding of the interactions among factors.
3. Optimization designs focus on only one or two factors, but in much more depth to gain a precise understanding of relationships between factors.

When there are many factors, many experimental runs will be necessary, even without replication. For example, experimenting with 10 factors at two levels each produces $2^{10}=1024$ combinations. At some point this becomes infeasible due to high cost or insufficient resources. In this case, fractional factorial designs may be used. As with any statistical experiment, the experimental runs in a factorial experiment should be randomized to reduce the impact that bias could have on the experimental results. In practice, this can be a large operational challenge.

Factorial experiments can be used when there are more than two levels of each factor. However, the number of experimental runs required for three-level (or more) factorial designs will be considerably greater than for their two-level counterparts. Factorial designs are therefore less attractive if a researcher wishes to consider more than two levels.

A full Factorial design combines the levels for each factor with all the levels of every factor. It covers all combinations and provides best data. However it consumes more time and resources. While a fractional Factorial design, uses too many of resources, or if a slightly non orthogonal array is accepted a fractional design is used. To analyze the data from a design of experiment, evaluating the statistic significance by computing one way ANOVA, or for more than one factor N-way ANOVA is essential. The practical significance can be evaluated through sum of squares, line or column charts, and normal probability chart.

Methodology

The scheme of the work carried out in this research is presented in the following flow chart:

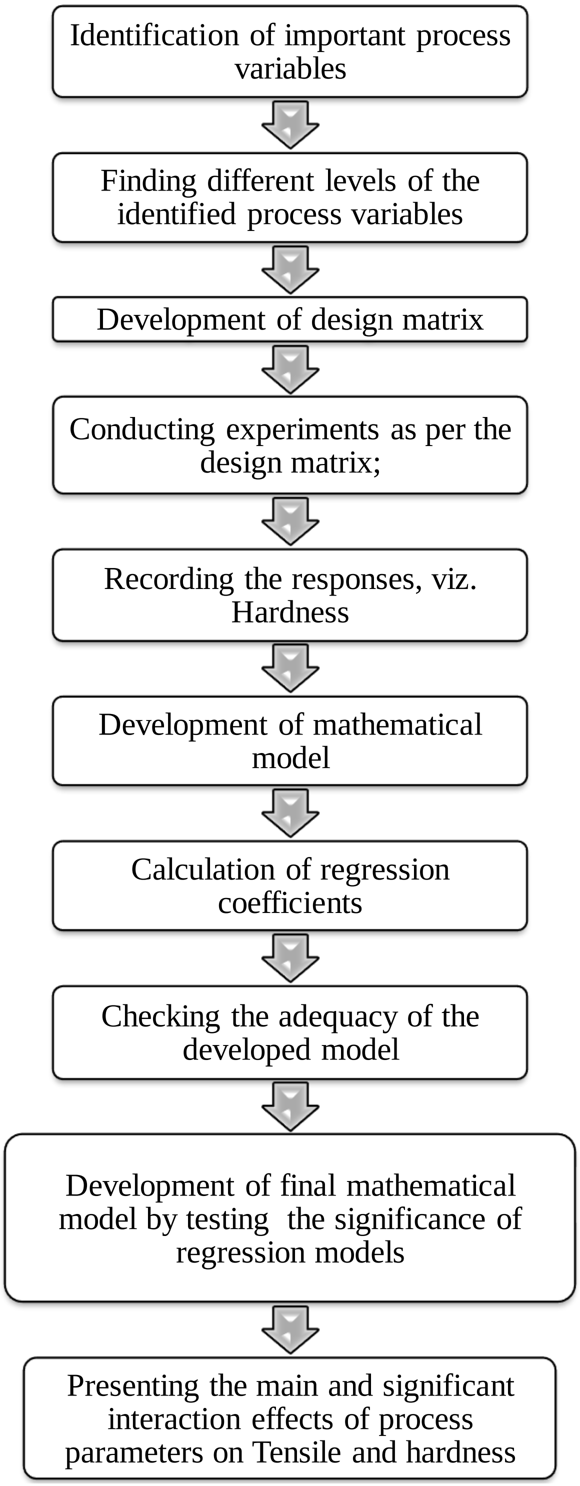

Figure 2: Flow Chart for scheme of the work

Identification of operating variables

Selection of process variables has considerable influence on the weld characteristics. Table1 shows independent controllable process variables, which were identified based on their significant effect on weld tensile strength and hardness to carry out the experiments. Experiments were carried out to join the Magnesium AZ91D alloys plates of size 100 mm (length) × 50 mm (width) × 6 mm (height). High Speed Steel is used as FSW tool material. Figure 3 shows the tool used for welding and the welded specimens are presented in figure 4.

Figure 3: Friction Stir Welding tool

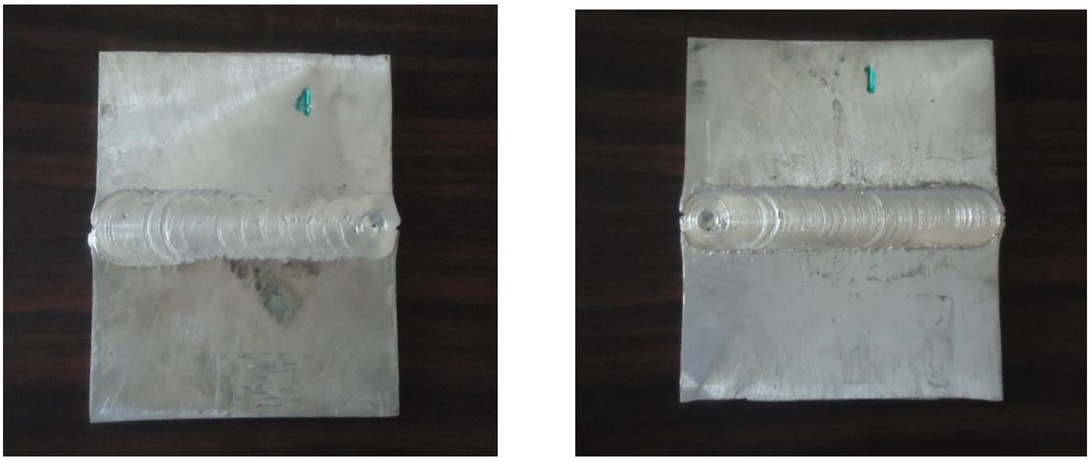

Figure 4: Photos of the top surfaces of as – welded specimens

Table 1: Chemical composition. AZ91

Al	Ni	Cu	Zn	Mg
9.1	0.0027	0.001	0.65	Bal.

Table 2 - Mechanical properties of weld metal

tensile strength (Mpa)	Yield Strength (Mpa)	Elongation (%)
293MPa	222.7MPa	13%

Finding different levels of the identified process variables

The levels for each factor were assigned based on the highest value and the lowest value of the factors determined through experimental trails. These values were based on the outcomes of trials runs. Highest value has been represented by "+" and the lowest value has been represented by "–"as mentioned in Table 3.

Table 3: Design matrix

S.No	Rotational speed (r.p.m)	Welding speed (mm/min)	Axial force (KN)
1	-	-	-
2	+	-	-
3	-	+	-
4	+	+	-
5	-	-	+
6	+	-	+
7	-	+	+
8	+	+	+

Development of design matrix

For conducting trial runs levels of these values were chosen randomly such that sampling fraction for these trials run was equal to zero, however rough range was taken from literature survey [12]. With the help of these trial runs effective and representative levels were developed for each variable. The factorials are also known as 2-k factorials, where 2 is the number of levels and k is no of important process variables. For full Factorial approach number of runs are equal to 2k whereas for half factorial or fractional factorial number of runs are equal to 2k-1.

Conducting experiments as per the design matrix;

Rockwell Hardness Test

The Rockwell hardness test carried out on the welded area of the AZ91D magnesium alloys. The Rockwell hardness scale is B-scale; the indenter is 1/8" Ball is used for the testing.The lowest hardness of FSW joint is observed in the TMAZ region. Elongated and deformed grains cause softening in the region which results in the reduction of hardness. Hardness was found higher in the weld region compared to the HAZ and BM region, irrespective of welding process. There are two main reasons for the improved hardness of stir zone. Firstly, since the grain size of stir zone is much finer than that of base metal, grain refinement plays an important role in material strengthening. Secondly, the small particles of intermetallic compounds are also a benefit to hardness improvement.

Recording the responses, viz. Tensile strength and Hardness

Table 4: Design matrix and their responses

S.NO	Rotational speed (r.p.m)	Welding speed(mm/min)	Axial force (KN)	Hardness (HZ)	Tensile Strength (kN)
1	1400	87.6	2	63.0	8.0
2	1600	87.6	2	61.0	7.8
3	1400	135	2	64.0	6.5
4	1600	135	2	62.0	9.0
5	1400	87.6	4	64.5	7.9
6	1600	87.6	4	62.2	8.4
7	1400	135	4	65.6	9.3
8	1600	135	4	64.5	7.0

Mathematical Model Developed

Assuming the values of responses as y1, y2, y3, y4, y5, y6, y7, y8 against the treatment combinations 1, 2, 3, 4, 5, 6, 7, 8 respectively Y as the optimized value of response. The response function represents any of the weld dimensions can be expressed as the following equation: Y = f (RS, WS, AF) and the relationship selected, being a second degree response surface, expressed as follows: Y = b0 + b1RS+ b2WS + b3AF + b12 (RSWS) + b13 (RSAF) + b23 (WSAF) + b123 (RSWSAF).

Calculation of regression coefficients

The values of the coefficient ware calculated with the help of following calculations

b0 = [(y1 + y2 + y3 + y4 + y5 + y6 + y7 + y8)] / 8
b1 = [(y5 + y6 + y7 + y8) - (y1 + y2 + y3 + y4)] / 8
b2 = [(y3 + y4 + y7 + y8) - (y1 + y2 + y5 + y6)] / 8
b3 = [(y3 + y4 + y5 + y6) - (y1 + y2 + y7 + y8)] / 8
b12 = [(y1 + y2 + y7 + y8) - (y3 + y4 + y5 + y6)] / 8
b13 = [(y1 + y2 + y3 + y4) - (y5 + y6 + y7 + y8)] / 8
b23 = [(y1 + y3 + y6 + y8) - (y2 + y4 + y5 + y7)] / 8
b123 = [(y2 + y3 + y5 + y8) - (y1 + y4 + y6 + y7)] / 8

Table 5: Estimated value of the coefficient of the models

b0	633.5	7.9875
b1	-9.25	0.6625
b2	6.75	0.5375
b3	8.5	-0.1875
b12	1.5	-0.0375
b13	-8.5	-0.012

b23	1..75	0.0625
b123	1.9	-0.0125

The values of different coefficients for different responses were calculated as per the modeling as given in table 3. These values of coefficients represent the significance of corresponding variable on the response. Higher value of coefficients signifies higher influence of the variable on the response. Inverse relationship between variable and response is found when the value of coefficient is negative.

Checking the adequacy of models developed

The estimated value of the coefficient of the model indicates as to what extent the important process variables affect the responses quantitatively [13]. The result through analysis of variance as given in Figures 6, 7, 8 and 9 shows that rotational speed, welding speed and axial force has the significant parameters that affect tensile and hardness. The interaction effects such as RSWS, WSAF, & RSWSAF also provide significant on tensile strength. There is no significant effect of RSAF on hardness. The interaction effects such as RSWS, WSAF & RSWSAF also provide significant on hardness. There is no significant effect of RSAF on hardness. The value of F- ratio for a desired level of confidence (95%) was achieved for the indicated model which is considered as adequate within the confidence limit. The final mathematical model as determined by the above analysis can be represented by following equation:

Tensile Strength = +7.9875+0.6625A+0.5375B-0.1875C-0.0375AB-.012AC+ 0.0625BC- 0.0125ABC.

Hardness =+633.50-9.25 A+6.75 B+8.50 C+1.50 A B -8.5 A C+1.75 B C+1.9 A B C.

Figures 6, 7, 8 and 9 shows the main and significant interaction effects of process parameters on tensile strength and hardness.

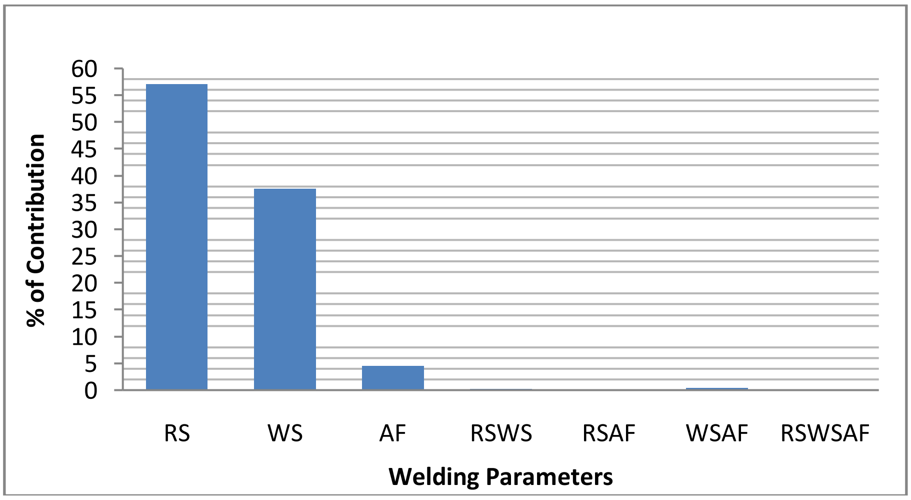

Figure 6: % contribution of process parameters on Tensile Strength

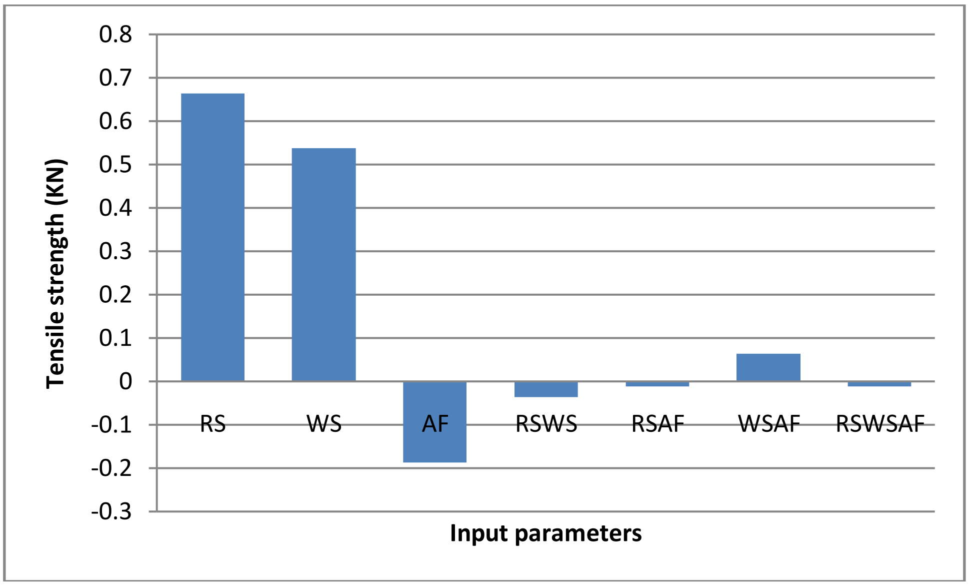

Figure 7: Tensile Strength vs Input parameters

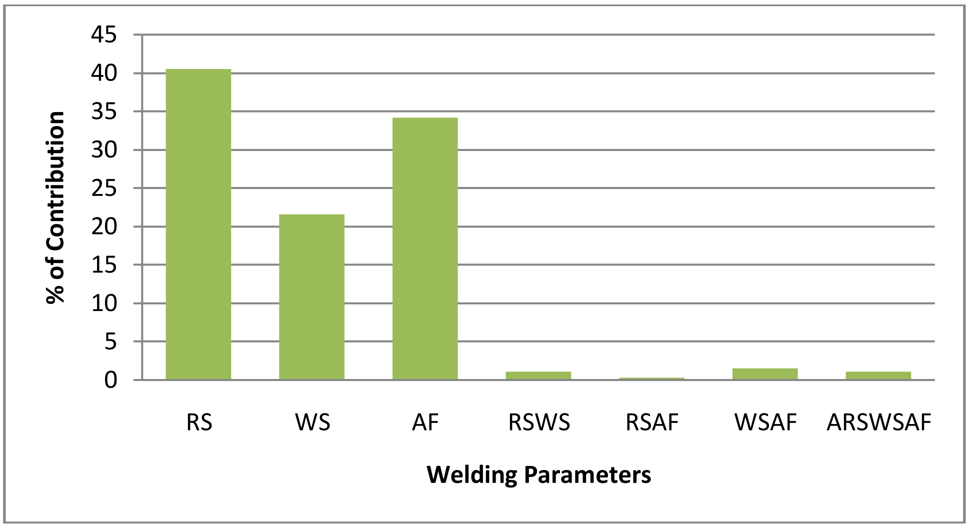

Figure 8: % contribution of process parameters on Hardness.

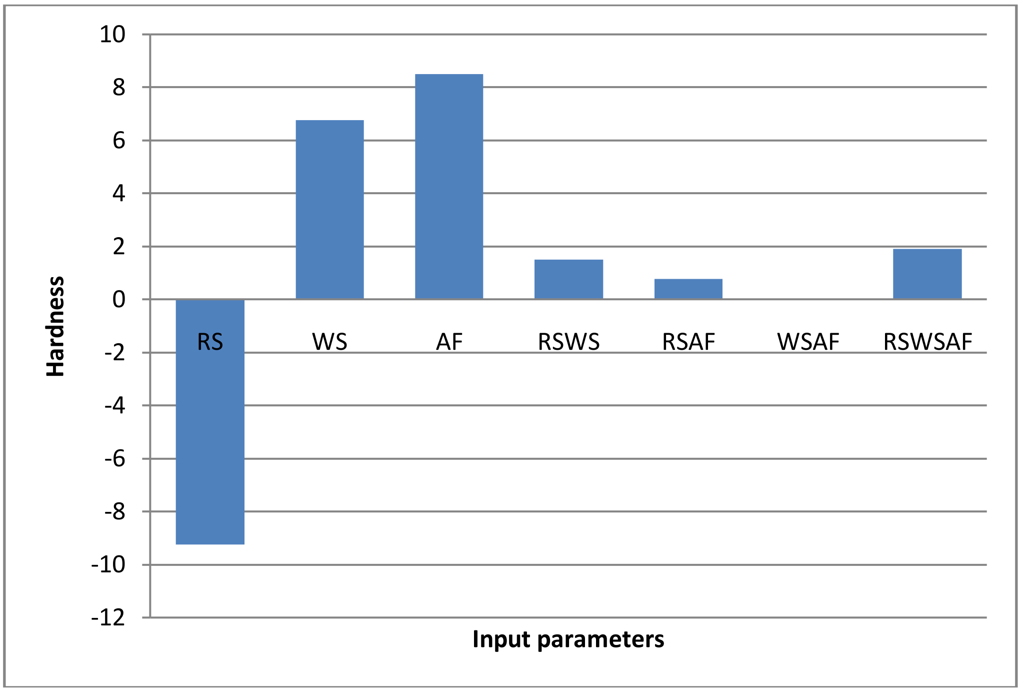

Figure 9: Hardness vs Input parameters

Conclusions

The study of the previous work reviews that a two level Factorial technique can be employed easily for developing mathematical models for predicting the tensile strength hardness in the weld zone. Results indicate that process variables influence FSW tensile for butt joint to a significant extent. Axial force has more predominant effect on the tensile than that of other parameters. Welding speed and rotational speed has the considerable factors that affect tensile strength. Results indicate that process variables influence FSW hardness for butt joint to a significant extent. Rotational speed has more predominant effect on the hardness than that of other parameters. Welding speed and axial force has the considerable factors that affect hardness.

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