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Simulated Annealing Based Parameter Optimization for Friction Stir Welding of Dissimilar Aluminum Alloys

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Abstract

Friction Stir Welding (FSW) is one of the latest solid state joining techniques being extensively used for joining many similar and dissimilar material combinations for structurally demanding applications and the results are promising. The weld qualities of the FSW joints depend on the process parameters used. Aluminum alloys AA2024 and AA7075 find applications in aircraft industries and pose challenges when joined using conventional fusion welding techniques. In this study, friction stir welding of dissimilar aluminum alloys AA2024-AA7075 is performed at different tool rotation speeds (TRS) and welding speeds (WS) as per central composite design with three factors and three-levels for each factor (face centred). Response surface methodology is used a mathematical model for predicting the tensile strength of the resulting joints was developed. The model is used to study the effect of the TRS and WS on the strength of the joints. The tensile strength of the joints is found to be affected by both the TRS and WS. Simulated Annealing is used to optimize the TRS and WS for maximizing the tensile strength of the joints. Optimum values of the TRS and WS are found to be 1087.6 rpm and 14.12 mm/min respectively. The maximum tensile strength of the joints is predicted to be 271.084 MPa when these parameters are used.

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Keywords: Friction Stir Welding; Tensile strength; RSM;Optimization; Simulated Annealing.

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1. Introduction

Friction stir welding (FSW) invented by The Welding Institute (TWI), in 1991[1, 2] is one of the relatively recent solid state welding technique. In FSW process a cylindrical tool with a shoulder, and a profiled pin, is slowly plunged into the abutting edges of the rigidly clamped work pieces and then translated along the length of the abutting edges. The rotating and traversing tool develops frictional heat that softens the surrounding work piece material and allows the tool to move along the joint line. The axial load and the traversing motion of the tool causes the plasticized material to flow from the front to the back of the tool. When the tool moves forward, the transported material cools down and consolidates to form a joint in solid-state at temperature below the melting point of base metals [3, 4].

The FSW process parameters control the heat generation, microstructure evolution and the joint properties of friction stir welding process. The key parameters include process parameters (tool rotation speed, welding speed and axial force) and the tool geometry (size and profile). In addition to the process parameters and tool geometry the axial down force, initial temper of the work piece, material of the tool and its hardness, material and thickness of backing plate, type of cooling arrangement and the clamping fixture also affect the FSW process. Selection of friction stir welding parameters that produce acceptable mechanical, micro structural, fatigue and corrosion properties is a primary requirement to obtain efficient, defect free friction stir welded joints.

Heat treatable aluminum alloys AA2xxx and AA7xxx are significant classes of alloys with high strength and low-weight properties and find wide applications in various industries [5, 6]. As a result, joining these alloys is an important need in a variety of applications. Occurrence of dendritic structure in the fusion zone and the accompanying decrease in weld strength during conventional fusion welding has hindered the wide-spread usage of these alloys [7]. Friction stir welding has paved way for joining these materials that were unweldable by conventional processes.

The effect of process parameters and tool design on thermal history and temperature distribution, material flow, microstructure evolution and properties during FSW of similar materials has been extensively studied and reported. Lee et al. [8] reported improvement in mechanical properties in the weld zone when FSW A356 alloys, with various welding speeds. Peel et al., [9] presented the effect of welding speed on the microstructure, mechanical property and residual stress of friction stir welded AA5083 aluminum alloys. Lakshminarayanan and Balasubramanian applied Taguchi technique to determine the most influential factors controlling tensile strength of the friction stir welded RDE-40 aluminium alloy joints [10].

Artificial neural network (ANN) models have been developed for the analysis and simulation of the correlation between process parameters and properties of friction stir welded joints [11, 12]. Lakshminarayanan and Balasubramanian predicted the tensile strength of friction stir welded AA7039 aluminium alloy using response surface methodology and ANN [13]. Muttineni and Vundavilli modeled FSW process using Genetic Algorithm trained neural network and used the same for online prediction of the mechanical properties of FSW process at different operating conditions [14]. Babajanzade et al. developed adaptive neuro-fuzzy inference systems (ANFIS) to study parameter effect and optimized FSW to get desired mechanical properties using simulated annealing [15] .

Joints with better mechanical properties result when optimum process parameters are used. Lertora and Gambaro [16] presented an approach to optimize FSW process parameters governing the tensile strength and the fatigue life of AA8090 Al-Li alloy. Tansel et al. [17] used genetically optimized neural network systems (GONNS) to estimate the optimal operating condition of the friction stir welding (FSW) process to join aluminum alloy AL 1080. Palanivel and Koshy Mathews [18] presented an empirical model for the tensile strength of FSW AA5083-H111 aluminum alloy and optimized process parameters. Jayaraman et al. [19] used Taguchi design to evaluate the effect of FSW process parameters on tensile strength of friction stir welded cast aluminum alloy A319 and reported optimum welding condition.

Dissimilar material friction stir welding has been a recent area of research and is required in a number of applications. The mechanical properties and microstructure of dissimilar friction stir welded A356/ 6061Al joints mainly depended on the materials fixed at the retreating side [20]. Park et al. investigated the effect of tool rotation speed and welding speed on the mechanical properties of dissimilar joints between 5052-O and 5083-H321 Al alloys fabricated using friction stir welding and predicted the optimal parameters [21] .

In this work dissimilar FSW of AA2024-AA7075 has been attempted for different combinations of tool rotation speeds and welding speeds. Response surface methodology (RSM) has been used to develop a mathematical model for tensile strength of the joints in terms of TRS and WS. The developed model is then used to optimize the process parameters using the simulated annealing technique.

2. Experimental Procedure

AA2024 and AA7075 plates of size 150 x 60 x 5 mm were friction stir welded using a vertical milling machine shown in Figure 1. The aluminium plates were rigidly clamped during the FSW trials in a mild steel fixture of thickness 20 mm. The tool was cylindrical and threaded with a shoulder diameter of 17.5 mm, pin diameter of 5 mm and height 4.65 mm. The rotating tool probe was plunged at the interface of the faying surfaces of the plates to be welded. After the dwell time, the tool was traversed forward at the end of which the joint formed. The tool is withdrawn after the weld is completed, leaving a hole at the end.

The specimens for tensile testing were prepared from the friction stir welded plates using a power hacksaw as per ASTM standard. The tensile strength (TS) of the specimens was found by tensile testing three specimens corresponding to each set of parameters. The average tensile strength of the three specimens was used.

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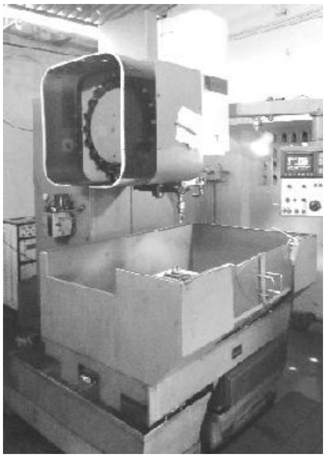

Figure 1 Experimental Setup Used

3. Development of the Model

A mathematical model for the tensile strength of dissimilar friction stir welded joints in terms of TRS and WS was developed using response surface methodology (RSM). FSW experiments were conducted as per face centered central composite design listed in Table 1 and the tensile strength of the joints was measured experimentally using tensile testing machine.

The tensile strength of the joints is expressed as a second order polynomial in terms of TRS (N) and WS (V) using response surface methodology [22]. The polynomial coefficients were determined using the statistical package Minitab. The adequacy of the developed model was assessed using ANOVA. Details regarding the regression model and ANOVA are not discussed here and can be found in Padmanaban et al [23]. The final model for the tensile strength of the welded specimens, with coefficients significant at 95 % confidence level is given by the Eq. (1), given below:

$$TS(MPa)=268.989+15.5N-5.667V-30.894N^2-50.394V^2 \quad (1)$$

Table 1 Matrix of Experiments and Results

S.No	N	V	TRS (rpm)	WS (mm/min)	TS (MPa)
1.	-1	-1	900	10	178
2.	1	-1	1200	10	210
3.	-1	1	900	20	169
4.	1	1	1200	20	198
5.	-1	0	900	15	220
6.	1	0	1200	15	252
7.	0	-1	1050	10	223
8.	0	1	1050	20	210
9.	0	0	1050	15	273
10.	0	0	1050	15	272
11.	0	0	1050	15	267
12.	0	0	1050	15	268
13.	0	0	1050	15	269

4. Optimization

In order to find the optimum tool rotation speed and welding speed that would yield the maximum tensile strength, the objective function is optimized using simulated algorithm. The simulated annealing is an optimization technique based on the analogy between slow cooling of critically heated solids, known as annealing and minimization. For maximization the negative of the objective function is used. The algorithm was coded in MATLAB.

4.1. Simulated annealing Algorithm [24, 25]

1. Start with an initial guess (X_i) and a high temperature.
2. Generate a new design point (Xi+1) in the vicinity of the current point randomly and find the difference in function values.

$$\Delta E = \Delta f = f_{i+1} - f_i \equiv f(X_{i+1}) - f(X^i)$$

If Δf is negative, accept the point X_{i+1} as the next design point.

3. When Δf is positive, accept the point X_{i+1} as the next design point only with a probability $e^{-\Delta E/kT}$. This means that if the value of a randomly generated number is larger than $e^{-\Delta E/kT}$, accept the point X_{i+1}; otherwise reject the point X_{i+1}.
4. When the point Xi+1 is rejected, then repeat steps 2 and 3. To simulate the attainment of thermal equilibrium at every temperature, a predetermined number (n) of new points $X_{i+1}$are tested at any specific value of the temperature T. If `Metropolis equilibrium' is realized, then go to Step 5, else go to step 2.
5. If the current value of temperature T is sufficiently small or when the changes in the function values (Δf) are observed to be sufficiently small, the solution has converged.

5. Results and Discussions

The effect of process parameters namely TRS and WS on the tensile strength of FS welded AA2024-AA7075 joints are depicted graphically in Figure 2 through Figure 4.The TS of all the joints were lower than the TS of the base materials and TS of the joints increase with increase in TRS upto 1050 rpm. The TS of the joints were found to decrease with further increase in TRS. It is observed from Figure 2, that the TS of joints fabricated at a TRS of 1200 rpm, are lower than those fabricated at 1050 rpm and 900 rpm. The tensile strength of the joint made at a TRS of 1050 rpm was found to be the maximum. At low TRS, low heat generation results in inefficient mixing of the materials and hence weak joints. The occurrence of defects at high TRS also reduces the TS of the joints.

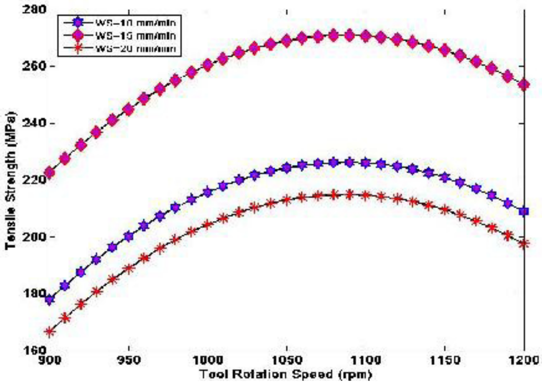

Figure 2. Variation of TS with TRS

The effect of WS variation on the TS of the joint at different WS is shown in Figure 3. Similar to TRS, increase in WS upto 15 mm/min results in an increase in the TS of the joints. When the WS was increased to 20 mm/min the tensile strength of the resulting joint was found to decrease. Similar trend was observed at all values of TRS. At higher WS, the weld area is exposed to frictional heating for a shorter time, causing poor plastic flow of the metal and formation of voids [26] that act as stress raisers during testing of the joint and weaken it.

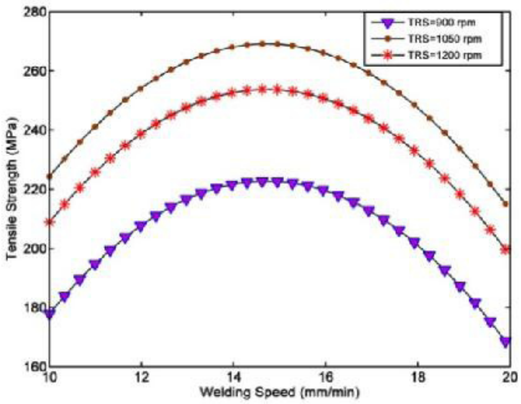

Figure 3. Variation of TS with WS

The contour plot of TS at various TRS and WS of FS welded joints is depicted in Figure 4. From the plots, it can be inferred that strength of the FS welded joints between AA2024-AA7075 will be high when the TRS and WS are within 1075 to 1125 rpm and 13 to 15 mm/min respectively. Optimum values of TRS and WS can be found by applying optimization techniques.

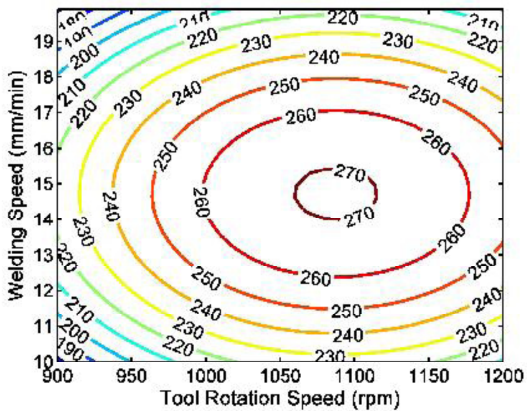

Figure 4. Contour plot of TS

The optimum tool rotation speed and welding speed for maximizing tensile strength of friction stir welded dissimilar aluminum alloy AA2024 and AA7075 joints found by the application of simulated annealing algorithm are 1087.6 rpm and 14.72 mm/min. The corresponding tensile strength of the joints is 271.084 MPa

6. Conclusions

Dissimilar aluminum alloys AA 2024 and AA 7075 were friction stir welded under varying TRS and WS, and response surface methodology (RSM) was used to develop a mathematical model for TS in terms of TRS and WS and the model was used to investigate the effect of TRS and WS on the TS of the joints. The following conclusions are made from the investigations.

- AA2024 and AA7075 dissimilar combinations can be succesively joined by using Friction stir welding.
- The TS of the joints were found to depend on both TRS and welding speed (WS).
- The tensile strength of the joints was found to increase with an increase in the TRS upto 1050 rpm and then decrease with increase in TRS.
- Similar to TRS, increase in WS resulted in an increase in TS until a WS of 15 mm/min and then TS decreased with increase in WS.
- The optimum tool rotation speed and welding speed for joining AA2024-AA7075 as found by using simulated annealing are 1087.6 rpm and 14.72 mm/min.

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