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Process Parameter Optimization for Friction Stir Welding of dissimilar Aluminum Alloys

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Abstract

The friction stir welding (FSW) process is a recent solid-state joining process capable of joining wide variety of materials. In this work the effects of tool rotation speed and welding speed on the tensile strength of dissimilar friction stir welded AA2024-AA7075 joints have been investigated. Tensile strength of the friction stir welded joints fabricated under various combinations of tool rotational speed and transverse speeds are measured experimentally. A mathematical model for tensile strength of the joints is developed using Response Surface Methodology in terms of process parameters. The model is used to study the effect of tool rotation speed and welding speed on tensile strength of the joints. Nelder Mead algorithm is used to predict the optimum tool rotation speed and welding speed which will maximize tensile strength.

Keywords: Friction stir welding, Tensile strength, Response Surface Methodology, Nelder Mead Algorithm

1. Introduction

Friction stir welding (FSW) is a solid state joining technique invented by The Welding Institute (TWI), Cambridge, UK, in 1991[1, 2]. The FSW process uses a, non-consumable cylindrical tool consisting of a shoulder, and a smaller diameter profiled pin, protruding from the tool shoulder. The rotating tool is slowly plunged into the abutting edges of the rigidly clamped work pieces till the shoulder makes intimate contact with the work piece surfaces till the pin is completely embedded within the through-thickness of the work pieces, but does not touch the bottom of the work pieces. The rotating tool initially develops frictional heat during tool plunge. This heat is then complemented through adiabatic shear of a finite volume of material in the close proximity of the tool pin. The frictional heat generated heat softens the surrounding work piece material and allows the tool to move along the joint line. The Traversing motion of the tool under the axial force causes the plasticized material to flow from the front to the back of the tool. This transported material then cools down and consolidates to form the solid-state joint. Temperature during welding does not exceed the melting point of base metals [3, 4].

The energy input to the FSW process, heat generation, microstructure evolution and the joint properties are controlled by the process parameters (Tool rotation speed, Welding speed and axial force) and the tool geometry (size and profile). The tool life also depends on the process parameters used. 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. The traversing force and side force are not considered to be process parameters, but have been used for monitoring the 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.

2. Literature survey

Aluminum alloys AA2xxx and AA7xxx are significant classes of alloys widely used in aerospace industry. These classes of aluminum possess high strength and low-weight properties which make them prevailing for industrial applications. AA7xxx series alloys are usually chosen for their high strength, while 2xxx series alloys are generally designated where fatigue is a challenging problem and for applications where higher service temperatures may be encountered. AA7075 and A2024 have numerous applications in common. [5, 6]. As a result, joining these alloys is so much needed in a variety of applications. These alloys are difficult to weld using the conventional welding processes such as tungsten inert gas welding and laser welding due to the formation of dendrite structure occurring in the fusion zone that leads to a drastic decrease of the mechanical. strength [7]. This has limited the wide-spread usage of these alloys. Friction stir welding has paved way for joining many 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 in literature. The relationship between FSW parameters and tensile properties of the 2017-T351 aluminium alloy joints has been investigated by Liu et al. [8]. Lee, et al. reported an improvement in mechanical properties at the weld zone when friction-stir-welding A356 alloys, with various welding speeds[9]. The effect of welding speed on the microstructure, mechanical property and residual stress of friction stir welded AA5083 aluminum alloys is presented in [10]. Record et al. concluded that tool rotation speed, welding speed, and plunge depth to be the three most significant factors of the FSW process from statistical experimentation [11]. Lakshminarayanan and Balasubramanian applied Taguchi approach to determine the most influential factors controlling tensile strength of the friction stir welded RDE-40 aluminium alloy joints[12]. Kulekci et al. reported the effects of the tool pin diameter and tool rotation on the fatigue behavior of friction stir welded (FSW) lap joints of AA 5754 aluminium alloy plates [13]. Empirical models have been developed for predicting the tensile properties of friction stir welded joints [14-17].

Modern soft computing and evolutionary optimization techniques also find application in analyzing the effect of parameters on FSW process. Y.K.Yousif et al. used Artificial neural network (ANN) to create a model for the analysis and simulation of the correlation between process parameters and properties of friction stir welded joints [18]. Similar approach has been made by Okuyucu et al. [19]. Lakshminarayanan and Balasubramanian predicted the tensile strength of friction stir welded AA7039 aluminium alloy using response surface methodology and artificial neural network[20]. 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 [21]. Babajanzade et al. modelled relationship between FSW process factors and main response using adaptive neuro-fuzzy inference systems (ANFIS) and optimized FSW for desired mechanical properties of AA 7075 plates using simulated annealing [22] .

The mechanical properties of the friction stir welded joints depend on the process parameters used. Optimum process parameters yield better mechanical properties. Benyounis and Olabi presented a review on the optimization of different welding processes using statistical and numerical approaches[23]. Optimum process parameters to maximize tensile strength of friction stir welded joints have been found using optimization techniques in [16].[24] presented an approach to optimise FSW process parameters governing the tensile strength and the fatigue life of AA8090 Al-Li alloy. [25] presented a systematic approach to optimize FSW process parameters (tool rotational speed and feed rate) through consideration of frictional power input. [26] computed created residual stresses due to friction stir welding using finite element method and used genetic algorithm to optimize process parameters for the minimization of the peak residual stresses and the maximization of the welding speed. [27] 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 presented a systematic approach to develop an empirical model for the tensile strength of FSW AA5083-H111 aluminum alloy in terms of the process parameters and then optimize it [28] . Response surface methodology has been used to predict the yield tensile strength and the hardness of friction stir welded aluminum alloys and also to optimize the FSW parameters to attain maximum yield strength of the welded joints [29] Jayaraman et al. evaluated the effect on tensile strength of FSW process parameters using Taguchi experimental design technique and reported optimum welding condition for maximizing tensile strength of friction stir welded cast aluminum alloy A319 [30]. Tutum et al. investigated optimum tool rotational speed and traverse welding speed in Friction Stir Welding (FSW) to minimize residual stresses in the work piece and maximize production efficiency [31].

Dissimilar material friction stir welding is required in a number of applications, and has been a recent area of research. Lee et al. reported that the mechanical properties and microstructure of dissimilar friction stir welded A356/ 6061Al joints mainly depended on the materials fixed at the retreating side [32]. 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 with a purpose of verifying optimal condition [33] .

In this work the effects of key process parameters namely; tool rotation speed (TRS) and welding speed (WS) on the tensile strength of dissimilar friction stir welded AA2024-AA7075 joints have been investigated. Dissimilar FSW of AA2024-AA7075 has been attempted for different combinations of tool rotation speeds and transverse speeds. Tensile strength of the dissimilar friction stir welded AA2024-AA7075 joints are measured experimentally. Response surface methodology (RSM) has been used to develop a mathematical model for tensile strength of the joints (objective function) in terms of TRS and WS. This model is then used for optimizing the process parameters using the Nelder Mead optimization technique for maximizing joint tensile strength.

3. 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 mechanical properties of the base materials are given in Table 1Table 1The aluminium plates were rigidly clamped during the FSW trials in a fixture made from mild steel plate of thickness 20 mm. A cylindrical threaded tool with a shoulder diameter of 17.5 mm, pin diameter of 5 mm and height 4.65 mm was used for friction stir welding. The rotating tool probe was plunged to a predetermined depth 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 are prepared from the friction stir welded plates using a power hacksaw as per ASTM standard E8M-04 (Figure 2.). 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 is given in Table 2.

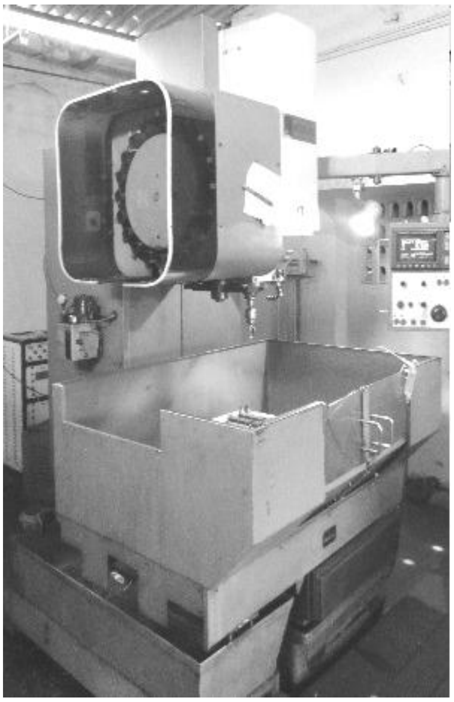

Figure 1 Experimental Setup Used

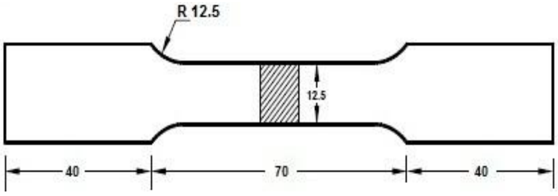

Figure 2 .Tensile Test Specimen, as per ASTM E8M-04 ([34])

4. Development of model

A Mathematical model for the tensile strength of dissimilar friction stir welded joints as a function of TRS and WS is developed using response surface methodology (RSM). FSW experiments are conducted as per face centered central composite design and the tensile strength of the joints are measured experimentally using tensile testing machine. The results are listed in Table 2

Table 1. Base Material Properties

Material	Yield Strength (MPa)	Tensile Strength (MPa)	Percent Elongation	Micro-hardness (VHN)
AA2024 -T3	324	469	19	137
AA7075-T6	503	572	11	175

Table 2 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

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. Details regarding RSM, experimental design and obtaining the regression model are not discussed here, but can be found in Raymond. H. Myers [35] In the present work, the coefficients were determined using the commercial statistical package Minitab and all the coefficients were evaluated and tested for their significance at 95 % confidence level. After determining the significant coefficients, the final model for determining the tensile strength of the welded specimens is given by the Eq. (1), given below:

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

The adequacy of the developed model is assessed using ANOVA and the results are tabulated in Table 3. If the probability value P is less than 5% for specific terms, then those terms are more significant in the developed model. The P-values for linear as well as quadratic terms are very small (less than 0.0001). In the above developed model, interaction effect of tool rotational speed with welding speed and the lack of fit are not significant. The lack of fit test, on the quadratic model has a large P-Value (>0.05), implying that the quadratic model is adequate. The coefficient of determination (R^2) whose value is equal to 0.9964 signifies that only less than 1% of the total variations are not explained by the model. In the same way, the adjusted value of R^2adj (=0.9904) indicates that non-significant terms are not included in the model. The predicted value of R^2 is also in accordance with adjusted value. The normal probability plot is shown in Figure 3, in which the residuals of the tensile strength lie on a straight line. This indicates that the errors obtained while comparing the predicted value by the model and the

Table 3 ANOVA

Source	DF	Sum of Squares	Mean Squares	F	P
Regression	4	16754.4	4188.60	550.08	0.000
Linear	2	1634.2	817.08	107.31	0.000
N	1	1441.5	1441.50	189.31	0.000
V	1	192.7	192.67	25.3	0.001
Square	2	15120.2	7560.12	992.86	0.000
N*N	1	2636.0	2635.99	346.18	0.000
V*V	1	7013.9	7013.88	921.12	0.000
Residual error	8	60.9	7.61		
Lack-of-Fit	4	30.6	7.64	1.01	0.498
Pure Error	4	30.4	7.59		
Total	12	16815.3			

SD = 2.75944, R2 = 0.9964, Press =161.412, R2 Pred = 0.9904, R2 Adj =0.9946 measured values are distributed normally. For the developed model, the errors are normally distributed and the lack of fit probability is not less than 5%, hence the developed model is highly adequate.

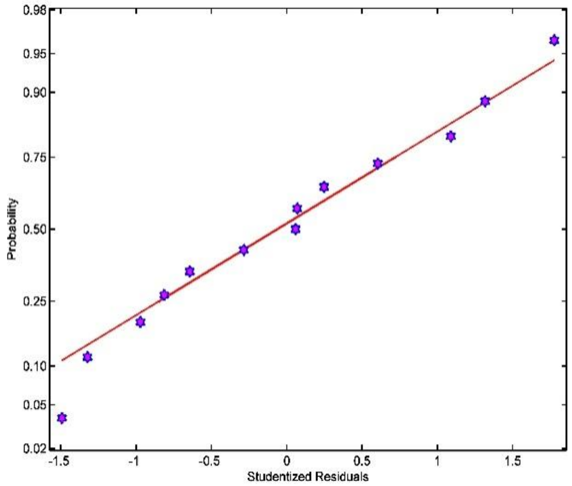

Figure 3. Normal Probability Plot of Residuals

5. Effect of process parameters

The developed model is used to study the effect of TRS and WS on the tensile strength of FS welded AA2024-AA7075 joints. The results are depicted graphically in Figure 4.through Figure 7.

5.1 Effect of Tool Rotation Speed

The TS of all the joints tested were noted to be lower than the TS of the base materials. It is observed from Figure 4, that TS increases when the TRS is increased from 900 rpm, till TRS of 1050 rpm. The TS of the joints were found to decrease with further increase in TRS. The tensile strength of the joint made at a TRS of 1050 rpm was found to be the maximum. At low TRS, the material softening is not sufficient due to low heat generation and therefore, results in inefficient mixing of the materials. Hence the TS of the joints were found to be low. Higher TRS generates more heat , and hence increases the stirring effect of the pin producing flash and forming tunnel defects. Similar effect has been reported in their work by Elangovan and Balasubramanian [36] .

Also, higher heat input increases the peak temperature and causes grain growth. Elangovan et al. [34] observed that increased TRS may cause significant increase in turbulence in the weld zone, which affected the regular metal flow and thereby reducing the TS of the joints. Similar variation patterns of TS are observed for different WS with TRS remaining the same. TS of joints fabricated at a WS of 20 mm/min, are found to be lower than those fabricated at 10 and 15 mm/min.

5.2 Effect of Welding Speed

The variation of TS of the FS welded AA2024-AA7075 joints for different WS are shown in Figure 5. It is seen from Figure 5 that for a fixed value of TRS an increase in WS, resulted in an increase of the TS of the joints untill a WS of 15 mm/min. The TS of the joints was found to decrease with further increase in WS to 20 mm/s. The same trend was observed at all values of TRS. It is observed from Figure 5, that the TS of joints fabricated at a TRS of 1200 rpm, are lower than those fabricated at 1050 rpm and 900 rpm. The weld area is exposed to frictional heating for a shorter time at higher WS, resulting in insufficient heating and poor plastic flow of the metal. It is reported by Elangovan and Balasubramanian [36] that increased WS results in void-like defects in the joints that act as stress raisers which affect the TS of the joint.

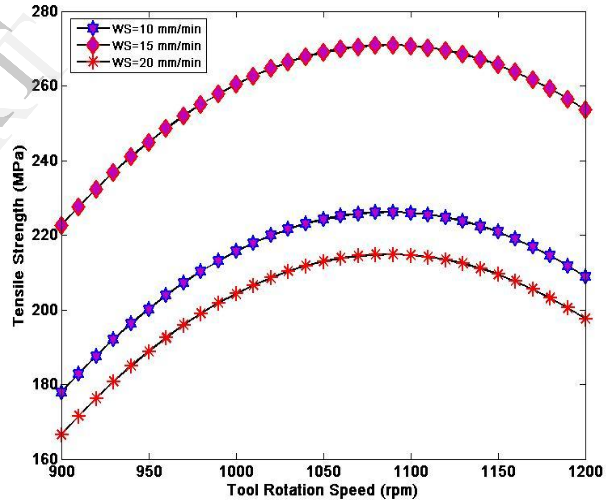

Figure 4. Variation of TS with TRS at different WS

Figure 6 and Figure 7 depicts the surface plot and contour plot of TS at various TRS and WS of FS welded joints respectively. From the plots, it can be inferred that for maximum joint tensile strength at a TRS of 1100 rpm, a minimum weld feed rate of 13 mm/min is required. Upon analysis of the plots we can observe that better FS welded joints between AA2024-AA7075 can be obtained 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 such as Nelder-Mead algorithm.

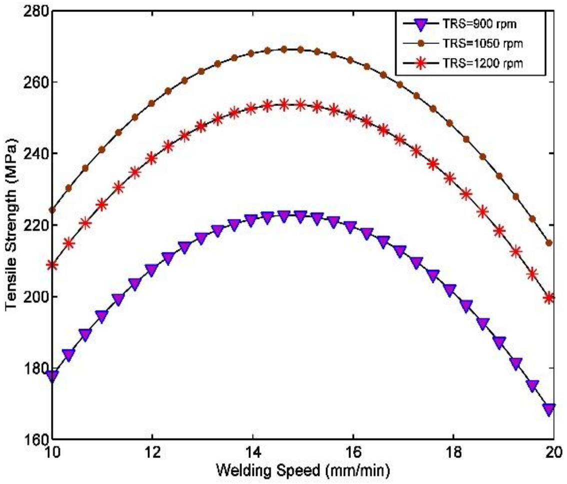

Figure 5. Variation of TS with WS at different TRS

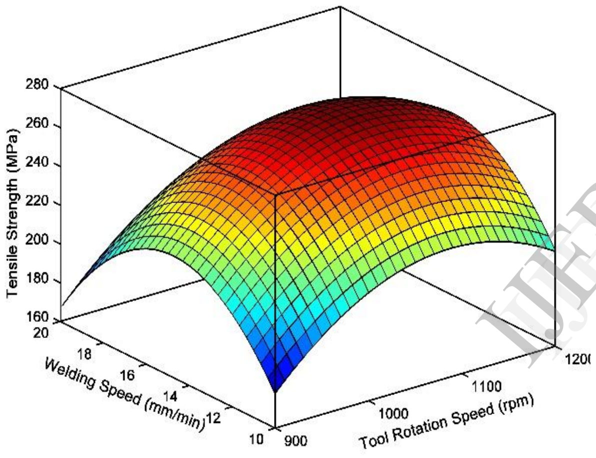

Figure 6. Surface plot of Tensile Strength

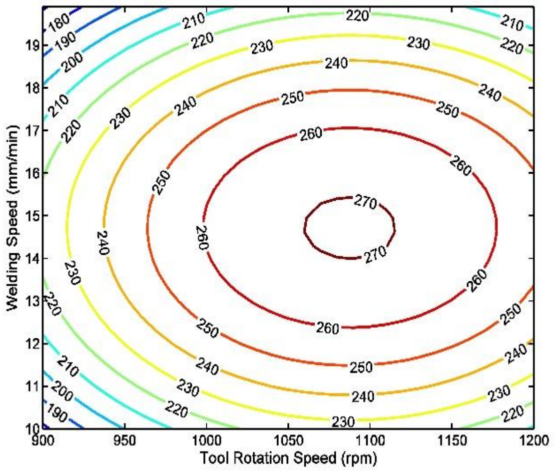

Figure 7. Contour plot of Tensile strength

6. 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 Nelder Mead optimization technique. The Nelder-Mead Algorithm, also called as downhill simplex method is a numerical optimization method for unconstrained optimization and has been used extensively to solve parameter estimation (and other) problems for almost 40 years. Its computational process is simple and it does not require calculation of derivatives. It only uses the values of the objective function without any derivative information. It is a fast algorithm to search for a local minimum and applicable for multi-dimensional optimization. It converges to minima by forming a simplex and using this simplex to search for its promising directions.

The basic idea of simplex method is to compare the values of the objective function at n+1 vertices of a general simplex and move the simplex gradually towards the optimum point iteratively. A simplex is defined as a geometrical figure which is formed by (n+1) vertices (n: the number of variables of a function). In every iteration, simplex iteration method (SIM) always starts calculating a reflected point of the worst point through the centroid point. According to this value, SIM algorithm will do reflection or extension, contraction or shrink to form a new simplex. In other words, the function values at each vertex will be evaluated in every iteration and the worst vertex with the highest value will be replaced by another vertex which has just been found. Otherwise, a simplex will be shrunk around the best vertex. This process will be repeated iteratively until a desired error value is satisfied. The process is represented by the flow chart shown in Figure 8. For maximization the negative of the objective function is used. The algorithm is coded in MATLAB 7.11.0. Details of the algorithm and its operation can be found in [37].

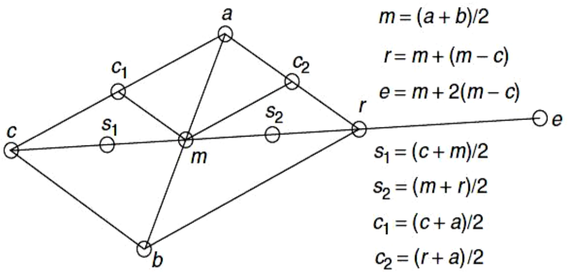

Figure 8. Nelder Mead algorithm

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 Nelder Mead algorithm are 1087.6 rpm and 14.72 mm/min.

7. Conclusions

Dissimilar aluminum alloys AA 2024 and AA 7075 were friction stir welded under varying TRS and WS, and the TS of the joints were measured. RSM was used to develop a mathematical model (regression) 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.

- Friction stir welding can be used to join AA2024 and AA7075 in dissimilar combinations.
- The tool rotation speed and welding speed are found to affect the tensile strength of the FS welded AA2024-AA7075 joints.
- Increasing the tool rotation speed increases the tensile strength of the FS welded AA2024-AA7075 joints.
- Increasing the welding speed resulted in a decrease in the tensile strength of the FS welded AA2024-AA7075 joints.
- The optimum tool rotation speed and welding speed for joining AA2024-AA7075 as found by using Nelder Mead algorithm are 1087.6 rpm and 14.72 mm/min.

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