



Statistical analysis and optimization of tensile strength of Al7075 butt joint produced by friction stir welding and submerged friction stir welding via response surface methodology and desirability approach

M. Vahdati^{1,*}, M. Moradi²

¹ Faculty of Mechanical and Mechatronics Engineering, Shahrood University of Technology, Shahrood, Iran

² Department of Mechanical Engineering, Malayer University, Malayer, Iran

ABSTRACT: The thermal cycles involved in friction stir welding process cause softening in the joint of heat-treatable aluminum alloys. To overcome this limitation, submerged friction stir welding process has been developed. In this study, firstly, the butt joints were produced from Al7075-T6 alloy using friction stir welding process. To this end, the response surface methodology was selected as the experiment design technique. So, the factors such as tool rotational speed, tool feed rate, tool shoulder diameter, and tool tilt angle were identified as the input variables. Then, a statistical analysis of variables affecting the tensile strength of joints was performed. Afterward, the butt joints were produced using submerged friction stir welding process based on the optimal values of tool feed rate and tool tilt angle. The obtained results from analysis of variance and regression analysis of experimental data confirmed the accuracy of regression equations. Furthermore, it is shown that the linear, interactional and quadratic terms of the tool rotational speed and tool shoulder diameter are effective on the ultimate tensile strength of the underwater welded joints. Also, the optimal condition of input variables was determined using the desirability method. In addition, the optimal condition has been confirmed by implementing the verification test.

Review History:

Received: Mar. 12, 2020

Revised: May. 16, 2020

Accepted: Aug. 18, 2020

Available Online: Aug. 26, 2020

Keywords:

Statistical analysis

Optimization

Tensile strength

Friction stir welding

Response surface methodology

1- Introduction

Friction Stir Welding (FSW) was first developed for the welding of aluminum alloys and subsequently applied to various materials and alloys [1]. Although the heat input in this process is smaller than the fusion welding, nevertheless, the softening phenomenon is generally observed in the FSW of heat-treatable aluminum alloys. On the other hand, Submerged Friction Stir Welding (SFSW) is introduced as an improved method of the FSW in which water is used as the cooling fluid and plays an important role in adjusting the temperature gradient of the welded joint [2]. Therefore, considering the advantages of FSW and SFSW in joining aluminum heat-treatable alloys, in this study, statistical analysis, mathematical modeling, and optimization of parameters affecting the tensile strength of Al7075-T6 butt joint were investigated for both processes.

2- Statistical Analysis and Optimization of FSW Process

The ultimate tensile strength is used to evaluate the tensile strength of the produced joints in the FSW and SFSW processes. Also, four variables, including tool rotational speed, tool feed rate, tool shoulder diameter, and tool tilt angle, were selected as the experimental input variables, and each of them was investigated at five levels (Table 1).

The Response Surface Methodology (RSM) is used as the design of the experiments method [3]. In this research, the approximation function as a second-order model is used. The Design-Expert software is used to design experiments and statistical analysis. Fig. 1 shows the placement of the parts in the form of butt joint in the fixture. Then, the FSW tests were done according to the 31 parameter combinations using the FP4MK universal milling machine.

The tensile test is used to measure the ultimate tensile strength of the welded joints. Data analysis was performed using analysis of variance. The following relationship presents the regression equation of the ultimate tensile strength as a function of the coded input variables:

$$\begin{aligned} (UTS)^{-0.3} = & 0.16 - 7.563 \times 10^{-3} N - 1.007 \times 10^{-3} S \\ & - 4.078 \times 10^{-3} D + 3.517 \times 10^{-3} A + 0.013 N^2 \\ & + 8.71 \times 10^{-3} S^2 + 7.646 \times 10^{-3} D^2 + 9.902 \times 10^{-3} A^2 \end{aligned} \quad (1)$$

As can be seen in Eq. (1), the linear effect of input variables on the ultimate tensile strength according to their importance, are as following: tool rotational speed, tool shoulder diameter, tool tilt angle and tool feed rate. In this study, the desirability method is used as an optimization technique [3]. The purpose

*Corresponding author's email: vahdati@shahroodut.ac.ir



Table 1. Experimental factors and the extent of their changes in the FSW process

Variable	Symbol	Unit	-2	-1	0	+1	+2
Rotational speed	<i>N</i>	rpm	400	600	800	1000	1200
Feed rate	<i>S</i>	mm/min	20	40	60	80	100
Shoulder diameter	<i>D</i>	mm	9	12	15	18	21
Tilt angle	<i>A</i>	deg	0	1.5	3	4.5	6

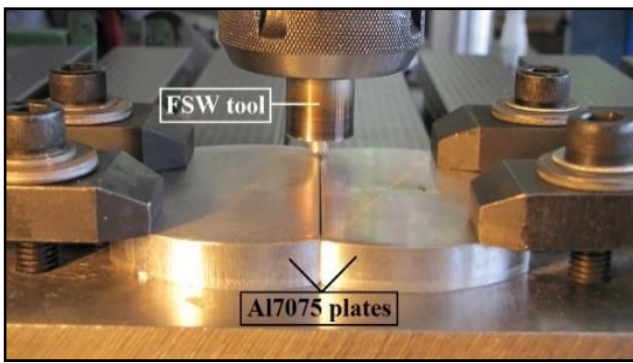


Fig. 1. Execution of the FSW process

of the desirability function is to maximize the ultimate tensile strength. Table 2 shows the optimal combination of input variables with the highest desirability value (0.976) to achieve the maximum value of ultimate tensile strength.

3- Statistical Analysis and Optimization of SFSW Process

Since the tool rotational speed and tool shoulder diameter were identified as the most important linear terms affecting the ultimate tensile strength of the FSW joints, and also since the optimum values of the input variables of the FSW are calculated, two variables of tool rotational speed and tool shoulder diameter were selected as the input variables of the SFSW, and each of them was investigated at three levels (Table 3).

Table 3. Experimental factors and the extent of their changes in the SFSW process

Variable	Symbol	Unit	-1	0	+1
Rotational speed	<i>N</i>	rpm	800	1000	1200
Shoulder diameter	<i>D</i>	mm	15	18	21

Table 2. Optimal values of FSW input variables

Variable type	Symbol	Unit	Optimal value
Input	<i>N</i>	rpm	971.47
	<i>S</i>	mm/min	62.59
	<i>D</i>	mm	18.14
	<i>A</i>	degree	2.05
Response	<i>UTS</i>	MPa	445.001

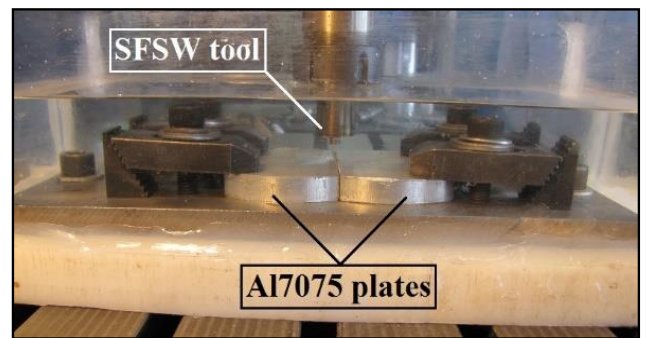


Fig. 2. Execution of the SFSW process

Fig. 2 shows the placement of the plates in the fixture. As can be seen, the fixture and the workpieces are submerged in a water tank. The value of water depth in which the tool and workpiece were submerged is equal to 55 mm. The SFSW experiments were performed according to the 10 parameter combinations.

The following relationship presents the regression equation of the ultimate tensile strength as a function of the coded input variables:

$$\begin{aligned}
 (UTS)^{-3} = & 1.745 \times 10^{-8} - 6.814 \times 10^{-10} N \\
 & + 8.393 \times 10^{-11} D + 3.371 \times 10^{-10} ND \\
 & - 3.999 \times 10^{-9} N^2 - 3.416 \times 10^{-9} D^2
 \end{aligned}
 \tag{2}$$

As can be seen in Eq. (2), the linear effects of input variables on the ultimate tensile strength according to their importance are as follows: tool rotational speed and tool shoulder diameter. Also, the quadratic effects of input variables according to their importance are as following: tool rotational speed and tool shoulder diameter. Table 4 shows the optimal combination of input variables with the highest desirability value (equal to 1) to achieve the maximum value of ultimate tensile strength.

4- Conclusions

In this paper, statistical analysis and optimization of the tensile strength of Al7075 butt joint produced by FSW and

Table 4. Optimal values of SFSW input variables

Variable type	Symbol	Unit	Optimal value
Input	N	rpm	1200
	D	mm	15
Response	UTS	MPa	481.875

SFSW were performed using response surface methodology and desirability approach. The important results of this study are summarized as follows:

- Analysis of variance results in the FSW process showed that the first-order parameter N (tool rotational speed) and the second-order term N^2 were identified as the most important terms affecting the ultimate tensile strength of the FSW joints.

- Based on the analysis of variance results in the SFSW process, the second-order term N^2 is the most important term affecting the ultimate tensile strength of the SFSW joints.

- The regression equation was calculated to predict the value of ultimate tensile strength of the produced joints in both FSW and SFSW as a function of the linear, interactional and quadratic effects of input variables. Therefore, it is possible

to select the appropriate combination of input variables to achieve the maximum response variable.

- The optimal values of the FSW and SFSW input variables were calculated to obtain the maximum ultimate tensile strength. The desirability values were 0.976 and 1 for FSW and SFSW processes, respectively. Therefore, the high values of the desirability function indicate that the optimization process has successfully achieved the research target.

References

- [1] W.M. Thomas, E.D. Nicholas, Friction stir welding for the transportation industries, *Materials and Design*, 18 (1997) 269-273.
- [2] R. Rouzbehani, A.H. Kokabi, H. Sabet, M. Paidar, O.O. Ojo, Metallurgical and mechanical properties of underwater friction stir welds of Al7075 aluminum alloy, *Journal of Materials Processing Technology*, 262 (2018) 239-256.
- [3] M. Vahdati, M. Moradi, Statistical analysis and optimization of the yield strength and hardness of surface composite Al7075/Al₂O₃ produced by FSP via RSM and desirability approach, *Iranian Journal of Materials Forming*, 7 (1) (2020) 32-45.

HOW TO CITE THIS ARTICLE

M. Vahdati, M. Moradi, *Statistical analysis and optimization of tensile strength of Al7075 butt joint produced by friction stir welding and submerged friction stir welding via response surface methodology and desirability approach*, Amirkabir J. Mech. Eng., 53(Special Issue 4) (2021) 637-640.

DOI: [10.22060/mej.2020.18104.6735](https://doi.org/10.22060/mej.2020.18104.6735)



