Statistical analysis and optimization of the tensile strength of Al7075 butt joint produced by FSW and SFSW via RSM and desirability approach

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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, 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.

KEYWORDS

Statistical Analysis, Optimization, Tensile Strength, Friction Stir Welding, Response Surface Methodology.

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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 lower than the fusion welding, nevertheless, the softening phenomenon 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 of aluminum heat-treatable alloys, in this study, statistical analysis, mathematical modeling, and optimization of parameters affecting the tensile strength of Al7075-T6 butt joint was investigated for both processes.

2. Statistical Analysis and Optimization of the 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).

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

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

The response surface methodology (RSM) is used as the design of experiments method [3]. In this research, the approximation function as a second-order model is used. The Design Expert software used to design of experiments and statistical analysis. Figure 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.

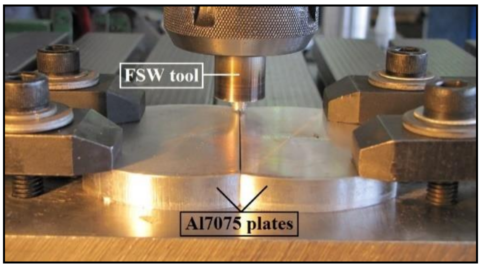

Figure 1. Execution of the FSW process

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

$$\begin{aligned}(UTS)^{-0.3} &= 0.16 - 7.563\times10^{-3}N - 1.007\times10^{-3}S \\ &-4.078\times10^{-3}D + 3.517\times10^{-3}A + 0.013N^2 \\ &+8.71\times10^{-3}S^2 + 7.646\times10^{-3}D^2 + 9.902\times10^{-3}A^2\end{aligned} \tag{1}$$

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 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.

Table 2. Optimal values of FSW input variables

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

3. Statistical Analysis and Optimization of the 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	N	rpm	800	1000	1200
Shoulder diameter	D	mm	15	18	21

Figure 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.

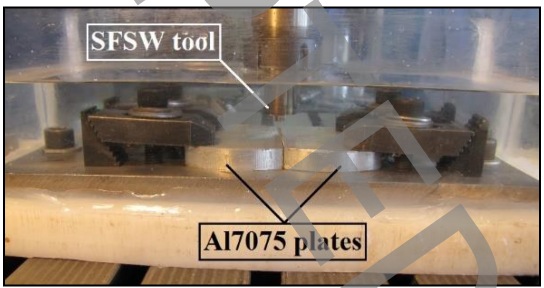

Figure 2. Execution of the SFSW process

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

$$(UTS)^{-3} = 1.745\times10^{-8} - 6.814\times10^{-10}N + 8.393\times10^{-11}D + 3.371\times10^{-10}ND - 3.999\times10^{-9}N^{2} - 3.416\times10^{-9}D^{2} \quad (2)$$

As can be seen in Eq. 2, the linear effect 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 effect 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.

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

4. Conclusion

In this paper, statistical analysis and optimization of the tensile strength of Al7075 butt joint produced by FSW and SFSW were performed using response surface methodology and desirability approach. The important results of this study are summarized as following:

- ANOVA 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 ANOVA 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 desirability function indicate that the optimization process has successfully achieved the research target.

5. References

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