Statistical Regression-based Modeling of Friction Stir Welding of AL7075

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ABSTRACT: *Friction stir welding (FSW) is a solid state welding process, which is used for the welding of aluminum alloys. It is important to note that the mechanical properties of the FSW process depends on various process parameters, such as spindle speed, feed rate and shoulder depth. In the present study, two different tool materials, such as high speed steel (HSS) and H13 are considered for the welding of Al 7075. This paper provides an insight into the measurement of force required for welding and external surface temperature measurement for three input parameters, namely spindle speed, feed rate and shoulder depth and their corresponding three levels. During experimentation the data related to force along x and z directions, and heat transferred to the tool are recorded using dynamometer and IR camera. Regression analysis is performed to predict the forces and heat transfer to the tool for different parametric combinations.*

Key words: Friction Stir Welding, Regression analysis, Response surface methodology

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1. Introduction

The friction stir welding (FSW) was invented by The Welding Institute, UK in 1991 [1]. It is a solid state welding process and was initially utilized for joining of aluminum alloys [2] and most often on large pieces which cannot be easily heat treated to recover temper characteristics. In FSW, a rotating shouldered tool plunges into the butt plates and locally plasticizes the joint region during its movement along the joint line. A cylindrical-shouldered tool, with a profiled threaded/unthreaded probe (nib or pin) is rotated at a constant speed and fed at a constant traverse rate into the joint line between the two butted pieces of sheet or plate material. The parts have to be clamped rigidly onto a backing bar in a manner that prevents the abutting joint faces from being forced apart. In this process, heat is originally derived from the friction between the welding tool (including the shoulder and the probe) and the material to be welded. The heat generated causes the material to soften at a temperature less than its melting point temperature and joining of the plates take place. Friction stir welding can be used for joining of many types of materials and metals, if suitable tool materials and their designs for the work pieces are identified. In FSW process, the tool axis is typically tilted by a few degrees (2^o or 3^o) from the vertical in order to facilitate consolidation of the weld. The process has been used for manufacture of butt welds, overlap welds, T-sections and corner welds. It is to be noted that for each of these geometries, specific tool designs are required [3]. Moreover, the heat generated during the welding process causes the micro structural changes. Nelson et. al [4] observed a pancake microstructure with unrecrystallized regions consisting of rod-like or bar-like shaped sub regions in the parent material. The mechanical properties were also influenced by the type of welding method. Ericson and Sandstorm [5] concluded that the fatigue strength of FS welded Al-Mg-Si alloy 6082 was higher than that of MIG-plus and TIG welds of the same material, with narrower geometry of the joints.

In FSW heat is generated by a combination of friction and plastic dissipation during plastic deformation of the metal. Early experimental studies showed that the majority of the heat generation occurs at the shoulder/work piece interface [6]. Then, a thermal model [7] for FSW was developed utilizing multi physics finite element package. For modeling this problem, a fixed tool approach was employed by moving the work piece towards the tool. The tool tilt angle was assumed to be zero. It was observed that the aluminum alloy had temperature dependent yield strength. In [8], the authors studied the influence of pin profile and rotational speed of the tool of FSW welding on AA2219 aluminum alloys. Five different tool pin profiles, such as straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square were used to fabricate the joints. It was observed that square tool pin produces mechanically sound and defect free welds compared to other tool pin profiles. It is important to note that several researchers were tried to establish the analytical relationships between the process parameters and the responses. However, it could be difficult to establish the said input-output relationships due to the inherent complexity of the process. Moreover, the statistical modeling using Design of Experiments (DOE) [9] was proven to be an effective tool for studying the influence of various process parameters on the quality of the FSW process.

Full-factorial design of experiments was used by Jayaraman et.al [10] to analyze the effect of rotational and transverse speeds and axial tool force on the tensile strength of the FSW joint. Laxminarayanan et. al [11] utilized the Taguchi method to optimize the FSW process parameters using a tensile test specimen. Moreover, a complete review of Taguchi optimization of process parameters in friction stir welding was explained in [12]. It is important to note that response surface methodology was also used to model the fusion welding process [13], and allows the development of an empirical methodology.

In the present paper, process modeling of FSW has been carried out with the help of response surface methodology, however with a set of different parameters used in the above mentioned paper. Two different tool materials, such as HSS and H13 are used for the friction stir welding of AL 7075 aluminum alloy. Three inputs, namely spindle speed, feed rate and shoulder depth are considered as input parameters and feed force (F_x), downward force (F_z) and heat flow (H) are treated as the outputs.

2. Materials and Methods

The basic principle of operation of FSW process is shown in Figure 1. In order to establish the input-output relationships of FSW process, three process parameters, namely spindle speed (S), feed rate (F) and shoulder depth (D) are taken as input parameters and feed force (F_x), downward force (F_z) and heat flow rate (H_f) are considered as outputs.

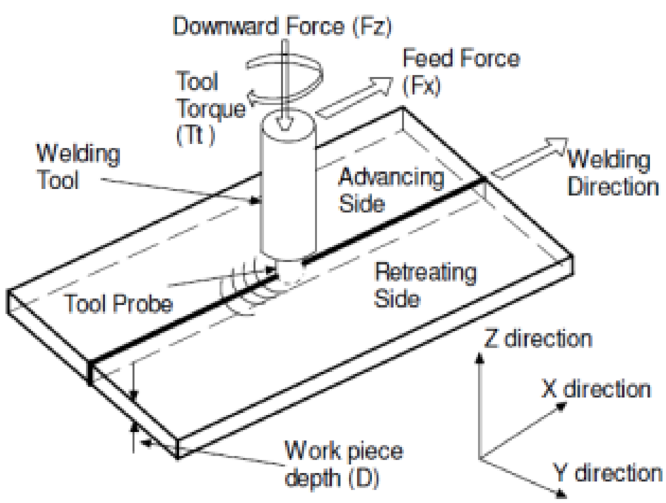


Figure 1. Schematic diagram showing the operation of FSW process

Figure 2 shows the schematic diagram of input-output model of the FSW process. Two different tool materials, such as H13 and HSS are used for welding of the AL 7075 aluminum alloy.

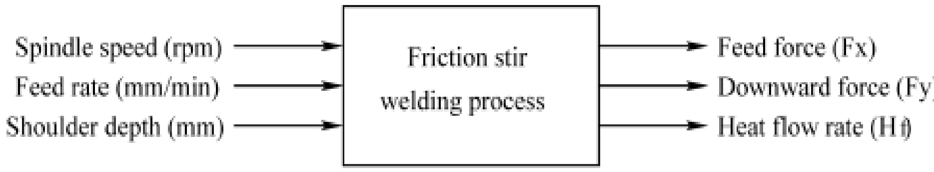


Figure 2. Input and output variables of FSW Process

The ranges of the chosen input parameters used in this study [14], which is the work done by the one of the authors of this manuscript are shown in Table. 1.

S. no	Parameters	Levels		
	Description	Notation	High (+1)	Low (-1)
1	Spindle speed (rpm)	S	1.5	0.8
2	Feed rate (mm/min)	F	239	165
3	Shoulder depth (mm)	D	0.095	0.035

In the present paper, response surface methodology (RSM) is used to develop the non-linear model of the FSW process. In most RSM problems, the form of the relationship between the response and the independent variables is unknown. Thus, the first step in RSM is to find a suitable approximation for the true relationship between y and the independent variables. Usually, a low-order polynomial in some region of the independent variables is employed. If the response is well modeled by a linear function of the independent variables, then the approximating function is the first-order model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \in \qquad (1)$$

If there is curvature in the system, then a polynomial of higher degree must be used, such as the second-order model.

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<} \sum_{j=2}^{k} \beta_{ij} x_i x_j + \in \qquad (2)$$

Many RSM problems utilize one or both of these approximating polynomials. Of course, it is unlikely that a polynomial model will be a reasonable approximation of the true functional relationship over the entire space of the independent variables, but for a relatively small region they usually work quite well.

The experiments are being conducted based on central composite design of experiments for non-linear modeling of FSW of aluminum alloys (AL7075). It is important to note that two different tool materials, such as H13 and HSS are used for the said purpose. Moreover, three replicates are considered for each combination of the input variables. Once the model is developed, the effect of individual parameters and their interaction terms are examined by conducting a significance test. MINITAB software is used for the said purpose. Further, the prediction accuracy of the models has been tested by passing fifteen experimental test cases selected at random.

3. Results and Discussion

Regression models have been developed for FSW of aluminum alloy using H13 and HSS tools. The results of these models are presented in the sub-sequent sub-sections.

FSW of AL 7075 using H13 Tool

The nonlinear regression equations that represent the relationship between the responses F_x, F_z and H_f in terms of input variables for H13 tool are given in Equations 3, 4 and 5, respectively.

$$F_x = 0.939483 + 0.00857282xS + 0.0322629xF – 2.95911xD – 0.000012404xS^2 – 0.0000478387xF^2 + 14.0404xD^2 + 0.0000167323xSxF – 0.00372222xSxD – 0.00190289xFxD \quad (3)$$

$$F_z = 41.0859 - 0.0434835xS + 0.200935xF - 65.6807xD - 0.00000148485xS^2 - 0.000431112xF^2 + 33.404xD^2 + 0.000139633xSxF + 0.110056xSxD - 0.224016xFxD \quad (4)$$

$$H_f = 126.875 + 0.165724xS + 0.0602858xF - 56.2729xD - 0.00017491xS^2 - 0.000156xF^2 + 14.3369xD^2 + 0.00001397xSxF + 0.153763xSxD - 0.0325967xFxD \quad (5)$$

Table 2 shows the results of ANOVA performed for testing the significance of the factors on F_x. The term 'DF' in Table 2 represents the degree of freedom that indicates the number of terms that will contribute to the error in prediction. Moreover, the terms 'Seq. SS' and 'Adj. SS' gives the sum of squares for each term and sum of squares after removing the insignificant terms, respectively. Similarly, the 'Adj. MS' is the mean square obtained after removing the insignificant terms from the response. The 'F' value of regression is used to test the hypothesis.

It is important to note that all the terms are found to be significant on F_x as the value of 'P' is found to be less than 0.05. Moreover, the coefficient of correlation for this model is seen to be equal to 0.953. The results indicate that the developed non-linear regression model based on central composite design is statistically adequate for making predictions. Similar tests are performed for other responses, such as F_z and H_f. It is interesting to note that all the terms are having significant contribution on the responses.

Source	DF	Seq SS	Adj. SS	Adj. MS	F	P
Regression	9	2260.90	2260.90	251.211	134.89	0.000
Linear	3	1795.08	1795.08	598.360	321.28	0.000
Square	3	214.47	214.47	71.489	38.39	0.000
Interaction	3	251.35	251.35	83.784	44.99	0.000
Residual error	10	18.62	18.62	1.862		
Lack-of-fit	5	18.62	18.62	3.725		
Pure error	5	0.00	0.00	0.000		
Total	19	2279.52				

Table 2. Results of ANOVA for the response – Fx

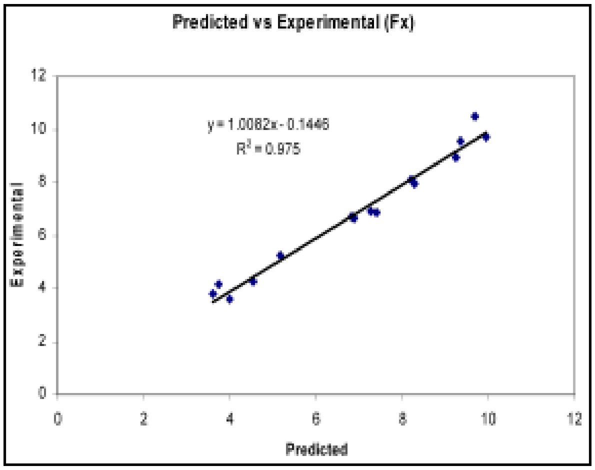
The prediction accuracy of the developed models can be determined by conducting conformity tests. In this procedure fifteen test cases are generated at random by assigning intermediate values to the process variables and for each combination the outputs are determined experimentally. The results are presented and discussed below. Figures 3 (a), (b) and (c) shows the comparison of the predicted outputs with their respective target values of FSW using H13 tool for F_x, F_z and H, respectively. The predicted response is taken along x-axis and the experimentally determined response is considered along the y-axis. The close fitness of values between experimental and predicted had shown the adequacy of the model.

FSW of AL 7075 using HSS Tool

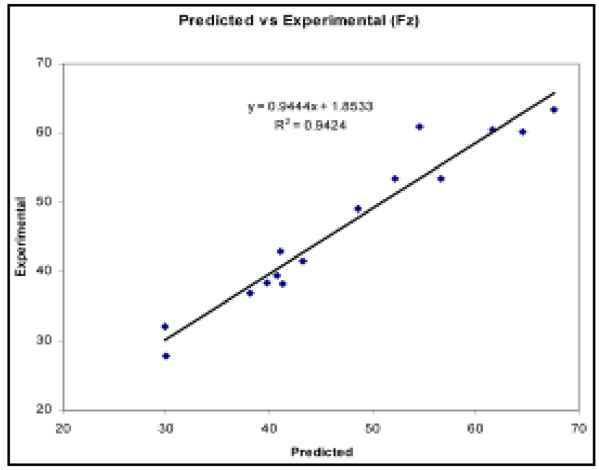
Similar type of study as mentioned earlier, has been conducted to determine the nonlinear regression equations for F_x, F_z and H_f, respectively for the friction stir welding of aluminum alloys using HSS tool.

$$Fx = -0.466074 + 0.00932342xS + 0.0114343xF - 3.04013xD - 0.0000130303xS^2 -0.0000113573xF^2 + 19.8586xD^2 + 0.00000564304xSxF - 0.00488889xSxD + 0.000131234xFxD \quad (6)$$

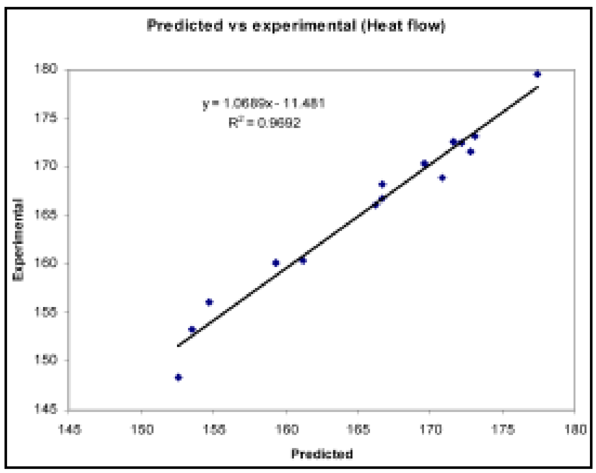
$$Fz = 28.6791 - 0.0261423xS + 0.139497xF - 48.8188xD - 0.00000765657xS^2 -0.000362532xF^2 -25.8788xD^2 + 0.000109318xSxF + 0.0845556xSxD - 0.0707349*F*D \quad (7)$$



(a) Plot for prediction of F_x



(b) Plot for prediction of F_z



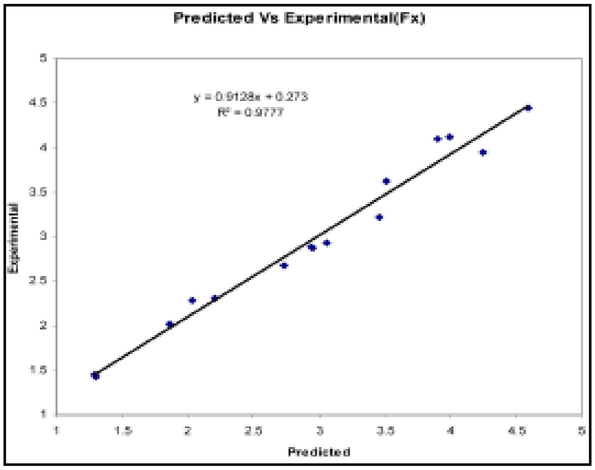
(c) Plot for prediction of H_f

Figure 3. Scatter plots for prediction of responses for H13 tool steel

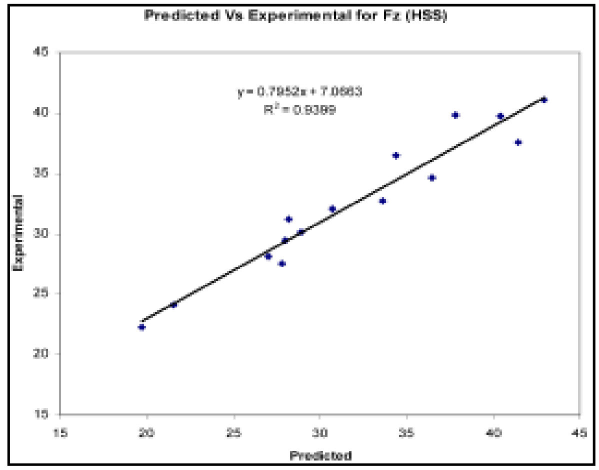
$$H_f = 154.974 + 0.202554xS + 0.0589808xF - 62.2329xD - 0.000239293xS^2 - 0.0000873638xF^2 + 9.81818xD^2 - 0.0000453412xSxF + 0.152611xSxD + 0.000590551xFxD \quad (8)$$

Here also, ANOVA test has been performed to test the significance of the input process parameters on the responses, such as F_x, F_z and H_f. The 'P' values are coming out to be less than 0.05, which indicates the significance of all the parameters on the responses. Moreover, the coefficient of correlation for this model is seen to be equal to 0.975. Thus, the developed models will be suitable for predicting the responses for the input parameters set within their limits.

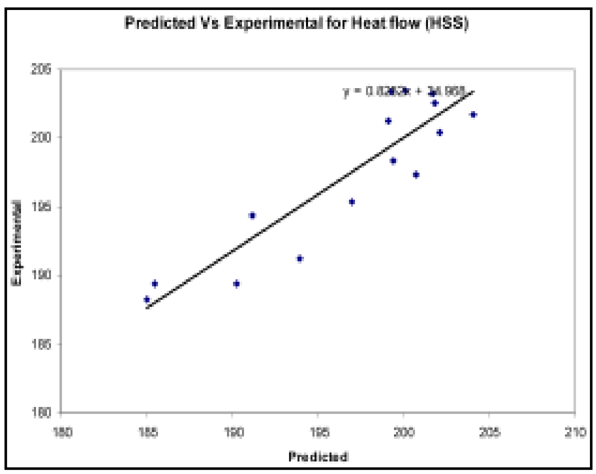
The scatter plots are drawn between experimental and predicted values for the FSW of aluminum alloys using HSS tool material. Figures 4 (a), (b) and (c) shows the scatter plots of the predicted outputs with their respective target values. It can be observed that the predictions are very close to the experimental results. It is to be noted that the FSW of Al7075 with H13 tool steel produces less heat. As a result of less heat the forces coming on the tool will be more, where as HSS produces more heat and the forces coming on to the tool is less. It is interesting to note that HSS is a better tool material for FSW of high meting point alloys, as the heat generated is more, which leads to lesser amount of forces coming on the tool. It is observed that the influence of feed rate is more on weld force along Fx compared to shoulder depth and spindle speed. It is also observed that the effect of shoulder depth is more significant on weld force along Fz compared to two other process parameters (Spindle speed and feed rate).



(a) Plot for prediction of F_x



(b) Plot for prediction of F_z



(c) Plot for prediction of H_f

Figure 4. Scatter plots for prediction of responses for HSS tool

Moreover, as the spindle speed increased, it is noticed that heat flow to the tool is increased and influence of spindle speed is more on heat flow compared to feed rate and shoulder depth.

4. Conclusions

The present paper deals with the modeling of FSW process of aluminum alloys, after considering two different tool materials, namely H13 and HSS. The influence of various process parameters, such as spindle speed, feed rate and shoulder depth on feed force, downward force and heat flow rate has been studied with the help of response surface methodology after conducting the experiments using central composite design. Moreover, ANOVA test has also been conducted to study the effect of various parameters on the responses, such as Fx, Fz and Hf. Further a comparison is being made among the two tool materials used in this study. It is observed that H13 tool has produced less heat when compared with HSS tool. Therefore, HSS tool is a better option for welding high melting point alloys. It is also interesting to determine the optimal values of these parameters that are responsible for the better performance of the FSW process using non-traditional optimization algorithms, such as genetic algorithms, particle swarm optimization etc., which can be considered in the future scope of the work.

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