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Empirical Modelling and Optimization of Friction Stir Welding Process Parameters Using Multiple Regression Method and Genetic Algorithm

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Abstract

Genetic algorithm has been proven as one of the most popular optimization techniques. In this study genetic algorithm has used to optimize the process parameters. Aim of the present study was to develop empirical model for predicting ultimate tensile strength and hardness in terms of spindle speed and welding speed using multiple (linear and nonlinear) regressions modelling method. Experiments were carried out on conventional milling machine by taking Al alloy HE 9 and HE 30 as work piece material and HCH Cr as tool. Finally, genetic algorithm has been employed to find out the optimal setting of process parameters that optimize ultimate tensile strength and hardness.MATLAB coding was used to develop the nonlinear model. And MATLAB optimization tool box was used to optimize the process parameter. It was found that the actual value of ultimate tensile strength is higher at spindle speed of 1000 rpm and welding speed of 16 mm/min. The hardness value which is calculated in terms of BHN is higher at spindle speed of 2000 rpm and welding speed of 25 mm/min.

Keywords: Genetic algorithm, Analysis of variance, Taguchi approach, Aluminium alloy.

Introduction
Optimization is an iterative process of finding the optimal parameters without violating the set constraints. Friction stir welding process operation in general can also be optimized by obtaining optimal values for parameters such as tool rotational speed, axial force, traverse speed, tool dimension and other such parameters. Several optimization techniques could be applied to optimize FSW models. However, as the FSW is relatively new technology, there have been only a few attempts to use mathematical optimization techniques to optimize the process. Some of the mathematical optimization techniques applied to FSW have been summarized in the following paragraphs. The effect of rotational and welding speed on tensile strength and fatigue strength of Al 6056 joints made by FSW. The influence of process parameters on the weld quality was assessed by analysis of variance methods using the experimental results. A complete two factor factorial experiment, with three replicates was performed by the authors. Menget al. [1] used a multi-targeted optimization with constraint based on genetic algorithm for optimization of stir head dimensions. The objective function employed was an analytically derived mathematical model relating heat input coefficient with tool parameters. The goal of optimization was to determine the shoulder diameter and pin diameter of the stirring tool for maximizing the tensile strength of the friction stir welds of aluminum-lithium alloy. In addition to design of experiment techniques, some evolutionary algorithms were utilized for optimization of FSW. Fratini and corona [2] investigated FSW lap joint resistance optimization using gradient techniques. They combined the gradient technique and the finite difference method to determine the optimal rotating speed and welding speed in order to maximize the joint strength per unit length. Nandanet al. [3] used genetic algorithm to determine four process parameters by minimizing the difference between the numerical model and experiments. The process parameters included variable friction coefficient, the extent of sticking, the heat transfer coefficient, and the extent of viscous dissipation converted into heat. These selected parameters were optimized by a genetic algorithm using a limited volume of measured temperatures at several monitoring locations during FSW of dissimilar aluminium alloys Al 1200 and Al 6061. Use of artificial neural network was proposed by okuyucuet al. [4] to obtain correlation between FSW parameters and mechanical properties of aluminium plates. Their attempt was to correlate the parameters rather than to optimize them. The input parameters were weld speed and tool rotational speed while the output parameters included mechanical properties such as tensile strength, elongation, hardness of weld metal and hardness of heat affected zone. The obtained model was used to calculate mechanical properties of welded al plates as a function of weld speed and rotational speed. The conventional parametric design of experimental approach is cumbersome and requires large number of experimental trials. Statistical techniques are often used to reduce the number of experiments conducted. Lakshminarayananet al. [5] used one such statistical technique known as

Taguchi's technique to determine the effect of three process parameters, i.e. tool rotational speed, traverse speed, and axial force on the tensile strength of friction stir welded rde-40 aluminum alloy. Jayaramanet al. [6] used a similar technique to find the effect of three process parameters on the tensile strength of friction stir welded A319 aluminium alloy. In both these studies, the authors performed analysis of variance to identify statistically significant process parameters.Hence, the aim of the present study is to develop empirical model for predicting ultimate tensile strength and hardness in terms of spindle speed and welding speed using multiple regressions modelling method and optimize the process parameters for maximizing ultimate tensile strength and hardness using genetic algorithm.

Material and Methods

In this investigation, aluminium alloy sheets of dissimilar material were welded. Workpiece materials considered for the study are HE 30 and HE 9 Al alloy. The sheet was cut to required size (175mm x 125mm x 6mm) by power hacksaw cutting and followed by grinding to remove the burr. The surfaces of both sheets were cleaned with acetone before the welding process. A conventional milling machine was used as friction stir welding machine (figure 1).Butt joint configuration was used to fabricate the friction stir welds. The joint was initially obtained by securing the plates in position using mechanical clamps. That is clamped on the backing plate which was bolted directly to the bed of the milling machine. The welding speeds and the rotational speeds were achieved manually by setting on machine. The rotational speeds of spindle were 1000 rpm, 1400 rpm and 2000 rpm and feed rates at 16mm/min, 20mm/min and 25 mm/min were chosen to represent low, medium and high settings respectively.A non-consumable tool made of high carbon high chromium (D2) was used to fabricate the joints. Welding tool with shoulder diameters of 18mm and tapered shank were used (figure 2).

Figure 1: FSW Experimental Setup

For the purpose of minimizing the experimental work, a simple and adequate experimental design named Taguchi's method is used. Experiments were designed using Taguchi's L_9 orthogonal array. Table 1 shows the process parameters and their levels and figure 3 shows the workpiece after friction stir welding.

Figure 2: FSW Tool High Carbon High Chromium Grade D2

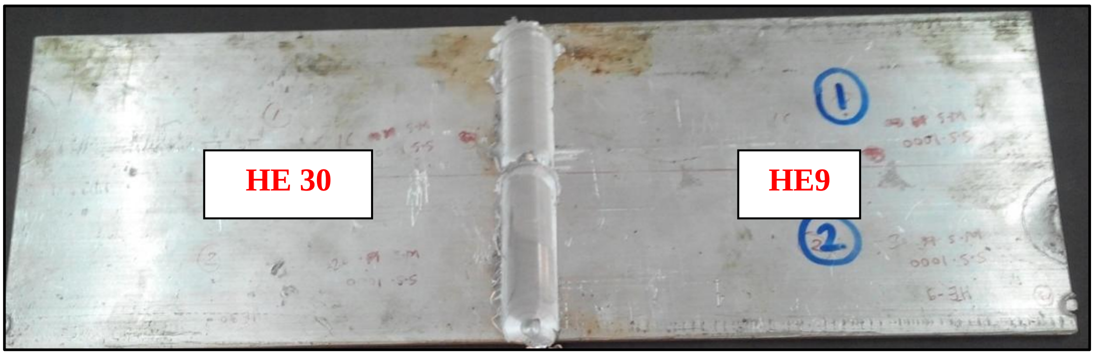

Figure 3: FSW of Aluminiumalloy HE30 and HE9

Table 1: FSW process parameters with its levels

Sr. No.	Factors	Notation	Units	Variable / Levels		
1	Rotational speed	N	rpm	1000	1400	2000
2	Welding speed	V	mm/min	16	20	25
3	Shoulder diameter	D	mm	18		
4	Plate thickness	T	mm	6		
5	Pin diameter	D	mm	6.5		
6	Pin height	H	mm	5.5		

The philosophy of Taguchi's method is to minimize the variations in product or systems characteristics. To determine the effect of each variable on the output, the signal-to-noise ratios are calculated for each experimental trial [8, 9]. For thisstudy the quality characteristic is to maximizeand the signal-to-noise is calculated using equations 1.

$$S/N_i = -10Log_{10}\left[\frac{1}{n}\sum_{j=1}^{n}\frac{1}{y^2}\right] \quad (1)$$

where, i = experiment number, j = trial number, y = observed value, n = number of trials for experiment i [8,9].

Results and Discussions

In order to develop the empirical modelsin terms of FSW process parameters forultimate tensile strength and hardness, experiments were conducted using L_9 orthogonal array as shown in table 2. Linear multiple regression modelling was carried out using MINITAB 16 statistical software. Also a nonlinear multiple regression modelling was developed by using MATLAB program.

Table 2: Taguchi Experimental Design With Observed Values

Spindle speed (rpm)	**Welding speed (mm/min)**	**Ultimate Tensile Strength (MPa)**	**Hardness (BHN)**
1000	16	58.74	67.85
1000	20	63.96	68.79
1000	25	59.65	70.98
1400	16	60.65	69.1
1400	20	59.2	69.98
1400	25	55.46	71.83
2000	16	50.39	70.95
2000	20	52.61	72.56
2000	25	48.65	74.1

Regression analysis has been performed to find out the relationship between input factors and UTS and BHN. During regression analysis it was assumed that the factors and the response are linearly related to each other. The general first order model was developed to predict UTS and BHN over the experimental region can be expressed as equation 2 and 3 respectively.

UTS= 76.951 - 0.0104632*Spindle speed - 0.246639*Welding speed (2)

BHN = 58.9356 + 0.00336096*Spindle speed + 0.335273*Welding speed (3)

Nonlinear regression analysis is based on determining the values of the parameters that minimize the sum of the squares of the residuals. However, for the nonlinear case, the solution must proceed in an iterative fashion. Optimization techniques can be used directly to determine the least squares fit. Equation 4 and 5 shows the nonlinear equation based on least square method obtained based on MATLAB coding [10].

$$UTS = 499.34 * SS^{-0.26711} * WS^{-0.0815} \quad (4)$$

$$BHN = 32.449 * SS^{0.068028} * WS^{0.095071} \quad (5)$$

Table 3: Response values based one experiments and linear regression model

Sr. No	Expt. UTSMPa	Expt. BHN	Linear UTS MPa	Linear BHN	% error for UTS	% error for BHN
1	58.74	67.85	66.24	62.63	12.77	7.69
2	63.96	68.79	66.24	62.63	3.56	8.95
3	59.65	70.98	66.24	62.63	11.04	11.76
4	60.65	69.1	62.05	63.97	2.31	7.41
5	59.2	69.98	62.05	63.97	4.82	8.57
6	55.46	71.83	62.05	63.97	11.89	10.93
7	50.39	70.95	55.77	65.99	10.69	6.98
8	52.61	72.56	55.77	65.99	6.02	9.05
9	48.65	74.1	55.77	65.99	14.65	10.94

Table 4: Response values based one experiments and non-linear regression model

Sr. No	Expt. UTSMPa	Expt. BHN	Nonlinear (UTS)	Nonlinear(BHN)	% error for UTS	% error for BHN
1	58.74	67.85	62.92	67.57	7.127	0.410
2	63.96	68.79	61.79	69.02	3.390	0.334
3	59.65	70.98	60.67	70.49	1.720	0.676
4	60.65	69.1	57.51	69.13	5.164	0.051
5	59.2	69.98	56.48	70.61	4.594	0.911
6	55.46	71.83	55.46	72.13	0.002	0.420
7	50.39	70.95	52.29	70.83	3.772	0.163
8	52.61	72.56	51.34	72.35	2.399	0.285
9	48.65	74.1	50.42	73.90	3.640	0.264

Table 3 and 4 shows response values for ultimate tensile strength and hardness values based on experiments, linear and nonlinear models. It can be seen that nonlinear model can predict the responses with lesser percentage error.

Single optimization of Ultimate tensile strength

The developed mathematical model from Regression method was used for maximization of ultimate tensile strength in friction stir welding of aluminium alloys

HE 9 and HE 30. The developed mathematical model was converted into a MATLAB (R2009a) function. This function was input to the GA Toolbox of MATLAB 2009a as the objective function. Upper and lower bounds were specified as per the levels of the machining parameters and the number of variables was set at 2. The population type was set to double vector, population size of 20 and a generation of 100 was used for the analysis. Constraint dependent creation function and scattered type of cross over function were used for the analysis. Crossover fraction was set at 0.9 and mutation fraction was set at 0.1. Multiple runs of the algorithm were carried out at different settings of the available options of GA Toolbox to fine tune the maximum response value. The best response is shown in figure 4 and 5. The best response value for ultimate tensile strength obtained from GA was 62.5416MPa with spindle speed of 1000 rpm and welding speed of 16 mm.

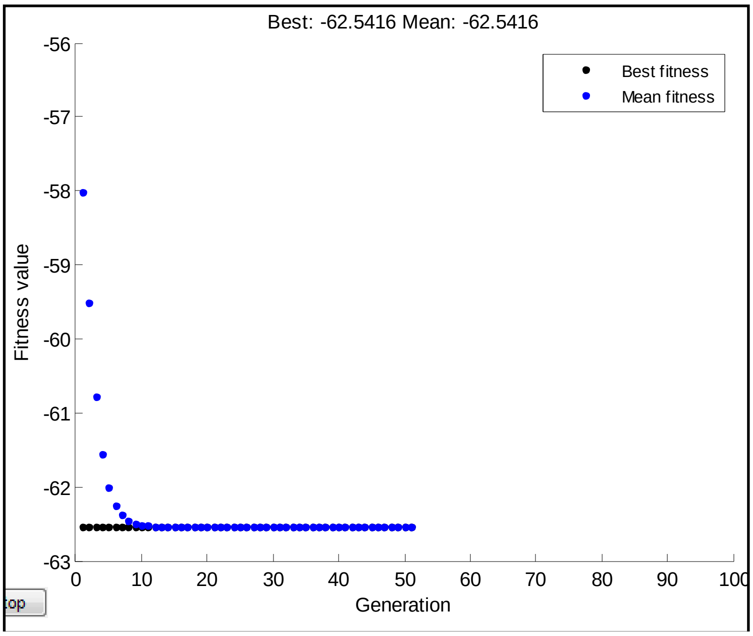

Figure 4: Best value for ultimate tensile strength for linear model

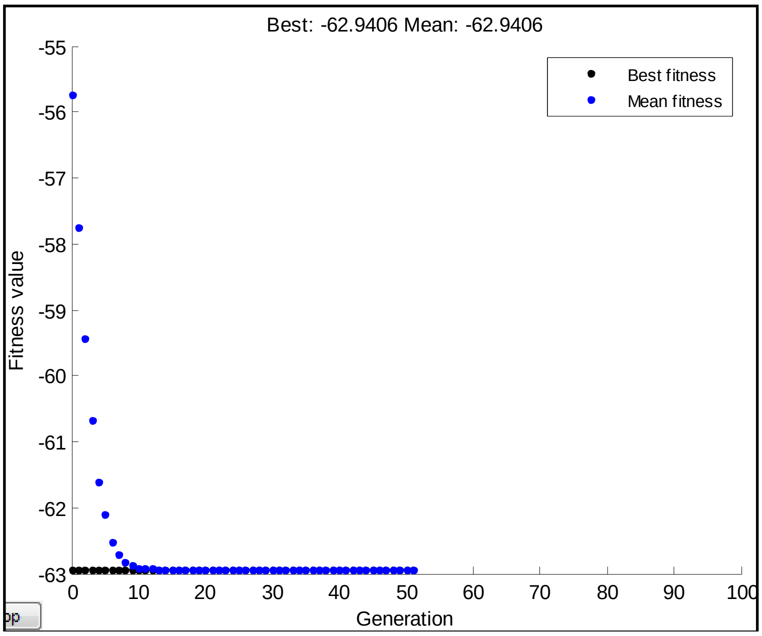

Figure 5: Best Value For Ultimate Tensile Strength For Nonlinear Model

Single optimization of Hardness (BHN)

The developed mathematical model from Regression method was used for maximization of hardness in friction stir welding of aluminium alloys HE 9 and HE 30. The developed mathematical model was converted into a MATLAB (R2009a) function. This function was input to the GA Toolbox of MATLAB 2009a as the objective function. Upper and lower bounds were specified as per the levels of the machining parameters and the number of variables was set at 2. The population type was set to double vector, population size of 20 and a generation of 100 was used for the analysis. Constraint dependent creation function and scattered type of cross over function were used for the analysis. Crossover fraction was set at 0.9 and mutation fraction was set at 0.1. Multiple runs of the algorithm were carried out at different settings of the available options of GA Toolbox to fine tune the maximum response value. The best response is shown in figure 6 and 7. The best response value for hardness obtained from GA was 74.0393 BHN with spindle speed of 2000 rpm and welding speed of 25 mm.

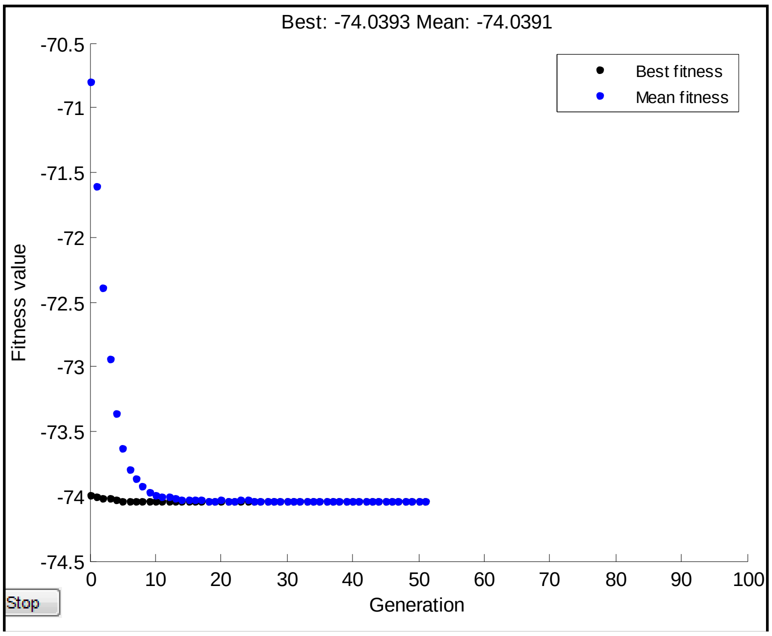

Figure 6: Best value for hardness for linear model

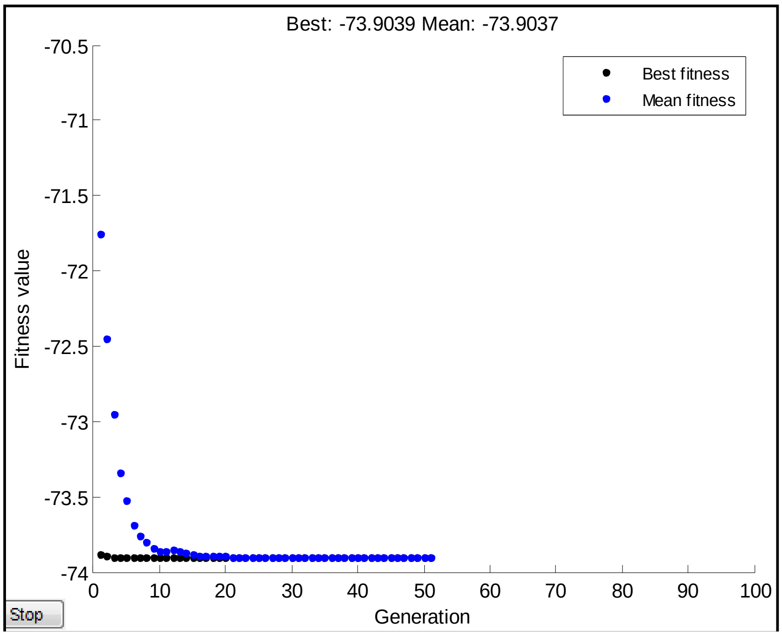

Figure 7: Best value for hardness for nonlinear model

Conclusions

Present study emphasis on investigating the optimal set of process parameters for maximizing ultimate tensile strength and hardness during friction stir welding of HE 30 and HE 9 aluminium alloy. Based on the experimental results and statistical analysis it was found that spindle speed and welding speed are significant process parameters that influence ultimate tensile strength and hardness. It was found that the actual value of ultimate tensile strength is higher at spindle speed of 1000 rpm and welding speed of 16 mm/min. The hardness value which is calculated in terms of BHN is higher at spindle speed of 2000 rpm and welding speed of 25 mm/min. Based on the experimental results it can be concluded that genetic algorithm helps to find out optimal setting of process parameters.

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