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Developing a Mathematical Model to Predict the Optimum Friction Phase Parameters for Friction Welding of High Speed Steel to Medium Carbon Steel

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ABSTRACT

This work was carried out in order to optimize the friction phase parameters, of friction welding of M2 high speed steel, to AISI 1040 medium carbon steel, namely; rotational speed, friction pressure and friction time. The experiments were designed as per Taguchi method. The optimization of the experimentally obtained results was carried out by trying three mathematical models, namely; a multiple linear regression model without interaction effect, a multiple linear regression model with interactions effect, and a second-order polynomial regression model. The three models were evaluated using the experimental data, the coefficient of multiple determination R^2, and Standard error of the regression (S), were used as the evaluation criteria of the models. The polynomial model was chosen, and optimized using a Genetic Algorithm. The optimal value of the joint strength of 411 MPa was obtained at the highest value of the time (44.9 sec.) and the pressure of 112 MPs and the speed of 1349 r.p.m.

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Introduction

High-speed steel HSS is one of the main tool materials. In order to save expensive steel, the cutting tool is produced as bimetallic: the working part is produced from the HSS steel, the tail part is produced from a medium carbon steel . The joints between the working and tail parts are produced by friction welding which is the most productive and economically efficient process. However, this method of joining components is associated with a number of difficulties reducing the strength of the welded joint. In particular, this is associated with the presence of defects in the form of shiny slip bands on the side of the high-speed steel and a ferritic interlayer on the side of structural steel[1]. In conventional friction welding, the main parameters of the welding conditions are the speed of rotation, the extension of the components, the welding allowance, welding time, heating and forging force and time. In his work titled " An Experimental Investigations On Friction Welding Of Dissimilar Metals" A.B Abdelsalam et.al [2] used a modified lathe machine as a direct drive friction welding machine to weld specimens of high speed steel, to medium carbon steel. The specimens were welded at different friction pressures, and different friction times, then heat treated. All the specimens were subjected to tensile tests. The study revealed that, a satisfactory joint efficiency was obtained by welding of high speed steel to carbon steel, the joint efficiency came to be about 47%. This work is aimed at developing a mathematical model for results obtained experimentally, then optimizing this model in order to find the optimum friction phase parameters that maximize the tensile strength.

Experimental Work:

Friction welding was carried out to joint M2 high speed steel and AISI 1040 carbon steel. Friction phase is affected by three factors (parameters): rotational speed, friction pressure and friction time. The three factors were chosen at three levels as shown in Table (1). The experiment was designed to investigate the achievement of the optimal strength of the joint (Y) .The experiment was designed, based on Taguchi method [3] with 3 replications. The design and the results are shown in Table (2).The experiments were carried out by modified lathe machine to work as continuous friction welding machine. Samples were welded at constant forging pressure 187 M Pa and 15 second forging time . The samples were heat treated (tempered and annealed), Group of samples consisted of 27 pieces, selected from each welding group, were non-destructively tested with x-ray for checking welding defect. Tensile tests were carried out and the results were tabulated in Table (3).

Table 1. Factors and their levels and values

Factors	code	Levels			Unit
		1	2	3	
Rotational Speed	X1	1000	1400	2000	Rpm
Friction Time	X2	25	35	45	Second
Friction Pressure	X3	62.5	87.5	112.5	M Pa

The mathematical model

A regression model was developed in order to relate the welding responses to the parameters and thereby to facilitate the optimization of the friction welding process. With these mathematical models, the objective function and process constraints can be formulated, and the optimization problem can then be solved by using Evolutionary Algorithms. The linear models can be expressed as follows: [4].

1- Model 1: Without interaction effect the multiple linear regression models is:

$$Y(X_1, X_2, X_3) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon$$

2- Model 2: With interaction effect the multiple linear regression models is:

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Table 2. The design and the results of the experiments

	X1	X2	X3	Ultimate Tensile Strength (MPa)		
				Y1	Y2	Y3
1	1000	25	62.5	338.232	298.44	298.44
2	1000	25	87.5	109.428*	363.102	89.532*
3	1000	25	112.5	258.648	258.648	363.102
4	1000	35	62.5	288.492	288.492	258.648
5	1000	35	87.5	258.648	174.09	218.856
6	1000	35	112.5	348.18	353.154	323.31
7	1000	45	62.5	238.752	139.272*	248.7
8	1000	45	87.5	407.868	149.22*	437.712
9	1000	45	112.5	397.92	417.816	343.206
10	1400	25	62.5	248.7	298.44	253.674
11	1400	25	87.5	358.128	353.154	313.362
12	1400	25	112.5	189.012*	-	338.232
13	1400	35	62.5	328.284	397.92	358.128
14	1400	35	87.5	64.662*	149.22	238.752
15	1400	35	112.5	333.258	397.92	104.454*
16	1400	45	62.5	363.102	338.232	358.128
17	1400	45	87.5	407.868	492.426	502.374
18	1400	45	112.5	437.712	397.92	432.738
19	2000	25	62.5	189.012	174.09	109.428
20	2000	25	87.5	338.232	353.154	308.388
21	2000	25	112.5	253.674	368.076	293.466
22	2000	35	62.5	248.7	338.232	392.946
23	2000	35	87.5	213.882	139.272*	338.232
24	2000	35	112.5	382.998	338.232	353.154
25	2000	45	62.5	397.92	378.024	333.258
26	2000	45	87.5	363.102	373.05	437.712
27	2000	45	112.5	348.18	338.232	-

$$Y(X_1, X_2, X_3)=\beta_0+\beta_1 X_1+\beta_2 X_2+\beta_3 X_3+\beta_{12} X_1X_2+\beta_{13} X_1 X_3+\beta_{23} X_2X_2+\beta_{123} X_1X_2X_3+\varepsilon$$

3- Model 3:The polynomial regression second-order mean function is given by

$$Y(X_1, X_2, X_3)=\beta_0+\beta_1 X_1+\beta_2 X_2+\beta_3 X_3+\beta_{12} X_1X_2+\beta_{13} X_1 X_3+\beta_{23} X_2X_3+\beta_{123} X_1X_2X_3+\beta_{11} X_1^{2}+\beta_{22} X_2^{2}+\beta_{33} X_3^{2}+\varepsilon$$

Where:

β_i = coefficients, and obtained by means of LEAST SQUARE

ε= Residual or Error, and is the difference between the fitted value and the predicted value

ANOVA: The general ANOVA of regression is shown in

Table 3. Analysis of Variance for Testing Significance of Regression in Multiple Regression

Source of variation	Sum of Squares	Degree of Freedom	Mean Square	F_0
Regression	SS_R	K	MS_R	MS_R/MS_E
Error or residual	SS_E	n-p	MS_E	
Total	SS_T	n-1		

Regression Model testing:

Test for Significance of Regression

The appropriate hypotheses are

$$H_0: \beta_1=\beta_2=\cdots=\beta_k=0$$
$$H_1: \beta_j \neq 0 \quad \text{for at least one } j \qquad (12\text{-}17)$$

The three models were evaluated using the experimental data of table (2), the coefficient of multiple determination R2, and Standard error of the regression (S), was computed for each model using Minitab 16.1 software, the results is shown in table (4). The polynomial model (model3) was chosen since it has the largest value of R^2 ans the least value of S, compared to model1 and model2.

Table 4. S, R^2, and R^2 (adj.) for the three models

Model number	S	R^2	R^2 (adj.)
Model1	62.6655	35.5%	21.4%
Model2	61.8514	44.0%	23.3%
Model3	60.720	54.6%	26.2%

Using Minitab 16.1 software, to model the experimental data of table (2), the polynomial regression second-order equation is:

Y = 1790 - 0.767 x1 - 69.5 x2 - 12.5 x3 + 0.0324 x1x2 + 0.0114 x1x3 + 0.481 x2x3- 0.000331 x1x2x3 - 0.000117 x1x1 + 0.374 x2x2 - 0.0169 x3x3

Table 5. ANOVA results of friction welding process parameters of the model3

Predictor	Coef	SE Coef	T	P
Constant	1790.1	958.1	1.87	0.080
x1	-0.7671	0.6347	-1.21	0.244
x2	-69.49	29.09	- 2.39	0.030
x3	-12.49	11.64	-1.07	0.299
x1x2	0.03244	0.01533	2.12	0.050
x1x3	0.011383	0.006132	1.86	0.082
x2x3	0.4807	0.2599	1.85	0.083
x1x2x3	-0.0003312	0.0001706	-1.94	0.070
x1x1	-0.0001166	0.0001040	-1.12	0.279
x2x2	0.3740	0.2479	1.51	0.151
x3x3	-0.01687	0.03966	-0.43	0.676

Table 6. Analysis of Variance for Testing Significance of Regression for Model3

Source	DF	SS	MS	F	P
Regression	10	70877	7088	1.92	0.118
Residual Error	16	58991	3687		
Total	26	129868			

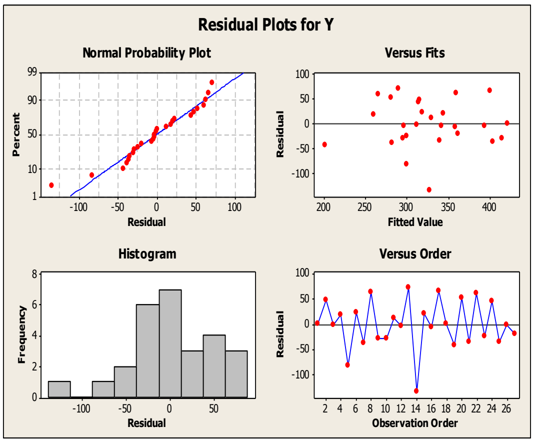


Fig 6. Graph of Residual Plots for Tensile Strength for the Model

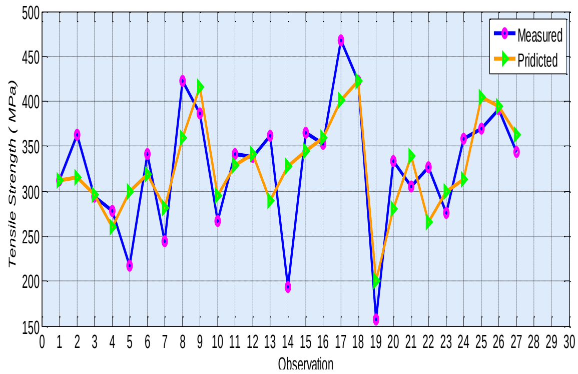


Fig 1. Graph of Measured and Predicted vs. Observation for the Model

Optimization:

The Basic Optimization Problem

- A fitness (objective) function F must be derived in terms of *n* parameter, that influence the response $x_1, x_2, \ldots, x_n$ as : [5]

$$F = f(x_1, x_2, \ldots, x_n)$$

- The most basic optimization problem is to adjust variables $x_1, x_2 \ldots, x_n$ in such a way as to minimize quantity *F*. This problem can be stated mathematically as

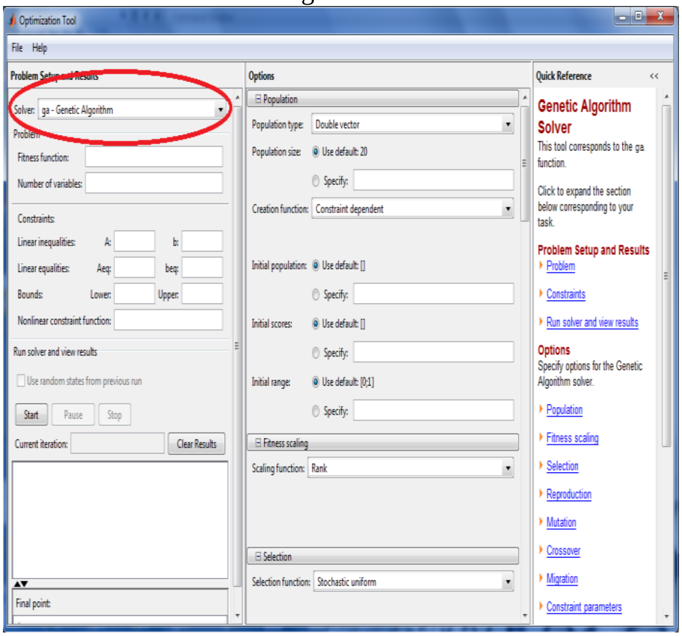
$$\text{Minimize } F = f(, x_1, x_2, \ldots, x_n)$$

- For finding the maximum of the objective function.

$$\text{Max } [f(\mathbf{x})] = -\min [-f(\mathbf{x})]$$

Many algorithms are used for optimization, in this research Genetic Algorithm was adapted to find the optimum parameters that maximize the tensile strength of the polynomial model. For the genetic algorithms, the chromosomes represent set of genes, which code the independent variables. Every chromosome represents a solution of the given problem. A set of different chromosomes (individuals) forms a generation by means of evolutionary operators, like selection, recombination and mutation an offspring population [6].

Genetic Algorithm Toolbox: Genetic algorithm has been implemented as a Matlab Toolbox, i.e. a group of related functions, named GAOT. The basic function is the ga function, which runs the simulated evolution .The command used in matlab command window is gatool



Optimization Procedure:

Optimization (maximization) of the tensile strength and determination of the process parameters were performed by Matlab genetic algorithm toolbox. The obtained mathematical model was used as the fitness function. The boundary values for process parameters are the following: speed (x1) between 1000 and 2000, time (x2) between 25and 50 and friction pressure (x3) between 50 and 115. Optimal forming conditions for a maximal tensile strength were achieved for the following evolutionary parameters:

- ➢ Population size 100
- ➢ Selection operator stochastic uniform
- ➢ Crossover probability 0.8
- ➢ Mutation probability 0.2
- ➢ Fitness parameter Tensile strength

Optimization Result: The optimal condition values were obtained as following:

- ○ Objective function value = 411.3835469718085 MPa
- ○ Speed (x1) = 1349.6665351878491 rpm
- ○ Time (x2) = 44.94291192583553 second

Friction Pressure = 111.95643558295001 MPa

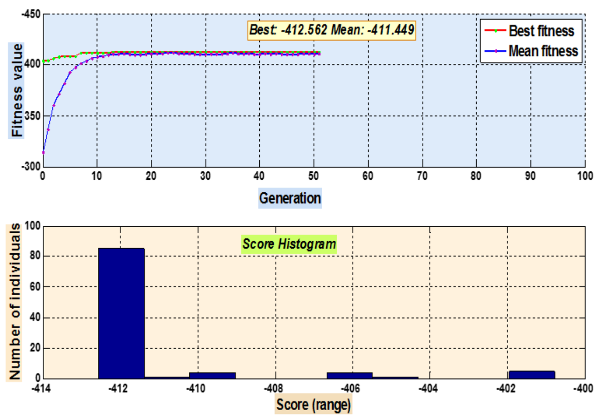


Figure 2. Optimized results in Genetic Algorithm

Discussion:

The p-value in the Analysis of Variance table (11) (0.118) shows that the model estimated by the regression procedure is significant at a-level of 010. This indicates that at least one coefficient is different from zero. The p-values for the estimated coefficients of X2, X1x2, X1X3, X2X3 and X1x2X3 are both, indicating that they are significantly related to the Joint Strength. The p-value for X3 and X1, indicating that they are not related to Joint Strength at a-level of 0.10. The R^2 value indicates that the predictors explain 54% of the variance in tensile strength. The adjusted R^2 is 26%, which accounts for the number of predictors in the model. Both values indicate that the model does not fit the data well. Observations 14, is identified as unusual because the absolute value of the standardized residuals are greater than 100. This may indicate they are outliers or experimental error. The histogram and the probability plot of the plot of the residual confirm this as shown by the bar on the far left side of the histogram of Fig. (6).

Conclusion

- Time has significant effect on the strength of the joint , Pressure has next effect on the joint and Speed has less effect
- To maximize the joint strength , the trend is to increase the time and pressure and hold the speed at specific value
- The model fitness of data could be improved if outliers were removed, e.g. if observations no. 14 was removed from the polynomial model, the value of $R^{2\ \text{would}}$ increase from 54% to 69%and S from 60.7 to 48.2.
- ANOVAs analysis show that x1 (the speed) has no significant effect on the model
- The polynomial model was used as a fitness function for the simulation
- The optimal value of the joint strength of 411 MPa was obtained at the highest value of the time (44.9 sec.) and the pressure of 112 MPs and the speed of 1349 r.p.m.

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