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Corrosionrate prediction model using Box-Cox transformation of friction stir processed Al-Si alloy

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Abstract.： In the present work ,the impact of friction stir processing (FSP) process parameters such as traverse feed rate, rotational speed and the type of pin profile tool (form and threaded cylindrical pin profiled tool geometry) on the pitting corrosion rate of A356 cast aluminum alloy was statistically investigated .Potentio dynamic polarization testing was conducted to determine the corrosion properties of the base alloy and the FSPed samples. It is found that, the most important parameter impacting pitting corrosion rate is the rotational speed, while the pin profile tool geometry has a second ranking parameter. The traverse feed rate has no statistical significant impact on corrosion rate .In addition to, the form tool pin profile produces a better pitting corrosion resistance of the stir zones compared to the threaded cylindrical pin profiled tool.Regression model was firstly used to develop the corrosion rate of FS processed A356 cast Al alloy .Then ,the plotting of residuals versus fitted values indicated a non-constant variance of this initial model, Box-Cox transformation was used to improve regression prediction model to the data and eliminate these drawbacks.

Keywords: Friction stir processing; Aluminium cast alloys; Corrosion;Box-cox transformation; ANOVA.

1. INTRODUCTION

Friction stir processing (FSP) is an extension of the friction stir welding (FSW) technique developed by TWI of United Kingdom in 1991. FSP is used to develop local and surface properties in chosen locations [1]. In the FSP process, a specially designed tool is rotated and immersed in the selected area of the metal plate, the tool consisting of pin and shoulder is traversed in the required direction until the desired area is processed [2]. In recent years, (FSP) has been recognized as a promising technique for improvement of the microstructure, mechanical properties and corrosion resistance of cast Al- Si alloys [3, 4]. A number of researchers [4-7] studied the effect of FSP on corrosion resistance and microstructure of aluminum alloys, They reported that the corrosion resistance of these alloys was improved by FSP due to significant microstructural refinement and eliminating porosity of the casting alloy.Presently, most studies have been addressed the effect of FSP/FSW parameters such as rotational speed and welding (transverse) speed on corrosion resistance of FSP and FSW zones [8- 11]. Limited number of studies has been carried out on the statistical analysis of FSP/FSW parameters. For example, Rambabu et al. [12] investigated the influence of welding parameters like tool pin profile, axial force, welding speed and rotational speed on the microstructure and corrosion resistance of friction-stir welded AA2219 aluminium alloy joints. They used response statistical tools and surface method to develop the mathematical model to predict the corrosion resistances of friction stir welded, to optimize the FSP parameters; the simulated annealing algorithm optimization approach was applied.

In this study, general full-factorial design method has been carried out to identify the significant parameters in FSP of cast Al-Si aluminum alloy in order to determine the optimal response values, in addition to defining the optimum level for all of these parameters, also, regression model have been developed to predict the corrosion rate.

The correlation between the control factors and responses are established by analysis of variance (ANOVA), interactions plot and main effect plot.

2 Experimental Procedure

2.1 Design of experiment

The statistical ANOVA is used to determine the significant and insignificant parameters that affects in the corrosion rate of the friction stir processed zones. Also, the relationship between selected process parameters and the response is examined by ANOVA.For this study, experiments with three factors, i.e., tool traversing speed, pin profile tool, and rotational speed in randomized order during conducting FSP. Three process parameters were accomplished for one replicate. The corrosion rate was the dependent variable for the set of experiments. The statistical analysis for the obtained results was studied by the Minitab 17 software. Friction stir processing (FSP) factors and their levels are listed in Table 1.

Table. 1. Process Parameters and their levels

Levels → Process parameter ↓	*Level* 1	*Level* 2	*Level* 3	*Level* 4	*Level* 5
Rotational speed (rpm)	**355**	**450**	**560**	**710**	**900**
traverse feed rate (mm/min)	**10**	**20**	**40**	------	------
Tool Pin Profile	**Threaded cylindrical (T)**	**Form tool (F)**	------	------	------

2.2 Fitting regression (prediction) model

In this investigation, the relationship between the response (corrosion rate) of friction stir processed zones for several combinations of the process parameters (rotational speed, tool traversing speed, and tool pin profile) was modeled by (polynomial) multiple quadratic regression in the traditional form offered in equation (1). The Minitab software has been used to create the suggested regression model.

$$\boldsymbol{CR} = \alpha_0 + \alpha_1 P_t + \alpha_2 S_r + \alpha_3 V_n + \alpha_4 P_t S_r + \alpha_5 P_t V_n + \alpha_6 S_r V_n + \alpha_7 P_t^2 + \alpha_8 S_r^2 + \alpha_9 V_n^2 \quad (1)$$

Where ***CR*** is the estimated of corrosion rate; α_1, α_2, … , α_9 are the coefficients which represent the change in ***CR*** that occurs when the factor increases by one unit and P_t, S_r, V_n are the tool pin profile, rotational speed, and tool traversing speed respectively.

The type of relationship between the response and independent factors was not known for represent an appropriate model, the relationship between ***CR*** and independent variables has been approximated appropriately, quadratic model was the most appropriate that produce higher value of R-Sq.

2.3 Details of experimentation

2.3.1 Materials and procedures

In the present investigation, A356 (Al-Si-Mg) cast Al alloy was selected as workpiece material. Plates having dimensions of [50 (width) × 300mm (length) × 10 mm (thickness)]. The chemical composition of the alloy is given in Table 2.The material was received as ingots.Friction stir processing was carried out on a vertical CNC milling machine in a single pass, using the threaded cylindrical pin profiled tool and form tool (F) with a pin length of 6 mm and shoulder diameter of 30 mm (Fig.1) In all experiments.

Table. 2. Chemical composition of A356 alloy (wt. %).

AL	Si	Fe	Cu	Mn	Mg	Zn
91.8	7.7	0.119	0.0007	0.0056	0.17	0.0042
Cr	Ni	Ti	V	Sn	Co	Pb
0.0011	0.0015	0.0886	0.0093	0.009	0.0091	0.0017

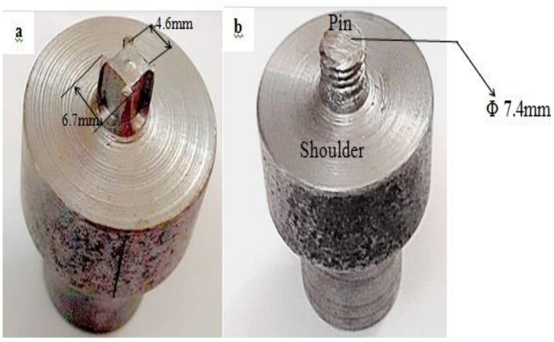

Fig.1.The tool dimensions of (a) the Form tool (F) and (b) the threaded cylindrical pin profiled tool used in this study.

2.3.2PotentiodynamicPolarization Measurements

The corrosion behavior was studied using potentio dynamic polarization techniques in FSP zones (stir zone) and as-received alloy. The corrosion experiments were accomplished using workstation Autolab PGSTAT 302 N – High-Performance potentiostat/galvanostat instrument with NOVA 1.10 software. All the experiments were carried out using a three conventional electrode cell; reference Ag/AgCl electrode, working electrode, platinum rod as a counter electrode, it is shown in Fig.2 , the samples were immersed to 3.5% NaCl solution at room temperature. Polarization measurements were carried out at potentials in the range from -1.5 V to 1.5 V (SCE) at scan rate of 2 mVs^{-1}. Tafel extrapolation was used to estimate resistance polarization (Rp) and corrosion rate by the cathodic and anodic polarization curves for the respective corrosion processes. Prior to the electrochemical tests, all exposed surfaces were wet-polished with using emery paper with a grit size of 1200 to achieve a mirror finish, degreased in acetone, Washed with twice distilled water, and then dried by dry air.

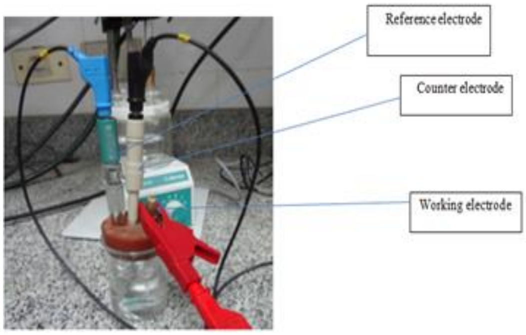

Fig.2.The electrochemical cell

3 Data analysis

3.1Analysis of variance (ANOVA) of corrosion rate

Table 3 shows the results of the ANOVA test for the corrosion rate of the FS processed samples. It has been assumed that the term interaction of the three factors does not exist. The sums of squares for three -factor interaction is accumulated and used to estimate an error.

Table.3. Analysis of Variance for the corrosion rate of SZ

Source	*DF*	*Adj SS*	*Adj MS*	*F-Value*	*P-Value*
Model	**21**	**600.294**	**28.585**	**5.29**	**0.010**
Linear	**7**	**349.412**	**49.916**	**9.23**	**0.003**
Tool profile	**1**	**58.151**	**58.151**	**10.75**	**0.011**
Feed (mm/min)	**2**	**5.363**	**2.682**	**0.50**	**0.627**
Rotational speed (rpm)	**4**	**285.898**	**71.474**	**13.22**	**0.001**
2-Way Interactions	**14**	**250.882**	**17.920**	**3.31**	**0.047**
Tool profile *Feed	**2**	**13.732**	**6.866**	**1.27**	**0.332**
Tool profile * rotational speed (rpm)	**4**	**202.884**	**50.721**	**9.38**	**0.004**
Feed* rotational speed (rpm)	**8**	**34.267**	**4.283**	**0.79**	**0.625**
Error	**8**	**43.268**	**5.408**		
Total	**29**	**643.562**			

Notes: S = 2.32561; R-Sq = 93.28%; R-Sq(adj) = 75.63%

It was concluded that both tool profile and rotational speed have statistically significant effect on the corrosion rate of the FS processed samples, because the P values for the two process parameters are less than 0.05. The p-value of 0.627 for the traverse feed rate is not less 0.05. Therefore, there is no significant effect. It was found that there is a significant interaction between tool pin profile and rotational speed ,ANOVA indicates that there is no statistically significant interaction between the pin profile and traverse feed rates or between rotational and traverse feed rates. Since R^2 is higher than 0.90, the model's capabilities are obvious.

Figure 3 shows general trends through creating plots of main effects for corrosion rate .It was shown that rotational speed has the highest significant effect on corrosion rate (highest slope) than the other factors and the influence of this parameter is directly proportional to corrosion rate responses .The pin profile (T) shows higher corrosion rate .It was concluded that corrosion rate was at minimum (optimal) when combination of rotational speed (350 rpm); traverse feed rate (20 mm/min); and pin profile (F). Figure 4 detects a real interaction between rotational speeds and pin profile. It was shown that there is no interaction between pin profile and traversing speeds or between rotational and traversing speeds, profile plot routes are crossed due to random variability. Figure 5 shows normal residual probability plot with roughly follow a straight line. This result examines the basic hypothesis applied in our test (residuals are normally distributed).

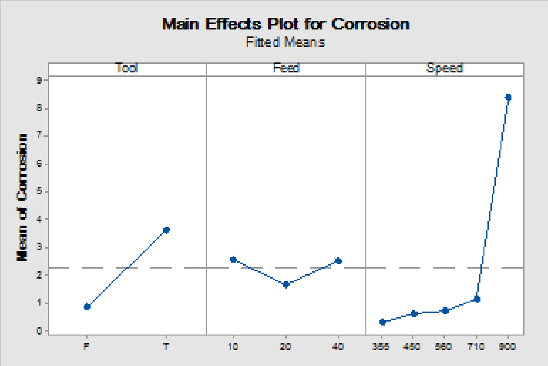

Fig. 3.Main affects plots for corrosion rateof SZ.

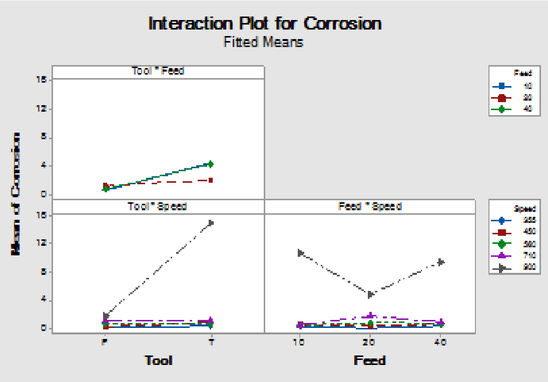

Fig. 4.Interactions plot for corrosion rateof SZ

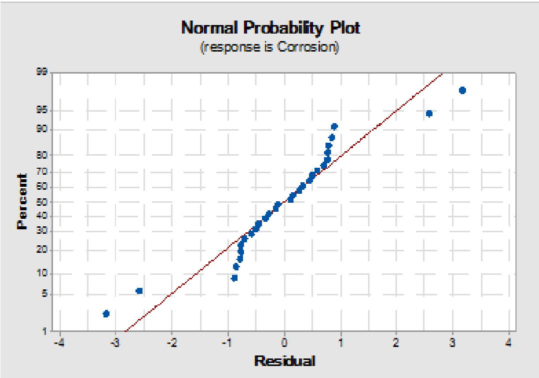

Fig. 5.Normal probability plot of the residuals for corrosion rate of SZ.

3.2 Fitting regression (prediction) model

The regression equation (2) for predicting was formulated by Minitab software which predict the average response of corrosion rate of the FS processed samples as a function of FSP processing factors (traverse feed rate, rotational speed, and tool profiles). Table 4 shows all input parameters of the FSP process used in the regression model and their transforming into coded form.

Corrosion rate of

$$NZ\ (\mu m/year) = -0.02 + 4.48\ P_t - 3.50\ V_n - 0.40\ S_r + 0.90\ V_n^{\,2} + 1.016\ S_r^{\,2} + 0.16\ P_t * V_n - 2.532\ P_t * S_r - 0.117\ V_n * S_r \quad (2)$$

Table.4. FSP process factors and their levels

FSP processing parameters	*Level*	*Code*
tool profile	T	1
	F	2
traverse feed rate (mm/min)	10	1
	20	2
	40	3
Rotational speed (rpm)	355	1
	450	2
	560	3
	710	4
	900	5

The response surface plot is shown in Figure 6. It can be seen that the highest corrosion rate occurs at the highest rotational speed and the threaded cylindrical pin profiled tool.

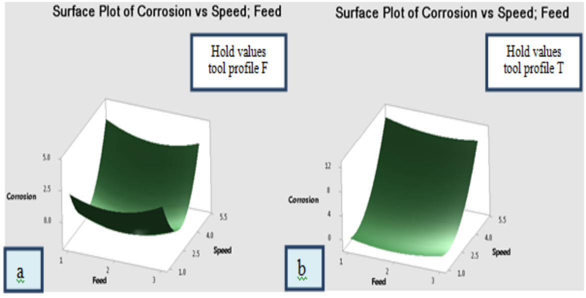

Fig. 6.The surface plot of corrosion rate as a function of rotational speed and feed rate of (a) the form tool (F), (b) the threaded cylindrical pin profiled tool.

Residual analysis is used to examine the validity of the proposed regression model; the normal residual probability plot is used to confirm the assumption that residuals were normally distributed, i.e. the plotted data of normal probability should normal probability a straight line ,some of the errors are placing outside the straight line as shown in Fig. 7, In addition to the residuals versus the predicted values(Figure 7) indicate a non-constant variance. Consequently, the model for the experiment has produced an obviously unreliable prediction in the very region where we would like this model to have good predictive performance .so, the transformation was necessary to improving the fit of the model to the data.

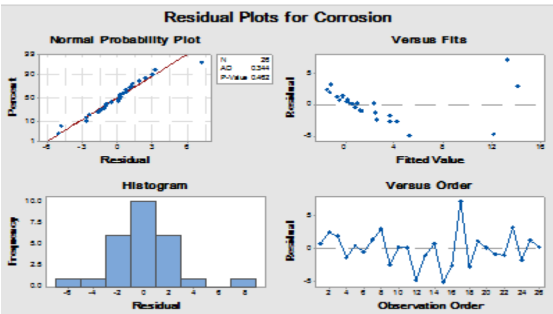

Fig. 7.Residuals plot for corrosion rateof SZ

3.3 Predictive model development with transformation

The Box - Cox method has been used to obtain better fit for the statistical model and to meet certain requirements. Residuals Analysis was studied to verify that the requirements are met. The Box-Cox transformation procedure was used by select the optimal transformation □(lambda) capable of adjusting the data so that the model is appropriate and will yield acceptable residual plots. Minitab software has been used to calculate the optimal lambda that should produce the best - fitting results. The confidence interval for □ is (-0.352655; 0.0953446) at 95% CI does not include 1, so transformation should be considered. The optimal value for □ is -0.117 and the rounded value is zero. This corresponds to a transformation of Y' = Log_eY. To predict the average response of corrosion rate, the final regression model after transformation in terms of coded parameter levels is shown in equation (3).

$$\ln(\boldsymbol{CR}) = -2.29 + 0.059\,S_r + 0.74\,V_n + 0.522\,P_t + 0.1482\,S_r^2 - 0.041\,V_n^2 + 0.001\,S_r*V_n - 0.217\,S_r*P_t - 0.259\,V_n*P_t \qquad (3)$$

Figure 8 represents the response surface plot of predicted corrosion rate after Box-Cox transformation. The residual plots for the corrosion rate after the Box-Cox transformation is displayed Figure 9. The normal probability plot of the errors (residuals) seems to follow a straight line indicating that the errors are distributed normally.The frequency histogram of the residuals reveals that the errors are normally distributed. Additionally, there is no evidence of any serious model inadequacies by checking the plots of the residual versus observation order or fitted value. Assumption that errors are uncorrelated random variables is confirmed.

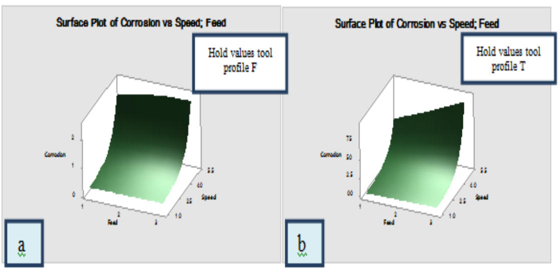

Fig. 8. The surface plot of corrosion rate as a function of rotational speed and feed rate of (a) the Form tool (F), (b) the threaded cylindrical pin profiled tool.

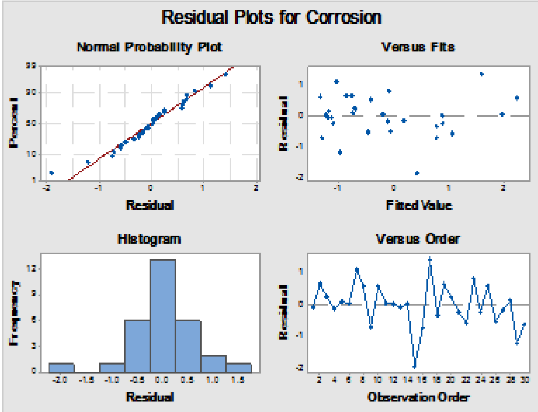

Fig. 9.Residuals plot for corrosion rate of SZ.

Table.5. Models Summary

Statistical Variable	S (Root Mean Square Error)value	R^2value	R^2 (Adj) value	R-sq (pred) value
Regression model without transformation	3.30965	64.26%	50.64%	4.24%
Regression model with transformation	0.801402	69.14%	57.38%	29.26%

The R^2 value used to quantitatively evaluate the correlation of the predicted and experimental responses. Table 5 appears the comparative of R^2 value, Adj R^2 value and Predicted R^2 value of quadratic models. It is clear from the table that the use of Box-Cox transformation increased the R^2 value from 64.26% to 69.14% and adjusted R^2 increased from 50.64% to 57.38% upon the transformation that shows the enhance prediction ability of model. According to the confirmed optimization results of the regression model with transformation, the minimum ***CR*** was obtained at the threaded cylindrical pin profiled tool, speed of 355 rpm and feed of 10 mm/min (**CR**$_{fitted}$ = 0.262831µm/year).

4 Conclusions

In this study, a statistical investigation was carried out to evaluate the influence of the FSP processing parameters [tool pin profile, rotational speed and tool traversing speed] on the corrosion rate of the nugget zones of A356 alloy. The general full-factorial design of experiments was used as statistical plan. ANOVA was used to determine the relative influence of each parameter and combination of parameters on response. The following findings can be drawn from the presented results:

1. Varying rotational speed and the tool profiles have a significant effect on the corrosion rate of the FS processed samples, i.e., corrosion rate of the stir zone are increased with increasing the rotational

speed. The influence of the traverse feed rate on the corrosion rate is not statically significant.

2. Based on the ANOVA findings, the most important parameter on the corrosion rate of the A356 alloy is the rotational speed, while the pin profile tool geometry is second ranking parameter.
3. The Form tool (F) pin profile produces a better corrosion resistance of the nugget zones rather than the threaded cylindrical pin profiled tool.
4. In this study, a non-transformed regression quadratic model was firstly developed. Then plotting residuals versus the predicted values of this initial model was found decreasing-shaped pattern. Box-Cox transformation was used to improve these drawbacks with optimal λ and a new model with a perfect normality and homo scedasticity was obtained. The implementation of Box-Cox transformation improved the coefficient R^2 value and Adjusted R^2 value from 64.26% to 69.14% and 50.64% to 57.38%, respectively, clearly indicates that the model's predictability is improved.

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