DEVELOPMENT OF STATISTICAL MODEL FOR PREDICTING HARDNESS OF FRICTION STIR WELDED DISSIMILAR ALUMINIUM ALLOYS

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ABSTRACT

Friction stir welding is a solid state joining process which uses a third body tool to join the two flaying surfaces. The various parameters which affect the quality of welded joint are welding speed, rotational speed, tool shoulder diameter, axial load, profile of tool shoulder and tool pin etc. Thus to obtain sound weld, the control over these parameters is important. Present study deals with the friction stir welding of two different grades of aluminium alloys i.e. AA 6101 and AA 6351. For obtaining the relation between response and variable Box-Behnken experimental design has been implemented. Three process parameters (rotational speed, welding speed and shoulder diameter) having three level has been considered and the measured response is hardness in Nugget Zone (NZ). Regression analysis has been performed for development of statistical model which predicts the hardness in NZ. For checking the adequacy of the developed model, ANOVA analysis has been performed and the model has been validated by performing validation experiments. The experimental and predicted value of hardness in NZ showed good agreement. The study also discuss about the effect of considered process parameters on hardness of NZ.

I. INTRODUCTION

Friction stir welding (FSW) is a solid state joining process invented in 1991 [1] at The Welding Institute, Cambridge, UK which uses a non-consumable rotating tool for joining. FSW involves basically four steps, plunge in period, dwell period, welding period, and plunge out period. During plunge in period non consumable rotating tool is inserted at the weld line until the top surface of plate is in contact with bottom surface of shoulder. Once the tool is inserted, a dwell period of predetermined period is provided which enables the plastic deformation of material to be welded. After dwell period, tool is provided movement in transverse direction along the joint line which results in joining of two plates without melting. The movement of tool along transverse direction depends on the length of joint line. After completion of welding the tool is retracted from the joint line leaving behind the hole. In the whole process tool serves as major heat source which generates heat due to friction between tool shoulder and plates.

Previous work by many researchers on FSW includes numerical thermal models, Finite element analysis (FEA) based on thermo-mechanical models, Computational flow dynamic of study of material flow during process, effect of various welding parameters, tool design effect, residual stresses induced during welding and optimization of welding parameters. Liu et al. [2-4] performed FSW in immersed water condition for study of strength improvement, and it was found that rapid cooling due to presence of water provide higher strength compared to strength obtained in FSW performed in air. Lee et al. [5] studied mechanical properties related to variation in microstructure of 6061 Al alloy. Results showed that non-symmetric stir zone exist due to tilt angle of tool and compared to base metal fine and smaller grain was observed in stir zone. In TMAZ elongated grain structure were observed and in HAZ was found to have similar grain size as that of BM. Vijayan et al. [6] performed multi-objective optimization of FSW process parameter using Taguchi based grey relational analysis. Objective of their study was to find optimum level of process parameter which will result in maximization of tensile strength with minimum power consumption. Based on grey relational analysis optimum process parameter obtained was rotational speed of 650 rpm, welding speed of 115 mm/min and axial load of 9 kN respectively. Kadaganchi et al. [7] performed optimization of process parameter of friction stir welding of AA 2014-T6 using Response surface methodology. The considered process parameter spindle speed, welding speed, tilt angle and tool pin profile and response were yield strength, tensile strength and % elongation. The result showed that FSW with hexagonal tool pin profile results in maximum tensile strength and elongation and increasing tilt angle results in better material flow under shoulder and will increase mechanical properties of joint. Joint fabricated with welding speed of 800 mm/min, rotational speed of 1000 rpm, tilt angel of 3.5° with hexagonal pin profile will have superior tensile strength. Sahu et al. [8] performed multi-response optimization of process parameter in friction stir welding of AM20 magnesium alloy using Taguchi grey relational analysis. Selected process parameters were welding speed, rotational speed, shoulder diameter and plunging depth. L18 orthogonal array were based on Taguchi method was considered. Grey relational analysis was used for ranking of process parameter. ANOVA was used to get percentage influence of each process parameter on quality of weld.

The present study deals with the development of statistical model for prediction of hardness in nugget zone (NZ). The adequacy of developed model has been checked by performing Analysis of Variance (ANOVA). For validation of developed model, validation experiments were performed and hardness in NZ was measured. The experimental measured hardness showed good agreement with that predicted from developed model.

II. EXPERIMENTAL PROCEDURE

Friction Stir Welding was performed on two different grades of aluminium alloys. AA 6351 and AA 6101 were welded by performing experiments on universal milling machine. Table 01 shows the chemical composition and mechanical properties of respective aluminium alloys. Tool used for experimental purpose was made up of H13 steel. Necessary heat treatment was provided to the tool for obtaining required hardness. Initially pilot experiments were performed and working range of process parameterswas decided. Table 02 shows the respective levels of rotational speed, welding speed and shoulder diameter. The hardness in NZ was measured using Vicker’s Hardness test equipment. For obtaining the relation between response (hardness) and variables (process parameter) Box-Behnken experimental design was implemented. Table 03 shows the various combination of process parameter obtained using Box-Behnken and their corresponding responses.

TABLE 01: Chemical Composition and mechanical properties of the alloys [9]

Material	Al	Si	Mg	Mn	Tensile Strength (MPa)
AA6101	98.90	0.50	0.60	-	97 MPa
AA6351	97.80	1.00	0.60	0.60	250 MPa

TABLE 02: Selected process parameter and their respective range

Process Parameter	Range		
	Level 01	Level 02	Level 03
Rotational Speed (N)	710	1000	1400
Welding Speed (S)	112	160	224
Shoulder Diameter (D)	15	17	19

TABLE 03: Various combination of process parameter and corresponding responses

Experiment No.	Rotational Speed (rpm)	Welding Speed (mm/min)	Shoulder Diameter (mm)	Hardness (HV)
A1	710	112	15	71
A2	1000	112	15	77
A3	1000	224	15	72
A4	1400	160	15	70
B1	710	112	17	80
B2	710	224	17	76
B3	1000	160	17	83
B4	1400	224	17	75
C1	710	160	19	69
C2	1000	112	19	78
C3	1000	224	19	74
C4	1400	160	19	73

III. RESULT AND DISCUSSION

3.1 Development of Statistical Model for Prediction of Hardness in Nugget Zone

The expression for second order Box-Behnken experimental design is given as [10]

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_1 X_1 + \sum_{i=1}^{n} \beta_2 X_1^2 + \sum \sum_{i<j} \beta_{ij} X_i X_j + \varepsilon \qquad (1)$$

Where Y is response, $X_i$are the factor or variable. This expression contains linear term X_i, quadratic term $X_i^2$and product terms X_iX_j and ε is the absolute error. The constant coefficients in the equation i.e. β_0, β_1, β_2... etc will be obtained by performing regression analysis in MS Excel. Equation 2 shows the statistical model obtained using regression analysis.

$$HV = -533.057 + 0.08423 * N - 0.07625 * S + 67.921 * D - 4.226 * 10^{-5} * N^2 + 0.000187 * \quad (2$$
$$- 2.0274 * D^2 - 6.3366 * 10^{-5} * N * S + 0.00183 * S * D + 0.000105 * D * N \quad)$$

The adequacy of the developed model was checked using Analysis of Variance (ANOVA). Table 04 shows the results of ANOVA analysis. From the table 04 it can be seen that the value of R^2 is about 99.25% which indicates that the develop model is adequate to predict the hardness in NZ with minimum error. Table 05 shows that the measured hardness in NZ and predicted hardness in NZ are in good agreement with each other.

TABLE 04: Results of ANOVA analysis

	df	SS	MS	F	Significance F	R Square	Adjusted R Square
Regression	9	192.217	21.3575	29.4792	0.033230317	0.99251813	0.958849727
Residual	2	1.4490	0.72449				
Total	11	193.666					

TABLE 05: Comparison of measured and predicted hardness

Experiment No.	Measured Hardness in NZ(HV)	Predicted Hardness in NZ (HV)
A1	71	71.23
A2	77	77.25
A3	72	71.75
A4	70	69.74
B1	80	79.23
B2	76	76.20
B3	83	83.11
B4	75	75.43
C1	69	69.32
C2	78	78.27
C3	74	73.59
C4	73	72.81

For confirmation of developed statistical model some conformation experiments were performed. These experiments were performed by random selection of process parameters and the results are shown in table 06. Thus this indicated that the develop model will help in predicting hardness in NZ if required inputs are provided. This model will provide valuable contribution in selection of input value of process parameter such that the combination of process parameters will result in maximum hardness in NZ.

TABLE 06: Results of conformation test

Rotational Speed (rpm)	Welding Speed (mm/min)	Shoulder Diameter (mm)	Measured Hardness in NZ (HV)	Predicted Hardness in NZ (HV)
710	160	15	71	69.18
1000	112	17	83	85.874
1400	224	19	68	69.09

3.2 Effect of Process Parameter on Hardness in NZ

The influence of process parameters on hardness is figure 01 using 3D response graph formed based on developed statistical model. Figure 01 (a) shows the relation between rotational speed and hardness. From the relation it can be observed that with the increase in rotational speed, initially hardness increases and attains an maximum value. While further increase in rotational speed will results in reduction of hardness. Lower rotational speed will results in insufficient heat generation which will lead to formation of defect in welded joints. Similarly with higher rotational speed improper consolidation of material will occur which ultimately results in formation of voids in weld zone and reduces mechanical properties of welded joint.

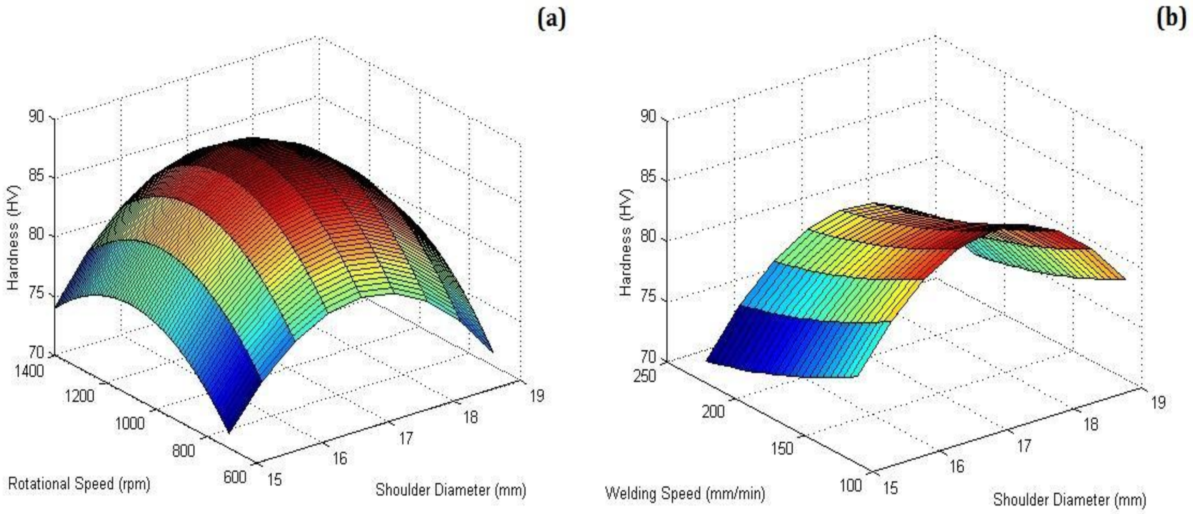

Figure 01 Effect of process parameter on hardness

Figure 01 (b) shows the relation between welding speed and hardness. From the relation it can be observed that with the increase in welding speed, hardness in NZ reduces. Increase in welding speed will results in insufficient generation of heat, due to the same proper consolidation of material will not occur and will result in formation of defect in welded joint which ultimately reduces the mechanical properties of joint. From figure 01(a) and (b)it can be seen that with the increase in shoulder diameter, hardness in NZ increases initially and reaches a maximum value. Whereas further increase in shoulder diameter leads to reduction of hardness in NZ.With lower shoulder diameter insufficient heat will be generated and it causes formation of defects in welded joint. Also with the higher shoulder diameter excessive heat will be generated which will leads to dissolution of strengthening precipitates present in base composite and thus will reduces the mechanical properties of welded joint. From both the plots it can be observed that the hardness in NZ is more sensitive towards rotational speed and shoulder diameter and is less sensitive towards welding speed.

IV. SUMMARY AND CONCLUSION

The present study deals with the joining of two dissimilar grads of aluminium alloys AA 6351 and AA 6101. A statistical model was developed using regression analysis and the adequacy of the developed model was checked using ANOVA analysis. Results of ANOVA analysis showed that the developed model was 99.25% adequate to predict the hardness of NZ. Thus a good agreement between measured and predicted value of hardness was observed. Furthermore effect of rotational speed on hardness was studied and it was concluded that with the increase in rotational speed, hardness increases initially, reaches a maximum value and the decreases. Similar trend was observed for shoulder diameter andinverse relation between hardness and welding speed was observed. The developed model will help in predicting hardness for various combination of process parameter and thus will play an important role in selection of process parameters.

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