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SENSITIVITY ANALYSIS OF FRICTION STIR WELDING PROCESS AND TOOL PARAMETERS FOR JOINING AA1100 ALUMINIUM ALLOY JOINTS

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ABSTRACT

This paper focuses on the development of empirical relationship for the prediction of tensile strength of friction stir welded aluminium alloy joints. Experimental part of the study is based on five level central composite designs of six (process and tool) parameters. In order to investigate the effects of input parameters on tensile strength, an empirical relationship is constructed by multiple regression analysis. A sensitivity analysis is carried out and compared the relative impact of input parameters on tensile strength in order to verify the measurement errors on the values of the uncertainty in estimated parameters. The results obtained show that developed empirical relationship can be applied to estimate the effectiveness of process and tool parameters for a given tensile strength. The tool hardness is more sensitive than shoulder diameter, axial force, rotational speed, pin diameter and welding speed.

Keywords: *Friction Stir Welding, AA1100 alloy, Central Composite Design, Regression Analysis, Sensitivity Analysis.*

1. Introduction

Friction stir welding (FSW) is a robust solid state joining process invented by Thomas [1] et al, 1991 at TWI. It is primarily a three stage process; a plunge, a dwell, and a welding stage. In the plunge stage, a hard non-consumable rotating tool penetrates the plates to be welded. In the dwell stage, the tool penetrates the metal and rotates without moving forward; where as the welding stage is the stage where the tool moves forward to form a weld bead. In recent years, FSW has become key process in joining field to yield high integrated solid-phase welds for aluminum alloys, magnesium alloys and copper alloys. During FSW process, operator cannot observe the weld quality and not directly interfere with the welding process. As the automation in the FSW process increases, direct effect of the operator decreases and the precise setting of parameters become much more important than manual welding processes. Yet, FSW has emerged as one of the most significant achievements in the field of joining of aluminum alloys [2-3].

In this paper, an empirical relationship between FSW parameters and tensile strength was constructed based upon the experimental data obtained by six parameters-five levels central composite design. The empirical equation, simulating the FSW process, was carried out by Multiple Regression Analysis (MRA) and a sensitivity equation was derived from this basic equations. This analysis generally requires a definition of an objective function and design parameters. In this study, the objective function was chosen as tensile strength, whereas process parameters and tool parameters (rotational speed, welding speed, axial force, shoulder diameter, pin diameter and tool hardness) were selected as the design variables. The present study mainly focuses on the determination of sensitivity characteristics of design parameters and the prediction of fine-tuning requirements of these parameters in FSW process. The results revealed considerable information about the effect of process parameters and tool parameters and optimum welding conditions.

2. Experimental Work

Rolled plates of 5 mm thickness, commercial grade aluminium alloy of AA1100 were cut into the required size (300 mm ×150 mm) by power hacksaw cutting and milling. Square butt joint configuration (300 mm × 300 mm) was prepared to fabricate FSW joints as shown in Fig. 1(a). The initial joint configuration was obtained by securing the plates in position using mechanical clamps. The direction of welding was normal to the rolling direction. Single pass welding procedure was followed to fabricate the joints. Non-consumable tools made of high carbon steel and high speed steels were used to fabricate the joints. The tool dimensions are shown in Fig. 1(b) and

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the chosen levels of the selected process parameters and tool parameters with their units and notations are presented in Table 1.

Table 1: Important FSW Process Parameters and their Levels for AA 1100 Aluminium Alloy

Factors	Units	Not.	Factor levels -2.38	-1	0	1	2.38
Rotational speed	rpm	N	562	700	800	900	1037
Welding speed	mm/min	S	40.54	75	100	125	159.5
Axial force	kN	F	3.62	5	6	7	8.37
Shoulder diameter	mm	D	7.86	12	15	18	22.13
Pin diameter	mm	d	2.6	4	5	6	7.37
Tool hardness	HRc	H	33	40	45	50	56

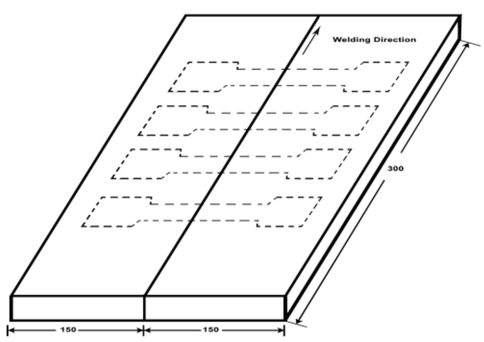

Fig. 1(a) Joint Dimensions (in 'mm')

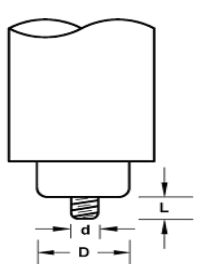

Fig. 1 (b) Nomenclature of FSW Tool

Based on six factors, five level central composite designs with 15 combinations of tools were made for different tool pin diameter, tool shoulder diameter and tool hardness. The tool hardness was varied by heat treatment. An indigenously designed and developed computer numerical controlled friction stir welding machine (3HP induction motor with brake; 22 kW spindle speed; 5000 RPM; 6 Ton) was used to fabricate the joints. Tensile specimens Fig. 1(c) were prepared as per the ASTM E8M-04 guidelines.

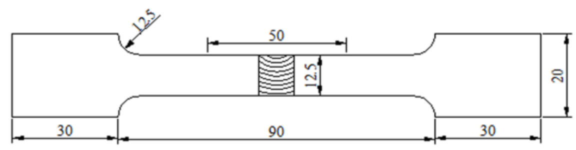

Fig. 1 (c) Dimensions of Tensile Specimen (in 'mm')

Tensile test was carried out in 100kN, servo controlled universal testing machine (FIE-BLUESTAR, India). The specimen was loaded at the rate of 1.5 Kn/min as per ASTM specifications. At each experimental condition, three specimens were tested and average values are presented in Table 2.

3. Developing an Empirical Relationship

Representing the tensile strength of the FSW joint by TS, the response is a function of rotational speed (N), welding speed (S), axial force (F), shoulder diameter (D), pin diameter (d) and tool hardness (H) and it can be expressed as

TS = f (Rotational speed, Welding speed, Axial force, Shoulder diameter, Pin diameter, Tool hardness)

$$TS = f(N, S, F, D, d, H) \quad (1)$$

The second order polynomial (regression) equation used to represent the response surface 'Y' is given by

$$Y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ij} x_i x_j + e_r \quad (2)$$

and for six factors, the selected polynomial could be expressed as

$$TS = b_0 + b_1(N) + b_2(S) + b_3(F) + b_4(D) + b_5(d) + b_6(H) + b_{11}(N^2) + b_{22}(S^2) + b_{33}(F^2) + b_{44}(D^2) + b_{55}(d^2) + b_{66}(H^2) + b_{12}(NS) + b_{13}(NF) + b_{14}(ND) + b_{15}(Nd) + b_{16}(NH) + b_{23}(SF) + b_{24}(SD) + b_{25}(Sd) + b_{26}(SH) + b_{34}(FD) + b_{35}(Fd) + b_{36}(FH) + b_{45}(Dd) + b_{46}(DH) + b_{56}(DH) \quad (3)$$

where b_0 is the average of responses and $b_1, b_2, \ldots, b_{66}$ are the coefficients that depend on respective main and interaction effects of the parameters. The value of the co-efficients was calculated using the following expressions,

$$b_0 = 0.110749(\sum y) - 0.018738 \sum (X_{iiy}) \quad (4)$$

Table 2: Design Matrix and Experimental Results

Exp no	Input parameter						Output Response
	Rotational speed (rpm)	Welding speed (mm /min)	Axial force (kN)	Shoulder diameter (mm)	Pin diameter (mm)	Tool hardness (HRc)	Tensile strength of welded joints (MPa)
1	-1	-1	-1	-1	-1	-1	69
2	1	-1	-1	-1	-1	1	89
3	-1	1	-1	-1	-1	1	75
4	1	1	-1	-1	-1	-1	90
5	-1	-1	1	-1	-1	1	85
6	1	-1	1	-1	-1	-1	96
7	-1	1	1	-1	-1	-1	82
8	1	1	1	-1	-1	1	99
9	-1	-1	-1	1	-1	1	80
10	1	-1	-1	1	-1	-1	85
11	-1	1	-1	1	-1	-1	76
12	1	1	-1	1	-1	1	89
13	-1	-1	1	1	-1	-1	77
14	1	-1	1	1	-1	1	92
15	-1	1	1	1	-1	1	86
16	1	1	1	1	-1	-1	97
17	-1	-1	-1	-1	1	1	77
18	1	-1	-1	-1	1	-1	85
19	-1	1	-1	-1	1	-1	73
20	1	1	-1	-1	1	1	88
21	-1	-1	1	-1	1	-1	76
22	1	-1	1	-1	1	1	93
23	-1	1	1	-1	1	1	84
24	1	1	1	-1	1	-1	98
25	-1	-1	-1	1	1	-1	81
26	1	-1	-1	1	1	1	94
27	-1	1	-1	1	1	1	90
28	1	1	-1	1	1	-1	99
29	-1	-1	1	1	1	1	89
30	1	-1	1	1	1	-1	95
31	-1	1	1	1	1	-1	90
32	1	1	1	1	1	1	93
33	-2.378	0	0	0	0	0	80
34	2.378	0	0	0	0	0	105
35	0	-2.378	0	0	0	0	83
36	0	2.378	0	0	0	0	90
37	0	0	-2.378	0	0	0	83
38	0	0	2.378	0	0	0	97
39	0	0	0	-2.378	0	0	82
40	0	0	0	2.378	0	0	90
41	0	0	0	0	-2.378	0	85
42	0	0	0	0	2.378	0	91
43	0	0	0	0	0	-2.378	81
44	0	0	0	0	0	2.378	87
45	0	0	0	0	0	0	101
46	0	0	0	0	0	0	100
47	0	0	0	0	0	0	101
48	0	0	0	0	0	0	102
49	0	0	0	0	0	0	101
50	0	0	0	0	0	0	99
51	0	0	0	0	0	0	98
52	0	0	0	0	0	0	103

$$b_i = 0.023087\sum (X_{iy}) \quad (5)$$

$$b_{ii}=0.0152625\sum(X_{iiy})+0.001217\sum\sum(X_{iiy})-0.018738(\sum Y) \quad (6)$$

$$b_{ij} = 0.03125\sum (X_{ij}Y) / n \quad (7)$$

where 'i' varies from 1 to n, in which X_i is the corresponding coded value of a factor and Y is the corresponding response output value (tensile strength) obtained from the experiment and 'n' is the total number of combinations considered (in this case n=52)
Tensile strength

$$(\mathbf{TS})=\{100.65+5.80(N)+1.44(S)+2.89(F)+1.68(D)+1.20(d)+1.11(H)+0.06(NS)-0.12(NF)-1.31(ND)-0.68(Nd)-1.56(NH)+0.18(SF)+0.25(SD)+0.125(Sd)-1.12(SH)-1.31(FD)-0.93(Fd)-0.43(FH)+1.87(Dd)-0.25(DH)-0.37(dH)-1.49(N^2)-2.55(S^2)-1.93(F^2)-2.64(D^2)-2.29(d^2)-2.29(H^2)\}\text{MPa.} \quad (8)$$

4. Sensitivity Analysis

4.1. The derivations of sensitivity equations

Sensitivity analysis is the most important step in the optimization problems, because it yields the information about the increment or decrement tendency of the design objective function with respect to the design parameter.

Table 3: Tensile Strength Sensitivities of (Process and Tool) Parameters (S=135 mm/min)

Axial Force (kN)	Rotational Speed (rpm)	Shoulder Diameter (mm)	Pin Diameter (mm)	Tool Hardness (HRc)	Tensile Strength (MPa)	Sensitivity					
						∂TS/∂N	∂TS/∂S	∂TS/∂F	∂TS/∂D	∂TS/∂d	∂TS/∂H
	562	7.8	2.6	33	22	19.22	-2.55	14.77	14.5	9.11	17.15
	562	7.8	2.6	33	22	19.22	-2.55	14.77	14.5	9.11	17.15
	700	12	4	40	62	12.66	-3.44	12.81	9.53	5.31	9.01
3	800	15	5	45	86	6.1	-3.93	10.85	4.56	1.51	0.87
	900	18	6	50	92	-0.46	-4.62	8.88	-0.41	-2.84	-7.27
	1037	22	7.3	56	80	-7.02	-5.31	6.92	-5.38	-6.08	-15.41
	562	7.8	2.6	33	36	19.1	-2.36	10.89	13.19	9.02	16.71
	700	12	4	40	74	12.54	-3.05	8.93	8.22	5.22	8.57
4	800	15	5	45	95	5.98	-3.74	6.97	3.25	1.42	0.43
	900	18	6	50	98	-0.58	-4.43	5.01	-1.72	-2.37	-7.71
	1037	22	7.3	56	83	-7.14	-5.12	3.04	-6.69	-6.17	-15.85
	562	7.8	2.6	33	46	18.98	-2.17	7.02	11.88	8.93	16.27
	700	12	4	40	82	12.42	-2.86	5.05	6.91	5.13	8.13
5	800	15	5	45	100	5.86	-3.55	3.09	1.94	1.33	-0.01
	900	18	6	50	100	-0.7	-4.24	1.12	-3.03	-2.47	-8.15
	1037	22	7.3	56	83	-7.26	-4.93	-0.83	-8	-6.27	-16.29
	562	7.8	2.6	33	53	18.86	-1.98	3.13	10.57	8.83	15.83
	700	12	4	40	86	12.3	-2.67	1.17	5.6	5.03	7.69
6	800	15	5	45	101	5.74	-3.36	-0.79	0.63	1.23	-0.45
	900	18	6	50	98	-0.82	-4.05	-2.75	-4.34	-2.56	-8.59
	1037	22	7.3	56	78	-7.38	-4.74	-4.72	-9.31	-6.36	-16.73
	562	7.8	2.6	33	56	18.74	-1.78	-0.74	9.26	8.74	15.39
	700	12	4	40	86	12.18	-2.48	-2.7	4.29	4.94	7.25
7	800	15	5	45	98	5.62	-3.17	-4.67	-0.68	1.14	-0.89
	900	18	6	50	93	-0.94	-3.86	-6.63	-5.65	-2.65	-9.03
	1037	22	7.3	56	70	-7.5	-4.55	-8.59	-10.62	-6.45	-17.17

Sensitivity analysis, a method to identify critical parameters and rank them by their order of importance, is paramount in model validation where attempts are made to compare the calculated output to the measured data. This type of analysis can study which parameters must be most accurately measured, thus determining the input parameters exerting the most influence upon model outputs [4]. Therefore, sensitivity analysis plays an important role in determining which parameter of the process should be modified for effective improvement [5]. Mathematically, sensitivity of a design objective function with respect to a design variable is the partial derivative of that function with respect to its variables [6].

In this present investigation the sensitivity equations are obtained by differentiating the developed empirical relation with respect to the factors of interest such as rotational speed, welding speed, axial force, shoulder diameter, pin diameter and tool hardness that are explored here [7].To obtain the sensitivity equation for tensile strength, the sensitivity equations (9),(10),(11),(12),(13), and (14) represent the sensitivity of tensile strength for rotational speed, welding speed, axial force, shoulder diameter, pin diameter and tool hardness respectively.

$$\partial TS/\partial N = 5.80+0.06S-0.12F-1.31D-0.69d-1.56H-3N \quad (9)$$

$$\partial TS/\partial S = 1.45+0.06N+0.19F+0.25D+0.12d-1.12H-5S \quad (10)$$

$$\partial TS/\partial F = 2.90-0.12N+0.19S-1.31D-0.093d-0.44H-3.88F \quad (11)$$

$$\partial TS/\partial D = 1.69-1.31N+0.25S-1.31F+1.87d-0.25H-5.28D \quad (12)$$

$$\partial TS/\partial d = 1.21-0.69N+0.12S-0.093F+1.87D-0.37H-4.61d \quad (13)$$

$$\partial TS/\partial H = 1.11-1.56N-1.12S-0.44F-0.25D-0.37d-5.98H \quad (14)$$

5. Discussion

5.1 Evaluation of sensitivity analysis results

The purpose of this investigation is to show the effectiveness of the factors by using the direct sensitivity analysis technique on the predictive equation. Results of tensile strength sensitivities for rotational speed, welding speed, axial force, shoulder diameter, pin diameter and tool hardness are shown in Table 3. In this study, the aim is to predict the tendency of tensile strength due to a small change in process parameters for FSW process. Sensitive information should be interpreted using mathematical definition of derivatives. Namely, positive sensitivity values imply an increment in the objective function by a small change in design parameter, whereas negative values state the opposite [8-9].

Figs. 2 to 7 give the sensitivity characteristics maps of FSW process. Fig. 2 shows the sensitivity of tool hardness on tensile strength, the variation of tool hardness causes large changes of tensile strength when tool hardness increases.

This means tool material hardness is more sensitive than the shoulder diameter, axial force, rotational speed and welding speed.

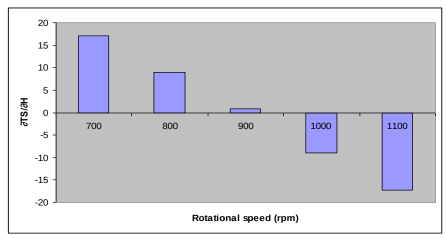

Fig. 2 Sensitivity Analysis Results of Tool Material Hardness (HRc)

The tensile strength of tool material hardness is more sensitive when increasing tool hardness. The tool material, which possesses higher hardness, will generate higher heat input due to higher co-efficient of friction. If this is the case, then the HSS tool should have generated higher heat input compared to their counterparts. However, the thermal (heat) conductivity of HSS tool is higher compared to HCS due to the presence of tungsten, chromium and vanadium. Though heat generated by HSS is higher than HCS, some amount of heat is dissipated to the tool shank due to higher thermal conductivity. Hence, the net heat flow in to the base metal is appreciably lower in the case of HSS compared to HCS, this lead to the insufficient working and poor consolidation of plasticized metal in the nugget region, which was evident from hardness measurements and tensile properties evaluation [10].

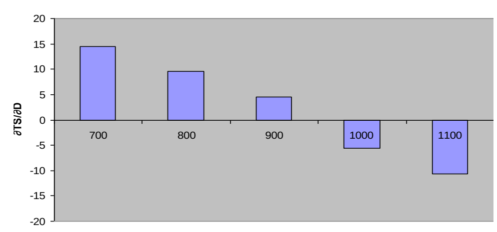

Fig. 3 Sensitivity Analysis Results of Shoulder Diameter (mm)

The hardness of mild steel, stainless steel and armour steel is much lower compared to HCS and HSS and hence the heat generation is not sufficient to cause the metal to flow plastically. The sensitivity of shoulder diameter is represented in Fig. 3, the results reveals that the variation of shoulder diameter has high impact on tensile strength when rotational speed increases. As rotational speed increased, the heat input per unit length of the joint increased, resulting inferior tensile properties due to rise in temperature, which increases grain growth, considerable increase in turbulence, which destroys the regular flow behavior available at lower speed. From, Fig.4 depicted that the variation of axial force is less sensitiveness of tensile strength when axial force increases.

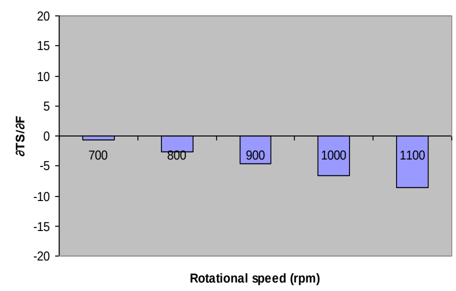

Fig. 4 Sensitivity Analysis Results of Axial Force (KN)

The heat input and temperature distribution during friction stir welding is due to frictional heat generation between the rotating tool shoulder and surface of the plate to be welded and in turn depends on co-efficient of friction. Hence axial force plays a significant role in friction stir welding process. The degree of material mixing and inter diffusion, the thickness of deformed aluminum lamellae, the material flow patterns highly depends on welding temperature, flow stress and axial force. Fig. 5 inferred the sensitivity of rotational speed on tensile strength.

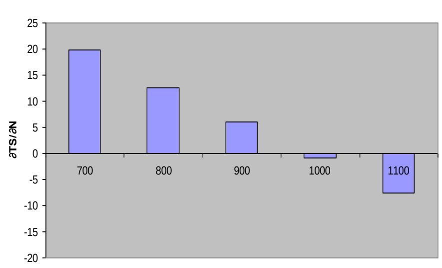

Fig. 5 Sensitivity Analysis Results of Rotational Speed (rpm)

When increasing the rotational speed tensile is increased and then decreased. It is mainly due to higher heat generation. As rotational speed increased, the heat input per unit length of the joint increased, resulting inferior tensile properties due to rise in temperature, which increases grain growth. Considerable increase in turbulence, which destroys the regular flow behavior available at lower speed, is also observed. Fig. 6 presented the Pin diameter sensitivity of tensile strength is positive sense. These sensitivities imply increment tendency in the predictive values of tensile strength.

Tool pin propel the material after it has undergone the plastic deformation. The second is due to the rotation of the pin that serves as the driving force for the flow. Due to high values of viscosity, the stirring effect is much more distinct in comparison to the extrusion driven flow.

In Fig.7 shows the sensitivity analysis of welding speed on tensile strength, the result reveals that the variation of welding speed has high impact on tensile strength when rotational speed increases.

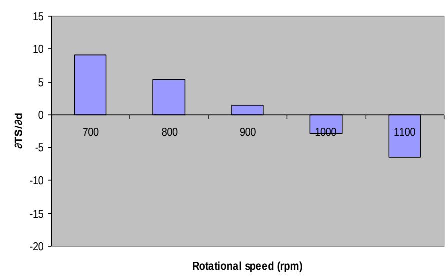

Fig. 6 Sensitivity Analysis Results of Pin Diameter (mm)

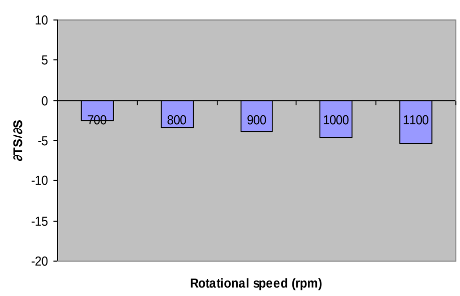

Fig. 7 Sensitivity Analysis Results of Welding Speed (mm/min)

Table 3 shows that, the sensitiveness of process and tool parameters of friction stir welding of AA1100 Aluminium alloy joints are presented. From the table it inferred that, the maximum tensile strength of 101MPa was observed for axial force of 8 kN, rotational speed of 900rpm, shoulder diameter of 15mm, pin diameter of 5mm, tool hardness of 600 Hv and welding speed are kept in constant value of 100 mm/min.

6. Conclusion

i. An empirical relationship was developed to predict the tensile strength of friction stir welded AA1100 aluminium alloy joints at 95% confidence level, incorporating FSW process and tool parameters.

ii. Tool hardness is more sensitiveness than other parameters followed by shoulder diameter, axial force, rotational speed, pin diameter and welding speed.

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