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Identification Of The Most Critical Friction Stir Welding Process And Tool Parameters To Attain A Maximum Tensile Strength Of The AA6061-T6 Aluminium Alloy

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Abstract-AA6061 aluminium alloy (Al–Mg–Si alloy) has gathered wide acceptance in the fabrication of lightweight structures requiring a high strength-to-weight ratio and good corrosion resistance. Compared to the fusion welding processes that are routinely used for joining structural aluminium alloys, friction stir welding (FSW) process is an emerging solid-state joining process in which the material that is being welded does not melt and recast. The FSW process and tool parameters play a major role in deciding the joint strength. In this paper relationship between the FSW parameters (tool rotational speed, welding speed, axial force, shoulder diameter, pin diameter, and tool hardness) and the tensile strength of the joint was established. Statistical tools such as analysis of variance (ANOVA), response surface methodology (RSM) were used to optimize the FSW parameters. Sensitivity analyses were used to identify the most critical parameters of the FSW process. From the test results welding speed is more sensitive than other parameters followed by rotational speed, tool hardness, axial force, pin diameter, and shoulder diameter.

***Keywords*:** Friction stir welding; Design of experiments; Analysis of variance; Response surface methodology; Sensitivity analysis; Optimization

1. INTRODUCTION

Heat treatable wrought aluminium–magnesium-silicon alloys conforming to AA6061 are of moderate strength and possess excellent welding characteristics over the high strength aluminium alloys [1-2]. Hence, alloys of this class are extensively employed in marine frames, pipelines, storage tanks, and aircraft applications. Although Al–Mg–Si alloys are readily weldable, they suffer from severe softening in the heat affected zone (HAZ) because of reversion (dissolution) of Mg_2Si precipitates during the weld thermal cycle. This type of mechanical impairment presents a major problem in engineering design. Compared to many of the fusion welding processes that are routinely used for joining structural alloys, friction stir welding (FSW) is an emerging solid-state joining process in which the material that is being welded does not melt and recast [3]. Defect-free welds with good mechanical properties have been made in a variety of aluminium alloys, even those previously thought to be not weldable. When alloys are friction stir welded, phase transformations that occur during the cooling cycle of the weld area of a solid-state type. Due to the absence of parent metal melting, the new FSW process is observed to offer several advantages over fusion welding. As the automation in the FSW process increases, the direct effect of the operator decreases and the precise setting of parameters become much more important than manual welding processes [4]. In order to obtain high-quality welds in automated welding processes, selection of optimum parameters should be performed according to engineering facts. Generally, welding parameters are determined by trial and error, based on handbook values, and manufacturers' recommendations. However, this selection may not yield optimal or in the vicinity of optimal welding performance. It may also cause additional energy and material consumption and may also result in low-quality welding. Therefore, it is important to study the stability of welding parameters to achieve high-quality welding. Predicting the effects of small changes in design parameters provide very important information in engineering design. Therefore, by a mathematically modelled prediction system, the effect of any changes in the parameters on the overall design objective can be determined. This kind of analysis is known as Design Sensitivity Analysis (DSA). Basically, Sensitivity Analysis (SA) yields information about the increment and decrement tendency of design objective function with respect to design parameters [5]. There are very few studies [6] in which sensitivity analysis is performed using a mathematical model for different fusion welding methods. The effect of FSW process parameters on the tensile strength of aluminium alloys is well documented in the literature. Similarly, the influence of FSW tool parameters on tensile properties of aluminium alloys is well reported in the literature. However, there is no literature available on the optimization of the FSW process and tool parameters on the tensile strength of aluminium alloys and hence the present investigation was carried out and the details are presented below.

2. SCHEME OF INVESTIGATION

2.1 Identifying The Important Process Parameters

From the literature [7] and the previous work done in our laboratory, the predominant factors which are having a greater influence on the tensile strength of the FSW process were identified. They are: (i) tool rotational speed, (ii) welding (traverse) speed, (iii) axial (downward) force,(iv) shoulder diameter, (v) pin diameter and (vi) tool hardness. These are the primary process and tool parameters contributing to the frictional heat generation and subsequently influencing the tensile properties of friction stir welded aluminium alloy joints.

2.2 Finding The Working Limits Of The Parameters

The chemical composition of base metal used in this investigation is presented in Table 1(a) and 1(b). Trial experiments were carried out using 5 mm thick rolled plates of AA6061-T_6 aluminium alloy to find out the feasible working limits of FSW parameters. The working range of each parameter was decided upon by inspecting the macrostructure (cross section of weld) for any visible defects such as tunnel defect, pinhole, kissing bond, lazy S, etc. From the above inspection, a few important observations were made and they are presented in Table 2. The chosen level of important process parameters and tool parameters with their units and notations are presented in Table 3.

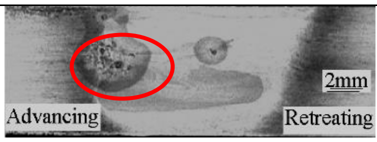
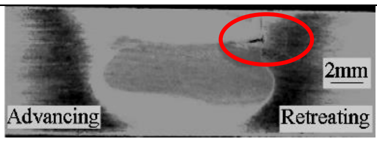
Table 1(a) Chemical composition (wt %) of base metal

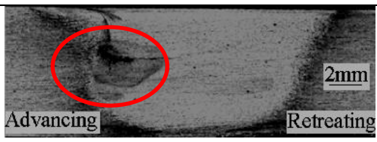
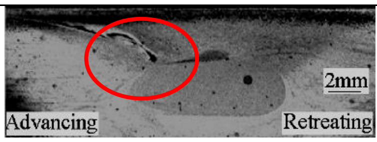
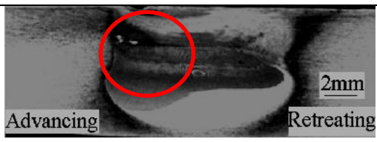
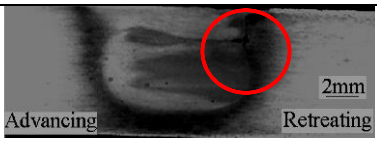
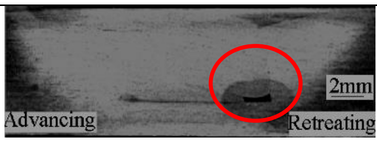
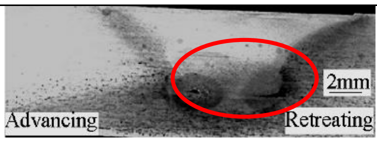
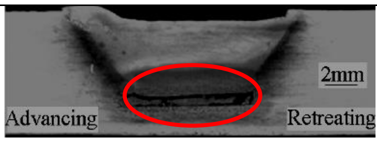
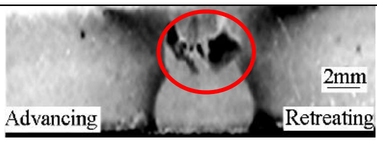
Element	Mg	Mn	Fe	Si	Cu	Al
Base metal (6061-T_6)	1.1	0.12	0.35	0.58	0.22	Bal

Table 1(b) Mechanical properties of the base metal

Material	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Vicker hardness ($Hv_{0.05}$)
Base metal (6061-T_6)	235	283	26.4	105

Table 2 Macrostructure observation of AA6061-T_6 aluminium alloy

Input parameters	Parameter range	Macrostructure	Name of the defect	Probable reason
Rotational speed	<800 rpm		Tunnel defect	Insufficient heat generation and Insufficient metal transportation.
Rotational speed	>1700rpm		Pinhole	Further, increase in turbulence of the plasticized metal.

Welding speed	<15mm/min		Tunnel defect	Excess heat input per unit length of the weld and no vertical movement of the metal.
Welding speed	>130mm/min		Kissing defect	Increase in welding speed resulted in poor plasticization of metal and associated defect.
Axial force	<2kN		Tunnel hole	Insufficient axial force and inadequate heat generation.
Axial force	>11kN		Wormhole	Additional axial force leads to excess heat input and thinning of the weld zone.
Shoulder diameter	<7mm		Pinhole	Insufficient stirring butt surfaces could be directly bonded without the metallic bond between oxide-free surfaces in the root part of the weld.
Shoulder diameter	>21mm		Pinhole	Excessive heat input due to softening and work hardening effect.
Pin diameter	<2.5mm		Piping defect	Asymptote heat generation and Insufficient metal transportation.
Pin diameter	>7mm		Tunnel defect	Excessive heat input due to softening.
Tool material hardness	<200Hv		Pinhole	Due to low frictional heat generation.
Tool Material Hardness	>900Hv		Wormhole	High frictional heat generation.

2.3 Developing The Experimental Design Matrix

By considering all the above conditions, the feasible limits of the parameters were chosen in such a way that AA6061-T_6 aluminium alloy should be welded without defects. Central composite rotatable design of second order was found to be the most efficient tool in response surface methodology (RSM) to establish the mathematical relation of the response surface using the smallest possible number of experiments without losing its accuracy. Due to a wide range of factors, it was decided to use six factors, five levels, central composite design matrix to optimize the experimental conditions. Table 3 presents the ranges of factors considered and Table 4 shows the 52 set of coded conditions used to form the design matrix. The coded values of any intermediate values can be calculated using the following expression:

$$X_i = 2\,[2X - (X_{max} + X_{min})] / (X_{max} - X_{min}) \qquad (1)$$

Where,
X_i is the required coded value of a variable X;
X is any value of the variable from X_{min} to X_{max};
X_{min} is the lower level of the variable;
X_{max} is the highest level of the variable.

Table 3 Important FSW process parameters and their levels for AA 6061-T_6 aluminium alloy

Factors	Units	Notation	Factor levels				
			-2.378	**-1**	**0**	**+1**	**+2.378**
Tool rotational speed	**(rpm)**	N	824	1100	1300	1500	1775
Welding speed	**(mm/ min)**	S	15.5	50	75	100	134.4
Axial force	**(kN)**	F	2.2	5	7	9	11.7
Tool shoulder diameter	**(mm)**	D	7.8	12	15	18	21
Pin diameter	**(mm)**	d	2.6	4	5	6	7.3
Tool hardness	**(Hv)**	H	243	450	600	750	956

Table 4 Experimental design matrix and results

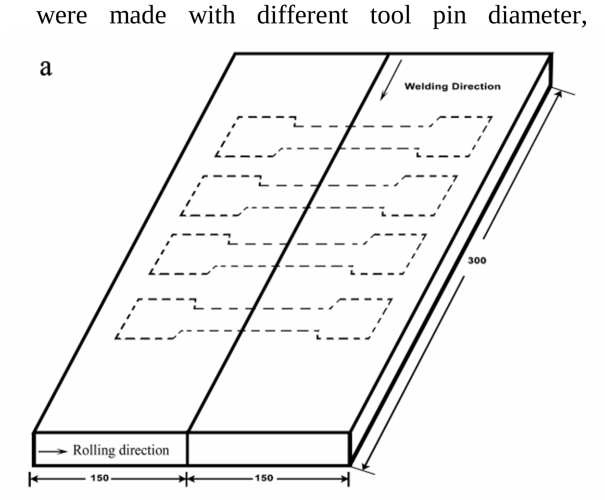
Exp no	Input parameter						Output response
	Tool rotational speed	Welding speed	Axial force	Tool shoulder diameter	Pin diameter	Tool hardness	Tensile strength (MPa)
1	-1	-1	-1	-1	-1	-1	165
2	1	-1	-1	-1	-1	1	179
3	-1	1	-1	-1	-1	1	182
4	1	1	-1	-1	-1	-1	178
5	-1	-1	1	-1	-1	1	191
6	1	-1	1	-1	-1	-1	195
7	-1	1	1	-1	-1	-1	191
8	1	1	1	-1	-1	1	202
9	-1	-1	-1	1	-1	1	184
10	1	-1	-1	1	-1	-1	190

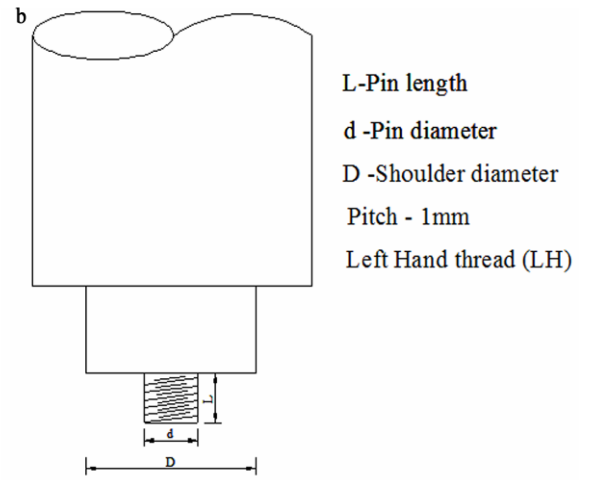
11	-1	1	-1	1	-1	-1	180
12	1	1	-1	1	-1	1	195
13	-1	-1	1	1	-1	-1	185
14	1	-1	1	1	-1	1	192
15	-1	1	1	1	-1	1	191
16	1	1	1	1	-1	-1	202
17	-1	-1	-1	-1	1	1	182
18	1	-1	-1	-1	1	-1	188
19	-1	1	-1	-1	1	-1	178
20	1	1	-1	-1	1	1	193
21	-1	-1	1	-1	1	-1	184
22	1	-1	1	-1	1	1	191
23	-1	1	1	-1	1	1	194
24	1	1	1	-1	1	-1	202
25	-1	-1	-1	1	1	-1	191
26	1	-1	-1	1	1	1	202
27	-1	1	-1	1	1	1	198
28	1	1	-1	1	1	-1	206
29	-1	-1	1	1	1	1	172
30	1	-1	1	1	1	-1	200
31	-1	1	1	1	1	-1	188
32	1	1	1	1	1	1	200
33	-2.378	0	0	0	0	0	187
34	2.378	0	0	0	0	0	207
35	0	-2.378	0	0	0	0	186
36	0	2.378	0	0	0	0	196
37	0	0	-2.378	0	0	0	188
38	0	0	2.378	0	0	0	201
39	0	0	0	-2.378	0	0	184
40	0	0	0	2.378	0	0	198
41	0	0	0	0	-2.378	0	188
42	0	0	0	0	2.378	0	198
43	0	0	0	0	0	-2.378	186
44	0	0	0	0	0	2.378	191
45	0	0	0	0	0	0	222
46	0	0	0	0	0	0	226
47	0	0	0	0	0	0	225
48	0	0	0	0	0	0	221
49	0	0	0	0	0	0	220

50	0	0	0	0	0	0	223
51	0	0	0	0	0	0	226
52	0	0	0	0	0	0	222

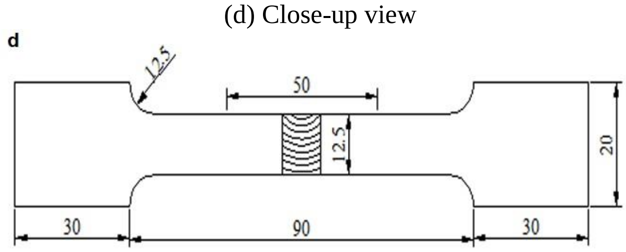
2.4 Conducting The Experiments And Recording The Responses

Rolled plates of 5 mm thickness, medium strength aluminium AA6061-T_6 alloy base metal, were cut to 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. 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. The joint dimensions are shown in Fig.1 (a). Single pass welding procedure was followed to fabricate the joints. Non-consumable tools made of high carbon steel were used to fabricate the joints. The tool nomenclature is shown in Fig. 1(b). Fifteen tools were made with different tool pin diameter, shoulder diameter and tool hardness. Five levels of tool hardness were obtained by heat treating high carbon steel in different quenching media (air, oil, water, furnace cooling). Fifty-two joints (Fig. 1c) were fabricated as per the condition dictated by the design matrix. The welded joints were sliced using a power hacksaw and then machined to the required dimension of tensile specimens as shown in Fig.1 (d). The specimens were prepared as per the ASTM E8M-04 guidelines. The tensile test was carried out in 100kN, servo controlled universal testing machine (make; FIE-BLUESTAR, India). The specimen was loaded at the rate of1.5kN/min as per ASTM specifications. At each experimental condition, three specimens were tested and average values are presented in Table 4.





(a) Joint dimensions (in 'mm') (b) Nomenclature of FSW tool
(c) FSW machine (d) Close-up view



(c) Fabricated joints (d) Dimensions of flat tensile specimens (in'mm')

Fig. 1 Experimental details

3. DEVELOPING AN EMPIRICAL RELATIONSHIP

Representing 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:

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

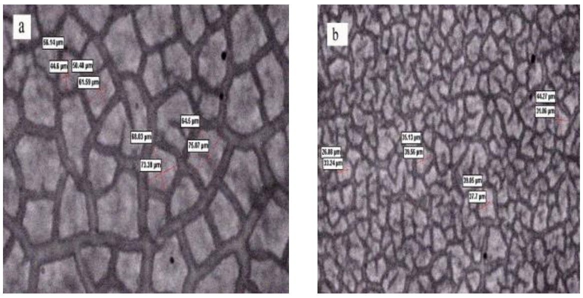
and for six factors, the selected polynomial could be expressed as

Tensile strength

$$\textbf{(}TS)=\{223.18+4.77(N)+2.60(S)+2.77(F)+2.64(D)+2.10(d)+0.85(H)+1.16(ND)+0.97(Nd)-1.22(NH)+0.97(SF)+1.09(SH)-3.78(FD)-3.22(Fd)-1.66(FH)-1.28(DH)-1.09(dH)-4.74(N^2)-5.80(S^2)-5.19(F^2)-5.80(D^2)-5.45(d^2)-6.25(H^2)\}\text{MPa} \quad (3)$$

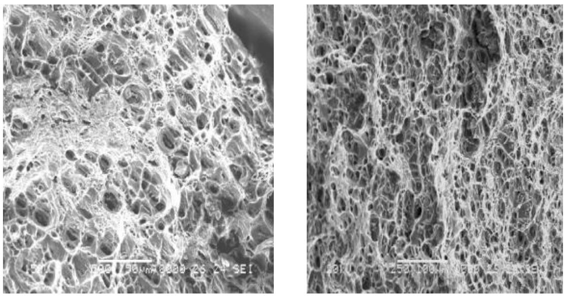
3.1 Validation

Three joints were fabricated using the optimum values of process parameters and average tensile strength of friction stir welded AA 6061-T_6 aluminium alloy was found to be 226 MPa, which shows the excellent agreement with the predicted values. Micrographs of Fig. (2b) shows the traverse section of FSW joint fabricated using optimum parameters reveals that there is no defect due to sufficient heat generation and contains finer grains in the weld zone. But in base metal contains coarse and elongated grains appear in Fig.2 (a). The average grain diameter was measured in the stir zone and it was found to be smaller (30 µm), compared to the base metal (55 µm). The fracture surfaces of the tensile tested specimens were characterized using SEM to understand the failure patterns. All the fracture surfaces invariably consist of dimples, which is an indication that the failure is the result of the ductile fracture. The fracture surface of the base metal Fig.3 (a) shows larger dimples than the stir zone Fig. 3(b).



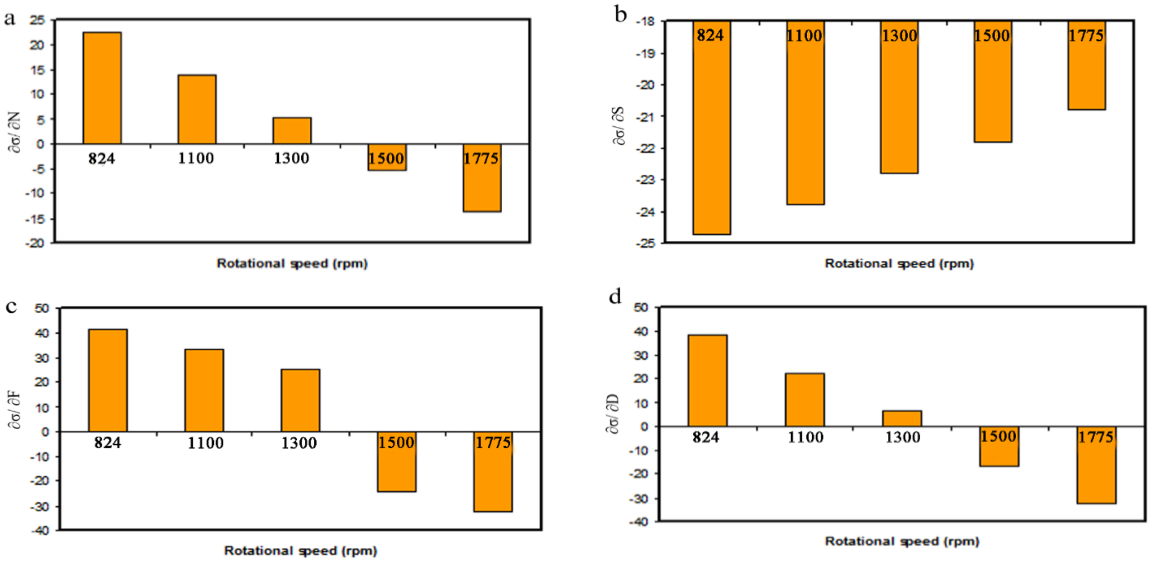
(a) Base metal **(b) Stir zone**

Fig. 2 Optical micrographs



(a) Base metal **(b) Stir zone**

Fig. 4 SEM fractographs of tensile specimens



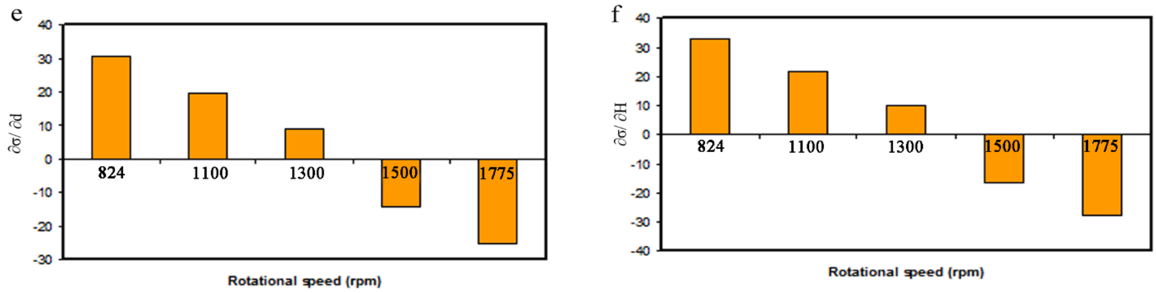


Fig. 4 Sensitivity analysis results: (a). Rotational speed (rpm); (b). Welding speed (mm/min); (c). Axial force (kN); (d). Shoulder diameter (mm); (e). Pin diameter (mm); (f). Tool hardness (Hv);

5. SENSITIVITY ANALYSIS

In this present investigation it is aimed to predict the tendency of tensile strength due to a small change in process parameters for the FSW process and 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. The sensitivity equations (4), (5), (6), (7), (8), and (9) represent the sensitivity of tensile strength for rotational speed, welding speed, axial force, shoulder diameter, pin diameter and tool hardness respectively.

$$\partial TS/\partial N=4.77-0.022S+0.53F+1.16D+0.97d-1.22H-9.48N \quad (4)$$

$$\partial TS/\partial S=2.60-0.22N+0.97F-0.031D+0.28d+1.09H-11.6S \quad (5)$$

$$\partial TS/\partial F=2.77+0.53N+0.97S-3.78D-3.22d-1.28H-10.38F \quad (6)$$

$$\partial TS/\partial D=2.68+1.16N-0.031S-3.78F+0.28d-1.28H-11.6D \quad (7)$$

$$\partial TS/\partial d=2.10+0.97N+0.28S-3.22F+0.28D-1.09H-10.9d \quad (8)$$

$$\partial TS/\partial H=0.85-1.22N-1.09S-1.66F-1.28D-1.09d-12.5H \quad (9)$$

Sensitivity 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. Fig.4 shows the sensitivity of rotational speed, welding speed, axial force, shoulder diameter, pin diameter, and tool hardness respectively on tensile strength. The small variation of welding speed causes large changes in tensile strength when the speed increases. The results reveal that the tensile strength is more sensitive to welding speed than rotational speed, tool hardness, axial force, pin diameter, and shoulder diameter.

6. CONCLUSIONS

From this investigation, the following important conclusions are derived.

1). An empirical relationship was developed to predict the tensile strength of friction stir welded AA6061-T_6 aluminium alloy joints at 95% confidence level, incorporating FSW process and tool parameters.
2). A maximum tensile strength of 225 MPa is exhibited by the FSW joints fabricated with the optimized parameters of 1410 rpm rotational speed, 80.25 mm/min welding speed, 7.34 kN axial force, shoulder diameter of 15.5 mm, pin diameter of 5.5 mm and tool hardness of 600 Hv.
3). Welding speed is more sensitive than other parameters followed by rotational speed, tool hardness, axial force, pin diameter, and shoulder diameter.

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