Predicting tensile strength and interface hardness of friction welded dissimilar joints of austenitic stainless steel and aluminium alloy by empirical relationships

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ABSTRACT

Friction welding can be used to join different types of ferrous metals and non-ferrous metals that cannot be welded by traditional fusion welding processes. The process parameters such as rotational speed, friction pressure, forging pressure, friction time and forging time play the major roles in determining the strength of the joints. In this investigation, an attempt was made to develop empirical relationships to predict the tensile strength and interface hardness of friction welded dissimilar joints of AISI 304 austenitic stainless steel (ASS) and AA6082 aluminium (Al) alloy using statistical tools such as design of experiments, analysis of variance and regression analysis. The developed empirical relationships can be effectively used to predict tensile strength and interface hardness of friction welded dissimilar joints of ASS-Al at 95% confidence level.

Key words: friction welding, austenitic stainless steel, aluminium alloy, design of experiments, analysis of variance, tensile strength.

1.0 INTRODUCTION

Joints of dissimilar metal combinations are employed in different applications requiring certain special combination of properties as well as to save cost incurred towards costly and scarce materials [1]. Conventional fusion welding of many such dissimilar metal combinations is not feasible owing to the formation of brittle and low melting intermetallics due to metallurgical incompatibility, wide difference in melting point, thermal mismatch, etc. Solid-state welding processes that limit extent of intermixing are generally employed in such situations. Friction welding is one such solid-state welding process widely employed in such situations [2].

Dobrovidov [3] investigated selection of optimum conditions for the friction welding of high speed steel to carbon steel. Ishibashi et al. [4] chose stainless steel and high speed steel as representative materials with an appreciably difficult weldability, and their adequate welding conditions were established. The distributions of the alloying elements at and near the weld interface with sufficient strength were analysed using X-ray microanalyser. Sahin [5] has analysed the variations in hardness and microstructure at the interfaces of friction welded steel joints. While using austenitic stainless steel, negative metallurgical changes like delta ferrite formation and chromium carbide precipitation between grain boundaries took place during fusion welding. These changes are eliminated by friction welding. The effect of friction time on the fully plastically deformed region in the vicinity of the weld has been investigated by Sathiya et al. [6].

Ananthapadmanaban et al. [7] have reported the effect of friction welding parameters on tensile properties of steel. Satyanarayana et al. [8] joined austenitic–ferritic stainless steel (AISI 304 and AISI 430) using continuous drive friction welding and investigated optimum parameters, microstructures-mechanical property and fracture behaviours. Yılmaz [9] investigated variations in hardness and microstructures in the welding zone of friction welded dissimilar materials. The effect of friction pressure on the properties of hot rolled iron based super alloy has been investigated by Afes et al. [10]. Meshram et al. [11] investigated the influence of interaction time on microstructure and tensile properties of the friction welding of dissimilar metal combinations. Recently, Paventhan et al. [12] optimized friction welding parameters to attain maximum tensile strength using Response surface methodology.

In rotary friction welding, in order to ensure good metallurgical integrity, it is necessary to break up and expel the contaminated surface layers. This is achieved with greater friction pressure and upset times. At the low friction pressure and forging pressures, the friction heat is not enough to soften the interfacial materials; and the interface temperature is relatively low due to low heat input. As time increases, the friction and contact area also significantly increases the heat generation on the interfaces, and in return flash is formed. Hence, axial shortening increases remarkably with the interface temperature rise and softening of materials following the extruding process under the rotary motion. Therefore, forging pressure, friction pressure and times are key parameters in controlling the formation of a perfect joint [13].

To prevent overheating in the welding region, friction pressure and friction time have to be carefully controlled. Pressure values applied in welding is very significant because it controls temperature gradient and affects rotational torque as well as power. Friction and forging pressure are directly related to geometry and material properties of parts to be welded and have a wide range. Over applied pressure values increase power needs accordingly. Due to increased energy input, higher pressures accelerate metal displacement ratio and reduces welding time resulting in heat band on the boundary. The variable of pressure can be controlled by the temperature in welding region and decrease in axial length. Optimum pressure must be applied to materials in order to get uniform deformations throughout [14]

From the literature review [3–14], it is understood that most of the published information on friction welding of dissimilar material focus on the microstructural characteristics, microhardness variations, phase formation and tensile properties evaluation. All the above mentioned investigations were carried out on trial and other basis to attain optimum welding conditions. No systematic study has been so far reported to predict tensile strength and interface hardness of friction welded dissimilar joints of austenitic stainless steel and aluminium alloy. Hence in this investigation, an attempt was made to develop empirical relationships to predict tensile strength and interface hardness of friction welded dissimilar joints of AISI 304 austenitic stainless steel (ASS) and AA 6082 aluminium (Al) alloy using statistical tools such as design of experiments, analysis of variance and regression analysis.

2.0 EXPERIMENTAL WORK

2.1 Evaluations of base metals properties

The base metals used in this investigation were extruded rods of austenitic stainless steel and aluminium alloy. The chemical composition of the base metals was obtained using a vacuum spectrometer (Make: ARL USA; Model: 3460). Sparks were ignited at various locations of the base metal sample and their spectrum was analyzed for the estimation of alloying elements. The chemical compositions of the base metals are given in **Table 1**. Tensile specimens were prepared to obtain the base metal tensile properties. ASTM E 8M-04 (ASTM, 2004a) guidelines were followed for preparing the test specimens. Tensile test was carried out in 100 kN, electro-mechanical controlled Universal Testing Machine (Make: FIE-BLUE STAR, India; Model: UNITEK-94100). The specimen was loaded at the rate of 1.5 kN/min as per ASTM specifications, so that tensile specimen undergoes uniform deformation. The specimen finally failed after the necking and the load versus displacement was recorded. The 0.2% offset yield strength was derived from the diagram. The percentage of elongation and reduction in cross sectional area were evaluated and the values are presented in **Table 2**. A Vicker's microhardness testing machine (Make: Shimadzu, Japan; Model HMV-2T) was employed for measuring the hardness of the base metals with 0.5 kg load. Microstructural examination was carried out using a light optical microscope (Make: MEIJI, Japan, Model: MI7100).

2.2 Finding the working limits of the welding parameters

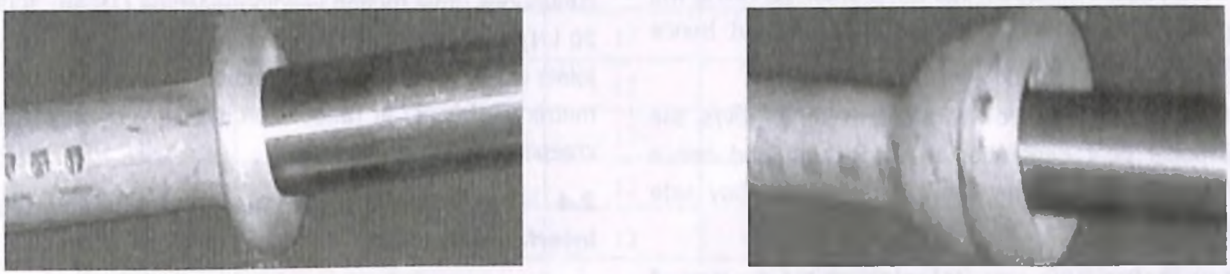
From the literature [3-12] the predominant factors which are having greater influence on tensile strength and interface hardness of friction welded (FW) joints were identified. They are: (i) friction pressure, (ii) forging pressure, (iii) friction time and (iv) forging time and (v) rotational speed. Though there are five factors, in this investigation, these factors are combined in such a way that to make as three factors. They are: (i) the ratio between friction pressure and friction time (F), (ii) the ratio between forging pressure and forging time (D) and (iii) rotational speed per second (N). A large number of trial

Table 1 : Chemical composition (wt %) of ASS and Al alloy

Elements	C	Mn	Si	P	S	Cr	Ni	Cu	Fe	Al
ASS (AISI304)	0.06	1.38	0.32	0.06	0.1	18.4	8.7	0.04	Bal	0.5
Al alloy (AA6061)	–	0.70	0.90	–	–	0.25	–	–	0.5	Bal

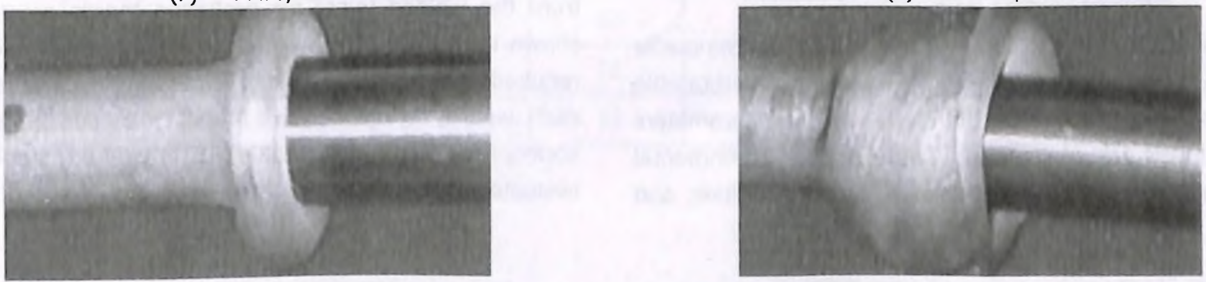
Table 2: Mechanical properties of ASS and Al alloy

Materials	Yield strength (Mpa)	Tensile strength (Mpa)	Elongation in 50 mm gauge length (%)	Reduction in cross sectional area (%)	Micro hardness @ 0.5 kg (Hv)
ASS (AISI 304)	410	560	30	24	300
Al alloy (AA 6082)	260	310	20	18	102



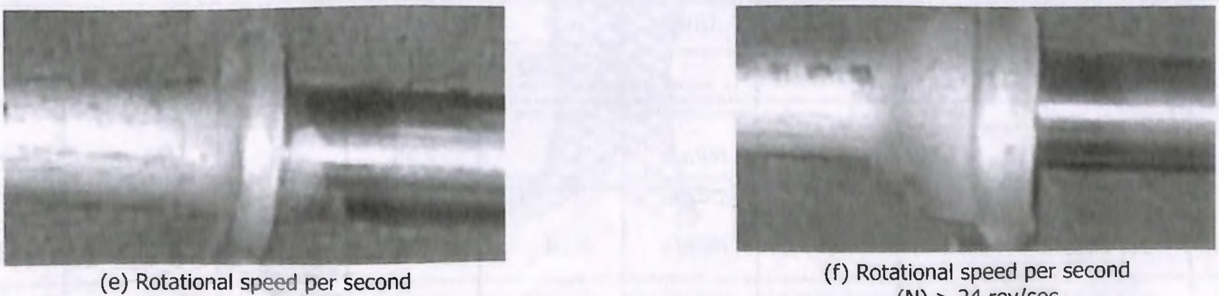
(a) Friction pressure per second (F) < 4 MPa/sec

(b) Friction pressure per second (F) > 20 MPa/sec



(c)Forging pressure per second (D) < 4 MPa/sec

(d) Forging pressure per second (D) > 20 MPa/sec



(e) Rotational speed per second (N) < 12 rev/sec

(f) Rotational speed per second (N) > 24 rev/sec

Fig. 2 : Photographs of the joint fabricated outside the feasible working limits

experiments were conducted to determine the working range of the above factors by varying one of the process parameters and keeping rest of them at a constant value. The working range was fixed in such a way that the friction welded joints should be free from any visible external defects.

(i) If the friction pressure per second was lower than 4 MPa/s, the joint was not properly bonded due to less heat generation and insufficient pressure (**Fig. 2a**).

(ii) If the friction pressure per second was more than 20 MPa/s, then the Al alloy underwent large deformation due to high heat generation and excessive pressure (**Fig. 2b**).

(iii) If the forging pressure per second was lower than 4 MPa/s, deformation of the material is low, then the joints were weakly bonded (**Fig. 2c**)

(iv) If the forging pressure per second was more than 20 MPa/s, then resulted in extensive deformation in the Al alloy side (**Fig. 2d**)

(v) If the rotational speed was lower than 12 rev/s, the frictional heat generation was too low and hence bonding was improper (**Fig. 2e**);

(vi) If the rotational speed was greater than 24 rev/s, the frictional heat generation was too high and hence excessive flash formation occurred in Al alloy side (**Fig. 2f**)

2.3 Developing experimental matrix & fabrication of joints

As the range of individual factor was wide, a central composite rotatable three-factors, five-level, central composite rotatable design matrix was selected. The chosen welding parameters and the levels are presented in **Table 3**. The experimental design matrix consisting 20 sets of coded condition and comprising a full replication three-factor factorial design of 8 points, 6 star points, and 6 center points was used (**Table 4**). The method of designing such matrix is dealt elsewhere [15]. The upper and lower limits of the parameters were coded as +1.682 and −1.682, respectively. The coded values for intermediate levels can be calculated from the following relationship [15].

$$X_i = 1.682\ [2X - (X_{max} + X_{min})]\ /\ (X_{max} - X_{min}) \qquad (1)$$

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;

Cylindrical rods of ASS and Al alloy having 12 mm diameter were cut to the required length of 75 mm by power hacksaw. The surfaces to be joined were faced using a lathe machine to fabricate friction welded joints. Hydraulic controlled, continuous drive friction welding machine (15 hp; 3000 rpm; 20 kN) was used to fabricate the joints. The friction welded joints were made as per the conditions dictated by the design matrix (**Table 4**) at random order so as to avoid the noise creeping output response.

2.4 Recording the responses (tensile strength and interface hardness)

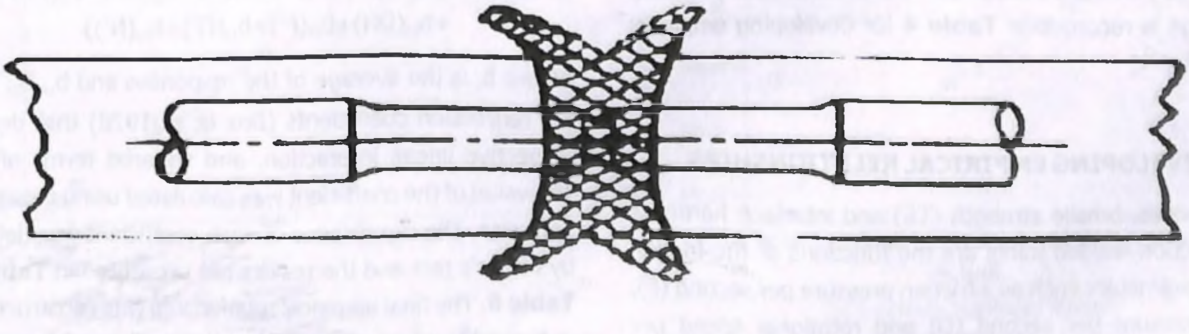
The schematic representation of extraction of tensile specimen from the welded joints for preparing tensile specimens is shown in **Fig. 3a**. The welded joints were machined to the required dimensions (**Fig. 3b**). Three tensile specimens from each welding conditions were fabricated as per the American society for Testing of Materials (ASTM E8M-04) standards to evaluate the tensile strength of the joints. Tensile test was

Table 3 : Feasible working range of the friction welding parameters

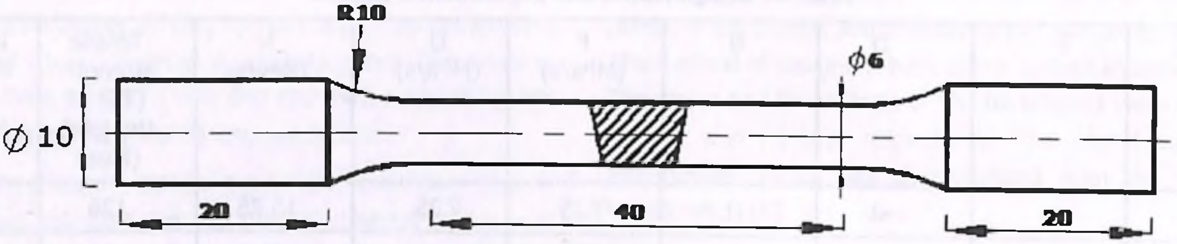
S.No.	Parameter	Notation	Unit	Levels				
				-1.682	-1.0	0	+1.0	+1.682
1	Friction Pressure per second	F	MPa/s	4	7.25	12	16.75	20
2	Forging pressure per second	D	MPa/s	4	7.25	12	16.75	20
3	Rotational speed per second	N	Rev/s	12	15	18	21	24

Table 4 : Design Matrix and Experimental Results

Expt. No.	F	D	N	F (MPa/s)	D (MPa/s)	N (Rev/s)	Tensile strength (TS) of the joint (Mpa)	Interface hardness (IH) of the joint (Hv)
1	-1	-1	-1	7.25	7.25	15.25	126	163
2	+1	-1	-1	16.75	7.25	15.25	142	156
3	-1	+1	-1	7.25	16.75	15.25	145	138
4	+1	+1	-1	16.75	16.75	15.25	159	135
5	-1	-1	+1	7.25	7.25	21.75	123	160
6	+1	-1	+1	16.75	7.25	1.75	105	181
7	-1	+1	+1	7.25	16.75	21.75	139	152
8	+1	+1	+1	16.75	16.75	21.75	104	178
9	-1.682	0	0	4	12	18	128	162
10	+1.682	0	0	20	12	18	107	172
11	0	-1.682	0	12	4	18	120	163
12	0	+1.682	0	12	20	18	143	142
13	0	0	-1.682	12	12	15	145	136
14	0	0	+1.682	12	12	24	125	171
15	0	0	0	12	12	18	197	115
16	0	0	0	12	12	17	175	121
17	0	0	0	12	12	18	190	113
18	0	0	0	12	12	18	188	118
19	0	0	0	12	12	18	189	122
20	0	0	0	12	12	18	198	120

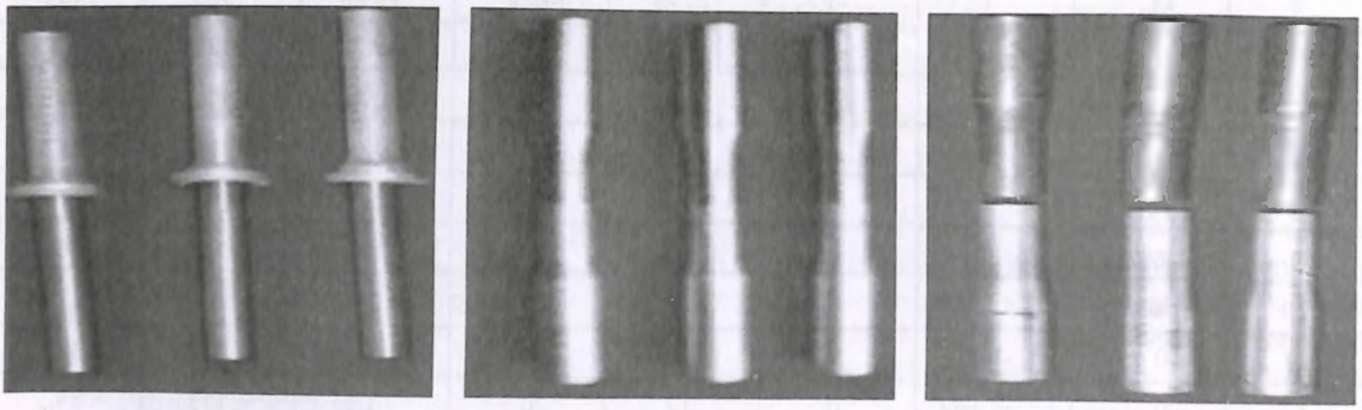


(a) The schematic representation of extraction of tensile specimen



(b) Tensile Specimen
(All dimensions are in mm)

Fig. 3 : Dimensions of tensile specimen



(a) Friction welded joints

(b)Tensile specimens
(before testing)

(c) Tensile specimens
(after testing)

Fig. 4 Photographs of welded joints and tensile specimens

carried out in 100 kN, electro-mechanical controlled Universal Testing Machine. The specimen was loaded at the rate of 1.5 kN/min as per the ASTM specifications. The average of three tensile tested specimen value of each condition was presented in **Table 4** for developing empirical relationship. **Fig. 4** shows the photographs of friction welded joints, tensile specimen before and after testing.

Vickers's microhardness testing machine (Make: SHIMADZU, Japan; Model: HMV-T1) was employed for measuring the hardness along the joint interface with 0.5 kg load @ 15 seconds dwell time. Five readings were taken in each joint and the average is recorded in **Table 4** for developing empirical relationship.

3.0 DEVELOPING EMPIRICAL RELATIONSHIPS

The responses, tensile strength (TS) and interface hardness (IH) of friction welded joints are the functions of the friction welding parameters such as a friction pressure per second (F), forging pressure per second (D) and rotational speed per second (N) and they can be expressed as [16].

$$TS = f\{F, D, N\} \quad (2)$$

$$IH = f\{F, D, N\} \quad (3)$$

The second-order polynomial (regression) equation used to represent the response surface

Y (TS or IH) is given by [15]

$$Y=b_0+\Sigma b_i x_i+\Sigma b_{ii} x_i^2+\Sigma b_{ij} x_i x_j, \quad (4)$$

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

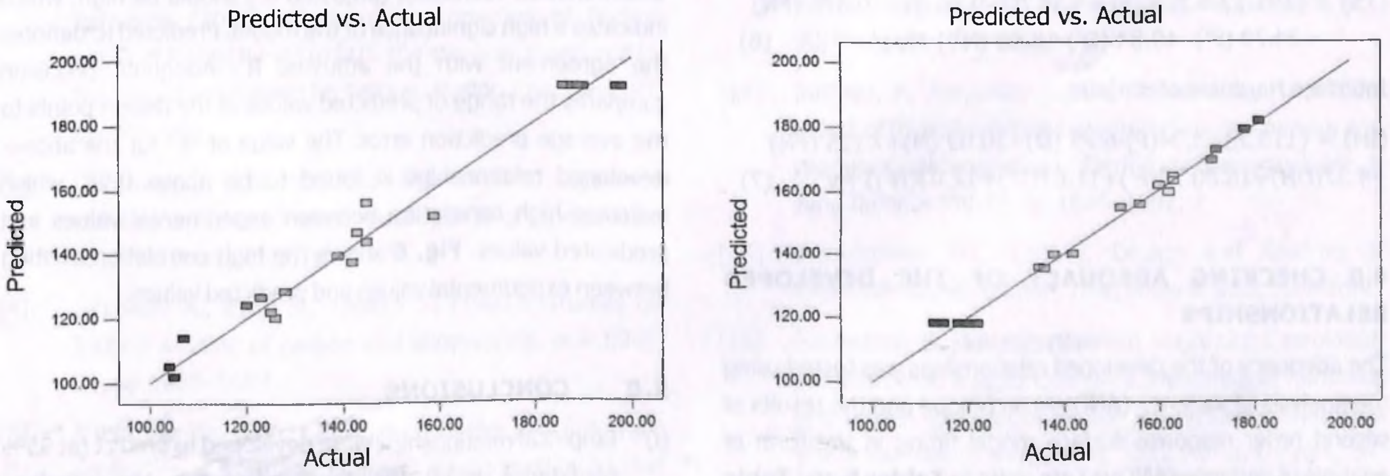
$$\text{TS or IH} = \{b_0+b_1(F)+b_2(D)+b_3(N)+b_{12}(FD)+b_{13}(FN) +b_{23}(DN)+b_{11}(F^2)+b_{22}(D^2)+b_{33}(N^2)\} \quad (5)$$

Where b_0 is the average of the responses and b_1, b_2, b_3,..., b_{44} are regression coefficients (Box et al.,1978) that depend on respective linear, interaction, and squared terms of factors. The value of the coefficient was calculated using Design Expert Software. The significance of each coefficient was determined by Fisher's test and the results are presented in **Table 5** and **Table 6**. The final empirical relationship was constructed using only significant co-efficients and the developed final empirical relationships are given below:

Table 5 : ANOVA Test Results for Tensile Strength Model

Source	Sum of Squares (SS)	Degrees of freedom (df)	Mean Square (MS)	'F' ratio calculated	'F' ratio from table @ 95% confidence level	*Whether significant or not?
Model	19497.93	9	2166.437	46.99242		
F	249.0287	1	249.0287	5.401708	4.96	Yes
D	588.9148	1	588.9148	12.77422	4.96	Yes
N	1327.305	1	1327.305	28.79072	4.96	Yes
FD	45.125	1	45.125	0.978811	4.96	No
FN	861.125	1	861.125	18.67876	4.96	Yes
DN	55.125	1	55.125	1.195722	4.96	No
F2	8857.895	1	8857.895	192.1376	4.96	Yes
D2	5674.015	1	5674.015	123.0757	4.96	Yes
N2	4988.381	1	4988.381	108.2035	4.96	Yes
Residual	461.0183	10	46.10183			
Lack of Fit	337.685	5	67.537	2.737987	0.1466	Not significant
Std. Dev.		6.789		R-Squared		0.9769
Mean		147.95		Adj R-Squared		0.9561
C.V. %		4.5892		Pred R-Squared		0.8606
PRESS		2780.85		Adeq Precision		18.601

*$F_{(1,10,0.05)}$ = 4.96; If F calculated > F_{table}, then the term is considered to be significant



(a) Tensile strength model

(b) Interface Hardness model

Fig. 6 : Correlation graphs

Table 6 : ANOVA Test Results for Interface Hardness Model

Source	Sum of Squares (SS)	Degrees of freedom (df)	Mean Square (MS)	'F' ratio calculated	'F' ratio from table @ 95% confidence level	*Whether significant or not?
Model	9637.004	9	1070.778	117.9321		
F	212.0817	1	212.0817	23.35801	4.96	Yes
D	624.0492	1	624.0492	68.7308	4.96	Yes
N	1391.692	1	1391.692	153.2766	4.96	Yes
FD	10.125	1	10.125	1.115135	4.96	Yes
FN	406.125	1	406.125	44.72932	4.96	Yes
DN	153.125	1	153.125	16.8647	4.96	Yes
F^2	4069.149	1	4069.149	448.1632	4.96	Yes
D^2	1965.013	1	1965.013	216.4203	4.96	Yes
N^2	2085.807	1	2085.807	229.7242	4.96	Yes
Residual	90.79614	10	9.079614			
Lack of Fit	27.96281	5	5.592562	0.445031	0.8025	Not significant
Std. Dev.		3.013		R-Squared	0.9906	
Mean		145.9		Adj R-Squared	0.9825	
C.V. %		2.065		Pred R-Squared	0.9689	
PRESS		302.26		R-Squared	29.53	

$^*F_{(1,10,0.05)} = 4.96$; If F calculated > F_{table}, then the term is considered to be significant

Tensile strength of the joint,

$$(TS) = \{191.13-4.270\ (F) +6.56\ (D)-9.86\ (N)-10.375\ (FN) -24.79\ (F^2) -19.84\ (D^2)-18.60\ (N^2)\}\ \text{Mpa} \qquad (6)$$

Interface Hardness of the joint,

$$(IH) = \{118.23+3.94(F)-6.75\ (D)+10.09\ (N)+7.125\ (FN) +4.37(DN)+16.80.79(F^2)+11.67(D^2)+12.03(N^2)\}\ \text{Hv} \qquad (7)$$

4.0 CHECKING ADEQUACY OF THE DEVELOPED RELATIONSHIPS

The adequacy of the developed relationships was tested using the analysis of variance (ANOVA) technique and the results of second order response surface model fitting in the form of analysis of variance (ANOVA) are given in **Tables 5** and **Table 6**. The determination coefficient (R^2) indicates the goodness of fit for the model. In this case, the values of the determination coefficient (R^2) indicate that the model does not explain only less than 5% of the total variations [17]. The values of adjusted determination coefficient (adjusted R^2) should be high, which indicates a high significance of the model. Predicted R^2 denotes the agreement with the adjusted R^2. Adequate precision compares the range of predicted values at the design points to the average prediction error. The value of 'R^2' for the above-developed relationships is found to be above 0.95, which indicates high correlation between experimental values and predicated values. **Fig. 6** shows the high correlation existing between experimental values and predicted values.

5.0 CONCLUSIONS

(i) Empirical relationships were developed to predict (at 95% confidence level) the tensile strength and interface hardness of friction welded dissimilar joints of AISI 304 austenitic stainless steel and AA6082 aluminium alloy incorporating friction welding parameters.

(ii) From the 'F' ratio calculation, it is understood that the factor N, rotational speed per second has predominant effect on tensile strength and interface hardness of the friction welded dissimilar joints of ASS-Al alloy. Similarly, the factor F, friction pressure per second is observed to be less significant in controlling the tensile strength and interface hardness of the friction welded joints.

(iii) From this investigation, it is found that th maximum tensile strength that could be attained in the friction welded dissimilar joints of ASS-Al alloy is 198 MPa under the welding conditions of F=12 MPa/s, D=12 MPa/s and N=18 rev/s.

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