Journal of Manufacturing Engineering, June 2016, Vol. 11, Issue.2 , pp 079-085

DEVELOPING EMPIRICAL RELATIONSHIP TO PREDICT THE TENSILE STRENGTH OF FRICTION STIR WELDED BUTT JOINTS OF AA2014-T6 ALUMINUM ALLOY

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ABSTRACT

The copper containing aluminum alloy (AA2014) has been widely used in aircraft structural applications due to exceptional characteristics of corrosion resistance, high strength to weight ratio and good formability. Welding of these grade of aluminum alloys is very difficult by fusion welding techniques. Because, the joints can become more susceptible to stress corrosion cracking and hot cracking, alloy segregation, etc. So, they are mechanically fastened rather than fusion welded. Friction stir welding (FSW) is a new solid state welding process, in which the material being welded does not melt and not involve any phase transformation. However, there are many FSW parameters controlling the strength and performance of the joints. Hence, in this investigation, an attempt has been made to develop empirical relationship to predict tensile strength of butt joints of AA2014 aluminum alloy incorporating predominant FSW parameters. The developed empirical relationship can be effectively used to predict the tensile strength of friction stir welded butt joints of AA2014 –T6 aluminum alloy at the 95% confidence level.

Keywords: *Friction stir welding, Al-Cu alloy, Butt joint, Tensile strength, Design of experiments, Analysis of variance.*

1. Introduction

Aluminum is the most prominent material to meet the challenges of future automotive regarding high strength to weight ratio, corrosion resistance, emissions, safety and sustainability [1]. High thermal and electrical conductivity cause problems in fusion and resistance welding of aluminum alloys [2]. Friction Stir Welding (FSW) is a solid state welding process and it is considered to be the most significant development in metal joining technique in the last decade, FSW was invented by The Welding Institute (TWI) UK, and it was initially applied to join aluminum alloys. However, the extended application of this welding process in industry still require accurate knowledge of this joining mechanism, and the metallurgical and mechanical properties changes it induces in the base materials [3]. Actually the effectiveness of the obtained joint is strongly dependent on several operating parameters [4]. First of all, the geometry parameters of the tool, such as tool pin height, shape of the profile and shoulder surface of the head, have greater influence on both metal flow and heat generation due to friction forces [5]. Secondly, the process parameters such as tool rotational speed, welding speed, and tool tilt angle etc., to be selected in order to improve nugget integrity that results in a proper microstructure and eventually in good tensile strength, fatigue strength and ductility of the joint [6].

In FSW process, heat generated by friction between the butting surfaces of the plates and the contact surface of a tool. It is composed of two main parts: shoulder and pin. Shoulder is the primary factor for the heat generation and for containing the plasticized material in the weld zone, while the pin stirs the material of the component to be welded, thus creating a joint [7]. This allows fabrication of defect-free welds characterized by good mechanical properties.

Wang et al [8] analyzed the effect of tool rotational speed on the microstructural characteristics and mechanical properties of bobbin tool friction stir welding (FSW) of third generation Al-Li alloy AA2198. The stir zone (SZ) exhibited hourglass shape and composed of fine grains and precipitates. When the tool rotational speed increases the grain size in the SZ increases and density of strengthening precipitates decreases. The joint line remnant became compressed in the shoulder driven zone and less in the pin driven zone. Zang et al [9] investigated the effect of important process parameters on microstructure and mechanical properties of FSW joints of high strength Al-Zn-Cu-Mg

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aluminum alloy. It was observed that the grains size in the SZ decreased with the tool rotational speed decreasing and welding speed increasing. Dhondt et al [10] investigated the mechanical properties of periodical microstructure induced by the FSW on Al-Cu-Li alloy and they found three types of microstructure heterogeneity namely, grain size, precipitate and texture bands. The grain size and θ_1 precipitates density decreases with the distance from the weld surface.

Essa et al [11] formulated the analytical model of heat generation for the use of eccentric type pin in FSW, they used two process parameters such as plunge force and peak temperature and validated in this model. Experimental result shows that less temperature is generated using eccentric type pin than non-eccentric pin under given set of FSW parameters. Liu et al [12] analyzed the effect of FSW parameters on dissimilar aluminum alloy to high strength steel. The UTS can reach 85% of aluminum base metal, which was attributed due to the intermetallic formation of FeAl or Fe_3Al with thickness of 1µm was formed at Al-Fe interface in the AS. Cai et al [13] investigated the microstructure and mechanical properties of 2060 aluminum Cu-Li alloy. The base metal is mainly strengthened by T_1 type precipitate with small amount of ϴ' and S', these strengthening precipitates were dissolved in the nugget zone, the dense dislocation and nano size co-cluster were found in the SZ. Rajakumar et al [14] analyzed the effect of FSW parameters on microstructure and mechanical properties of AA1100 aluminum joints with the different D/d ratio (1.8 to 4.2), the joints fabricated using D/d ratio of 3 yielded the maximum tensile strength compared to other joints. However, the effect of tool rotational speed on tensile strength of FSW AA2014 and AA7075 dissimilar aluminum joints. Five joints were made at different tool rotational speed; it was found that the maximum tensile strength was achieved at the rotational speed of 1500 rpm [15]. Krishnakumar et al [16] optimized the FSW parameters using response surface methodology, the test results show that increasing in frictional force and forging pressure resulted in increasing the tensile strength.

It is well known that the welding parameters play a major role in determining the weld quality as the process facts have not been disclosed so far and the selection of process parameters to join aluminum alloy is very difficult. Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques useful for the modeling and analysis of problems in which a response of one interest is influenced by several variables and the objectives is to optimize this response [17]. In this investigation, design of experiment (DoE) was used to reduce the number of experiments, in addition to develop an empirical relation between the joint strength and the welding parameters.

From the literature review [8-16], it is understood that the FSW parameters play major role in deciding the strength and performance of the joints. Though lot of research works have been carried out to understand the effect of individual FSW parameters on mechanical properties and microstructural characteristics, no attempt has been made so far to study the combined effect of all the parameters in a scientific method. Hence, in this investigation, an attempt has been made to develop an empirical relationship to predict tensile strength of friction stir welded butt joints of AA2014-T6 aluminum alloy.

2. Experimental

2.1 Identify important FSW parameters

The chemical composition and mechanical properties of base metal to be welded are presented in Table 1 and Table 2 respectively. The important FSW parameters were identified and selected from the literature. They are: tool rotational speed (N), welding speed (S), tool shoulder diameter (D) and tool tilt angle (Q). Table 3 shows the dimensions of tool used for FSW.

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

Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Al
0.8	0.13	4.8	0.8	0.7	0.06	0.05	0.01	92.4

Table 2. Mechanical properties of base metal

Material	0.2 %Yield stress (MPa)	Ultimate tensile stress (MPa)	Elongation in 50 mm gauge length (%)	Micro hardness 50g, 15 sec (HV)
AA2014	431	463	10	163

2.2 Feasible working range of FSW parameters

Trial runs were carried out using 2 mm-thick high strength aluminum alloy to find out the feasible working limits of FSW parameters. Different combinations of parameters were used to carry out the trial experiments. This was done by varying any one of the factors from minimum to maximum, while keeping the other parameter at constant values (Table 4). The feasible working limits of the individual parameters were identified by inspecting tunnel, lack of fill, worm holes defects, top surface of the weld, macrostructure (cross section of the weld) for a smooth appearance without any visible macro level defects such as pin hole and root defect.

Table 3. Dimensions of the FSW tool

Pin description	Pin diameter		Pin length (mm)	Taper angle in pin (°)	Thread pitch (mm)
	Major diameter (mm)	Minor diameter (mm)			
Threaded taper pin	2.0	1.5	1.5	9.46	0.75

The chosen levels of the selected process parameters with their units and notations are presented in Table 5.

2.3 FSW experiments and UTS evaluation

Fig.1 shows the butt joint configuration used in this investigation. Fig.2 displays the optical micrograph of base metal composed of elongated grains with uneven distribution of second phase particles.

Table 4. Macrostructure analysis for fixing the working range of FSW

Process parameters	Parameters range	Macro graph	Name of the defect	Reason for defect
Tool rotational speed	N> 1700 rpm		Cluster of worm hole	Excess heat input
Tool rotational speed	N<1300 rpm		Lack of fill	Insufficient heat input causes less plastic material flow
Welding speed	S>60 mm/min		Tunnel defect	Low plasticized material transportation
Welding speed	S<20 mm/min		Warm hole	High heat input produced
Tool shoulder diameter	D>8 mm		Cluster of worm holes	Excess heat input due to large area of contact
Tool shoulder diameter	D<4 mm		Tunnel defect	Low heat generation produced insufficient plasticized material transportation
Tool tilt angle	Q>2.5°		Cluster of worm hole	High forging pressure produced more strain hardening
Tool tilt angle	Q<0.5°		Lack of fill	Insufficient Forging force resulted low plasticized Material flow and consolidation

Table 5. FSW parameters and their working range

Sl.No	Parameters	Unit	Notation	Levels				
				-2	-1	0	+1	+2
1	Tool otational speed	rpm	N	1300	1400	1500	1600	1700
2 .	Welding speed	mm/ min	S	20	30	40	50	60
3	Tool shoulder diameter	mm	D	4	5	6	7	8
4	Tool tilt angle	deg.	Q	0.5	1.0	1.5	2.0	2.5

The average grain size of the base metal is 30µm.The FSW joints were made as per the conditions dictated by the design matrix (Table 6) at random order so as to avoid the noise creeping output response. Non-consumable tool made of super HSS alloy was used to fabricate the joints (Fig.3). A tool with a flat concave shoulder and tapered pin were used in FSW (Fig.4). A computer numerical controlled FSW was used to fabricate the joints. Tensile specimens were prepared as per the ASTM-E8-M04. At each condition, three specimens were fabricated and some of the fabricated FSW joints are displayed in Fig. 5.

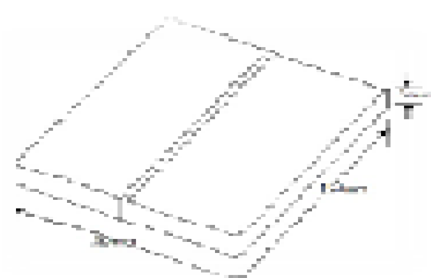

Fig.1 Joint configuration

Fig.2 Optical micrograph of base metal

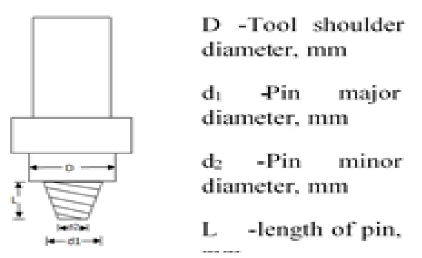

Fig.3 Schematic diagram of FSW tool

Fig.4 Fabricated FSW tools

Tensile test was carried out in 100-kN electromechanically controlled Universal Testing Machine (FIE-Blue star, India; model UNITEK-94100). The specimen was loaded at the rate of 1.5 kN/min as per ASTM specifications until the faying surfaces of the specimen were sheared off (Fig. 6), and the values of tensile strength were recorded and presented in Table 6.

Fig.5 Fabricated FSW joints

Fig.6 Fabricated tensile specimens

3. Developing an mathematical relationship

In this investigation, the response surface methodology (RSM) has been used to develop empirical relationship predict tensile strength of friction stir welded butt joints of AA2014 aluminum alloy in terms of the important FSW parameters. Tensile strength of FSW joint is a function of the welding parameters such as tool rotational speed (N), welding speed (S), tool shoulder diameter and tool tilt angle(Q), and it can be expressed as,

Tensile Strength of FSW joint= f (N,S,D,Q) (1)

Second-order polynomial (regression) equation used to represent the response surface Y is given by,

$$Y=bo+\sum bixi+\sum bixi_2+\sum bijxixj \qquad (2)$$

selected polynomial could be expressed as,

$$UTS=b_o+b_1(N)+b_2(S)+b_3(Q)+b_4(D)+b_{12}(NS)+b_{13}(NQ)+b(ND)+b_{23}(SQ)+b_{24}(SD)+b_{11}(N^2)+b_{22}(S^2)+b_{33}(Q^2)+b_{44}(D^2) \text{ MPa} \qquad (3)$$

Where b_o is the mean value of response and b_1, b_2, b_3 --- b_{44} are linear interactions and square terms of factors [18]. The value of co-efficient was calculated using Design Expert 8 at 95% confidence level.

The significance of each co-efficient was calculated from student t-test and p values, which are listed in Table 7,
value of "Prob>F" less than 0.05 be indicate that model terms are significant. In this case N, S, D, Q, ND, SD, SQ, N^2, S^2, D^2 and Q^2 are the significant terms. The final empirical relationship was constructed using only these co-efficient and the developed final empirical relationship of FSW joints of AA2014 Al alloy is given below

$$UTS=[+377.48+6.7(N)+14.54(S)+13.12(D)+25.37(Q)-0.062(N)S-2.81(ND)-0.19(NQ)-4.06(SD)-3.69(SQ)-18.69(DQ)-26.84(N^2)-14.59(S^2)-13.21(D^2)-23.71(Q^2) \text{ MPa} \qquad (5)$$

The adequacy of the model is tested by Analysis of Variance (ANOVA). The test results of the ANOVA are given in Table 8; the desired confidence level was 95%.

Table 6. Design matrix and experimental results

	Coded values				Actual values				Tensile strength
	N	S	D	Q	N	S	D	Q	(MPa)
1	-1	-1	-1	-1	1400	30	5	1	200
2	+1	-1	-1	-1	1600	30	5	1	242
3	-1	+1	-1	-1	1400	50	5	1	214
4	+1	+1	-1	-1	1600	50	5	1	257
5	-1	-1	+1	-1	1400	30	7	1	242
6	+1	-1	+1	-1	1600	30	7	1	248
7	-1	+1	+1	-1	1400	50	7	1	285
8	+1	+1	+1	-1	1600	50	7	1	309
9	-1	-1	-1	+1	1400	30	5	2	261
10	+1	-1	-1	+1	1600	30	5	2	285
11	-1	+1	-1	+1	1400	50	5	2	261
12	+1	+1	-1	+1	1600	50	5	2	299
13	-1	-1	+1	+1	1400	30	7	2	270
14	+1	-1	+1	+1	1600	30	7	2	266
15	-1	+1	+1	+1	1400	50	7	2	295
16	+1	+1	+1	+1	1600	50	7	2	304
17	-2	0	0	0	1300	40	6	1.5	218
18	+2	0	0	0	1700	40	6	1.5	242
19	0	-2	0	0	1500	20	6	1.5	239
20	0	+2	-2	0	1500	60	6	1.5	261
21	0	0	+2	0	1500	40	4	1.5	314
22	0	0	0	-2	1500	40	8	1.5	361
23	0	0	0	+2	1500	40	6	0.5	204
24	0	0	0	0	1500	40	6	2.5	247
25	0	0	0	0	1500	40	6	1.5	380
26	0	0	0	0	1500	40	6	1.5	370
27	0	0	0	0	1500	40	6	1.5	375
28	0	0	0	0	1500	40	6	1.5	361
29	0	0	0	0	1500	40	6	1.5	365
30	0	0	0	0	1500	40	6	1.5	364

The relationship may be considered to be adequate. If that the calculated value of the F_{ratio} of the developed relationship does not exceed the tabulated value of F_{ratio} for a desired level of confidence, and the model is found to be adequate. The model F value of 193.97 implies that the model is adequate. There is only a 0.01% chance that a model F value this large could occur due to noise. The lack of fit F value of 1.17 implies that the lack of fit is insignificant.

Table 7. Calculated values of coefficients

Coefficient	Factor Estimate
Intercept	377.48
N	6.7
S	14.51
D	13.12
Q	25.37
NS	-0.062
ND	-2.81
NQ	-0.19
SD	4.06
SQ	-3.69
DQ	-18.69
N^2	-26.84
S^2	-14.59
D^2	-13.21
Q^2	-23.71

There is only 36.54% chance that a lack of fit F values this large could occur due to interference. The Fisher's F -test with a very low probability value demonstrates a very high significance of the regression model.

Table 8. ANOVA test results

Source	Sum of Squares (SS)	df	Mean Square (MS)	F-Value	p-value Prob > F	
Model	65738.34	14	4695.6	193.97	< .0001	Significant
N	1080.04	1	1080.04	44.61	< .0001	
S	5075.04	1	5075.04	209.64	< .0001	
D	4134.37	1	4134.37	170.78	< .0001	
Q	15453.37	1	1545.37	638.35	< .0001	
NS	0.063	1	0.063	2.58	0.9601	
ND	126.56	1	126.56	5.23	0.0372	
NQ	0.56	1	0.56	0.023	0.8809	
SD	264.06	1	264.06	10.91	0.0048	
SQ	217.56	1	217.56	8.99	0.0091	
DQ	5587.56	1	5587.56	230.81	< .0001	
N^2	19758.53	1	1975.53	816.19	< .0001	
S^2	5838.33	1	5838.33	241.17	< .0001	
D^2	4789.72	1	4789.72	197.85	< .0001	
Q^2	15425.32	1	1542.2	637.19	< .0001	
Residual	363.12	15	24.21			
Lack of Fit	254.42	10	25.44	1.17	0.3654	Not significant
Pure Error	108.71	5	21.74			
Cor. Total	66101.47	29				
Std.Dev.	8.21		R-Squ.	0.9884		
Mean	284.63		Adj.R-squ.	0.9777		
C.V %	2.89		Pred.R-Squ.	0.9464		
PRESS	4690.8		Adeq.prec.	29.004		

The goodness of fit of the model is fitted by the determination coefficient (R^2). The coefficient of determination was calculated to be 0.9884 in response which implies that 98.8% of the experimental values confirm the compatibility with data as predicted by the model. The R^2 value should always be between 0 to 1. If a model is statistically good the R^2 value should be close to 1.0. Then adjusted R^2 value reconstructs the expression with the significant terms. The value of adj. R^2=0. 9777 is also high and indicates the high significance of the model. The pred. R^2 value is 0.9464 which means that the model could explain 94% of the variability in prediction. This is in reasonable agreement with the Adj. R^2 of 0.9777. The value of the coefficient of variation as low as 2.89, which indicates that the deviation between experimental and predicted values are low. Adequate measures of the signal to noise ratio, a ratio greater than 4 is desirable. During this investigation, the ratio is 29.004, which indicates an adequate signal. This model can be used to navigate the design space. Fig.7 shows the correlation graph of predicted and actual tensile strength of FSW joints, it could indicate the deviation between the actual and predicted tensile strength is low.

To check prediction capability of the developed relationship, three more confirmation experiments were carried out with the welding parameters chosen randomly from the feasible working range (Table 4). The actual response was calculated as the average of three measured results. Table 9 summarizes the experimental values, predicted values and the variation. The results reveals that the relationship developed is quite accurate since the variation in prediction is ±5 %.

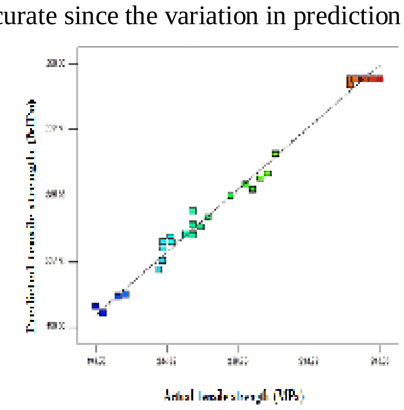

Fig.7 Correlation graph

Table 9. Validation test results for the developed empirical relationship

Tool rotational speed (rpm)	Welding speed (mm/ min)	Tool shoulder diameter (mm)	Tool tilt angle (◦)	Actual TS (MPa)	predicted TS (MPa)	Variation
1500	50	6	1.5	360.0	364.0	-4.0
1450	60	7	1.5	284.0	289.0	-5.0
1550	40	6	1.5	364.5	359.0	+5.0

4.0 Integrity of FSW joint

The FSW joint conventionally divided into four regions, stir zone (SZ), thermo-mechanical heat affected zone (TMAZ), heat affected zone (HAZ) and base metal (BM). The size of the SZ is closely related to the pin geometry. The formation of SZ is due to the combined effect of thermal and mechanical stresses caused by stirring action of the non-consumable rotating tool and axial force. The micrographs of the various region of the optimized FSW joint (Joint no 25) are shown in Fig.8. The SZ (Fig.8 (a)) shows fine and recrystallized equiaxed grains produced by severe plastic deformation. Fewer second phase strengthening precipitates of uniformly distributed Al_2Cu are observed in SZ, towards the weld bottom distinct onion ring pattern is also seen (Fig.8 (b)).

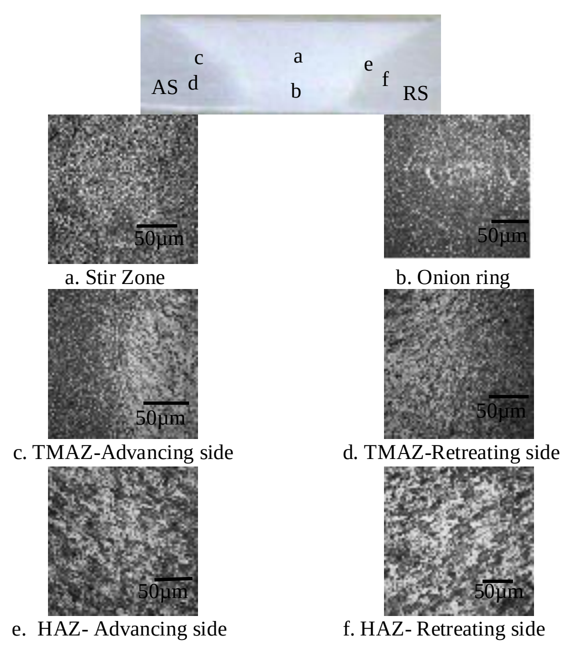

Fig.8 Optical micrograph of FSW joint (Joint No.25)

The micrographs of TMAZ are shown in Fig.8 (c) &Fig.8 (d). The TMAZ in FSW joint showed severely deformed non - recrystallized grains, but there is no significant grain coarsening in the HAZ (Fig.8 (e) & Fig.8(f)). The reason for lower tensile strength of AA2014-T6 aluminum alloy is due to different relative speeds of plastic material on advancing side and on retreating side which results in different microstructure. It is found on the advancing side; the speed gradient is greater than the retreating side. Microstructure changes rapidly and there are lack of necessary transition, and dissolution of strengthening precipitates in the TMAZ.

5. Conclusions

1. An empirical relationship has been developed and to predict the tensile strength of friction stir welded butt joints of AA2014-T6 aluminum alloy with 95% confidence level, incorporating predominant welding parameters.

2. A maximum ultimate tensile strength of 380 MPa could be achieved under the rotational speed of 1500 rpm, welding speed of 40 mm/min, tool shoulder diameter of 6 mm, and tilt angle of 1.5^o

3. Of the four process parameters investigated, the tool tilt angle (based on F value) was found to have the greater influence on tensile strength followed by welding speed, shoulder diameter, and rotational speed.

Acknowledgement

The authors wish to thank Aeronautical Development Agency (ADA), Bangalore, for the financial support to carry out this investigation through a R&D project no: FSED 83.07.03.

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