Journal of Manufacturing Engineering, September 2015, Vol. 10, Issue. 4, pp 207-214

DEVELOPING EMPIRICAL RELATIONSHIPS TO PREDICT THE STRENGTH OF FRICTION STIR SPOT WELDED AA6061-T6 ALUMINUM ALLOY AND COPPER ALLOY DISSIMILAR JOINTS

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ABSTRACT

Friction Stir Spot Welding (FSSW) is a variant of friction stir welding (FSW) process, in which the rotating tool is plunged into a material under high forging force to create a bond. It is employed to join dissimilar materials like aluminum and copper as it is a solid state welding processes, and helps to eliminate defects found in fusion welding processes. FSSW finds extensive application in the automobile and aerospace industries. In this investigation, an attempt is made to join aluminum alloy (AA6061) with copper alloy (commercial grade) by FSSW process. The effects of the four major parameters of FSSW process, namely Tool rotational speed (N), Plunge rate (R), Dwell time (T) and Tool diameter ratio (D) have been explored in this investigation. An empirical relationship has been developed by response surface methodology (RSM) to predict strength of the welded joints incorporating these parameters.

Keywords: *Friction stir spot welding, Copper alloy, Aluminum alloy, Dissimilar joint, Response surface methodology, Tensile shear fracture load.*

1. Introduction

Lightweight materials play an important role in the aircraft and automobile industries as they offer good performance to weight characteristics [1]. However, welding of aluminum with copper is difficult by fusion welding processes, because the difference in thermal conductivity and co-efficient of expansion results in porosity, spatter, alloy segregation, partially melted zone and liquidation cracking. In order to overcome the above problems solid state welding technique like Friction stir spot welding (FSSW) is preferred. The frictional heat produced between the rotating tool shoulder and base material surface is just sufficient to cause plastic deformation (without melting of base material). Hence, problems mentioned above are eliminated in FSSW. Further, shrinkage, distortion and residual stresses are negligible in FSSW, especially in case of thin sheets. In earlier days, the light weight metals were welded by resistance spot welding, laser spot welding, and riveting. However, these methods employed to join aluminum sheet metal have some disadvantages. Conventional resistance spot welding suffers from tool consumption during welding, distortion due to heat, and poor weld strength; porosity defects cannot be avoided in laser spot welding; riveting increases the weight and needs special tooling [2].

Friction stir welding (FSW) was developed by The Welding Institute (TWI), UK in 1991 [3, 4]. It offers various advantages such as plastic deformation, good mechanical and metallurgical properties, high joint efficiency, and eco-friendly process, which has received considerable attention in recent times to weld aluminum alloys [5–7]. Friction stir spot welding (FSSW) is a variant of Friction Stir Welding (FSW) process in which a series of solid state FSW spot welds are employed to join the dissimilar overlapping plates, by a non-consumable rotating tool.

Arul et al. [8] investigated the failure mechanism of friction stir spot welded AA5754 aluminum alloy joints and observed that the joint failure mechanism was necking and shearing. Pan et al [9] reported different failure modes like interfacial separation at shallow insertion depth, nugget pullout at highest strength, and perimeter failure at deepest insertion. Mitlin et al. [10] reported that tool pin plunge depth had a major effect on the failure mode of the joints and minor effect on the joint shear strength.

Badrinarayanan et al. [11] analyzed the effect of tool pin geometry on hook formation. Karthikeyan et al. [12] reported that different failure modes were observed in AA2024 aluminum alloy such as eyelet, partially curved, interfacial, and nugget pull out under

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various conditions, and the nugget pullout failure was observed for the maximum TSFL value. Yan et al. [13] showed that weld had three regions: plastic ring region, thermo mechanically affected zone, heat affected zone and parent metal. Mustafa et.al [14] used Taguchi techniques to predict the maximum strength in high density polyethylene sheet and analyzed the effect of process parameters on weld strength. Xiao song et.al [15] employed different shoulder and pin plunge speeds, and observed that the shoulder plunge speed affected the hook formation and tensile strength of weld, whereas there was no effect on the mechanical properties due to the pin plunge speed.

Zhang et al. [16] has further investigated the hooking phenomenon reported by Yazdanian and Chen [17], where the effect of probe length, welding speed and rotational speed was studied. It was shown that a longer probe length did not result in stronger joints, as sufficient plastic stirring occurred with probes slightly longer than the sheet thickness. The most influential factors were found to be probe length and rotational speed. Babu et.al [18] investigated the presence of Al clad layers and the base metal temper conditions, and found that these had no major effect on joint formation and joint strength.

From the literature review, it is understood that Friction Stir Spot Welding (FSSW) process is gaining importance worldwide to replace riveting and mechanical locking. A few investigators have focused on using design of experiments concept [12, 15, 18, 19, 21] and Taguchi technique [20] to optimize FSSW process parameters for joining similar alloys, especially aluminum alloys and magnesium alloys. Moreover, "Factorial", or "Classical DOE," technique is used with designed experiments. It allows finding factors which are most important and helps to identify important interactions among the factors. However, it doesn't predict the best factor levels to meet our goals. Taguchi technique helps in finding a “robust” answer to the experimental questions. It seeks an answer that is insensitive to factor variations, and does not predict the best combination of factors to achieve our goals, using a standard orthogonal array. The above mentioned drawbacks can be eliminated by Response Surface Methodology (RSM) technique. RSM is used to make contour plots of predicted behavior, which makes predicting the best combination of factors very easy and reliable.

However, the information available in open literature on FSSW of dissimilar joints using aluminum alloys and copper alloys are very scanty. Most of the published literature focused on similar thickness base material joined by FSW and FSSW process. Varying thickness base materials (AA6061- copper) are employed in automobile applications which are joined by spot welding, adhesive bonding and brazing processes. Hence, in this investigation, an attempt has been made to join the varying thicknesses (2.45 mm of Aluminum and 3.0 mm of copper) by FSSW process. Keeping this in mind, the present investigation was carried out to join AA6061 aluminum alloy with copper alloy by FSSW process and an attempt was also made to develop an empirical relationship to predict strength (tensile shear fracture load) of the welded joints incorporating FSSW parameters by Response Surface Methodology (RSM).

2. Experimental details

AA6061 aluminum alloy sheets with a thickness of 2.45 mm and commercial copper sheet of 3.0 mm thickness were used as base alloys in this investigation. The sheets were cut to required size by shear-off machine, followed by surface grinding to remove oxides and scales. The chemical composition and mechanical properties of the base alloys are presented in Tables 1 and 2 respectively.

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

Alloy	Zn	Ti	Fe	Cu	Al	Mn	Si	Mg
Copper	9.15	0.01	0.02	90.73	---	---	---	---
AA6061	0.25	0.15	0.7	0.15	95.8	0.33	0.53	0.69

Table 2. Mechanical properties of base alloys

Alloy	0.2% Yield strength (MPa)	Tensile strength (MPa)	Elongation in 50 mm gauge length (%)	Hardness @0.5kg (Hv)
Copper	220	268	28	267
AA 6061	276	310	12	107

Lap joints were fabricated as per the dimension given in Figure 1. The rolling direction of the material was kept parallel to the loading directions, and the joints were initially secured with the help of mechanical clamps. A non-consumable rotating tool made of high

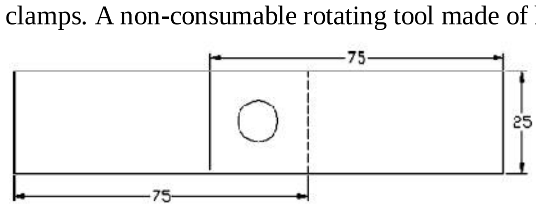


Fig. 1 Dimensions of Lap shear tensile specimen

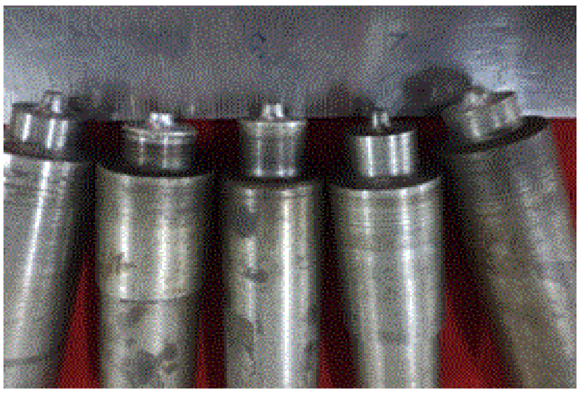


Fig.2 Photograph of tools used

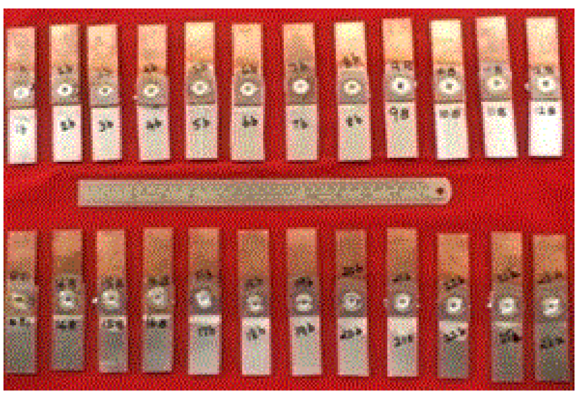


Fig.3 Fabricated FSSW joints

speed steel (HSS) was used to fabricate the lap joints. The tools with concave shoulder diameters of 11, 14, 16, 18 and 21 mm and a 0.8 mm pitch metric, left hand threaded pin of 4.5 mm diameter, as shown in Figure 2 were used to weld the joints. An indigenously designed and developed computer numerical controlled friction stir welding machine (4000 rpm, 22 kW, 6 t) was used to fabricate the lap joints.

From the literature, the process parameters that influenced the strength of FSSW joints were identified as tool rotational speed, plunge rate, dwell time and tool diameter ratio. A large number of trail experiments were conducted to determine the feasible working range of the above parameters by varying one parameter, while keeping the others constant. The working range was fixed based on the absence of visible defects and lower and upper tensile shear fracture loads (TSFL). The working range of each parameter and their levels are presented in Table 3.

A central composite rotatable, four factor, five level factorial design matrix was employed to minimize the number of experimental conditions. The experimental design matrix consisting of 30 sets of coded conditions (Table 4) and comprising a full replication of four-factor factorial design of 16 points, 8 star points and 6 center points was used.

Table 3. Process parameters and their working range

Sl. No.	Factor	Unit	Notation	Levels				
				-2	-1	0	1	2
1	Tool rotational speed	rpm	N	1600	1800	2000	2200	2400
2	Plunge rate	mm /min	R	5	6	7	8	9
3.	Dwell time	sec	T	15	20	25	30	35
4	Tool diameter ratio	--	D	2.5	3.0	3.5	4.0	4.5

The upper and lower limits of the parameters were coded as +2 and -2 respectively. The coded value for intermediate levels was calculated from the relationship,

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

Where X_i is the required coded value of a variable X and X is the value of the variable from X_{min} to X_{max}. The joints were welded as per the conditions dictated by the design matrix in a random order to avoid noise in the output responses. For each condition, three specimens were fabricated and some of the welded joints are shown in Figure 3. Lap shear tensile test was carried out in a 100 kN electromechanically controlled universal testing machine and the specimen were loaded at the strain rate of 1.5 kN/min until the faying surface of specimen sheared off. The average of the three tensile lap shear–tested values was used for the further analysis. The Tensile Shear Fracture load (TSFL) for each condition is presented in Table 5, along with the corresponding photographs of the cross-sectional macrograph, the top view of top sheet, the bottom view of top sheet and the top view of bottom sheet.

3.Developing an Empirical Relationship

The tensile shear fracture load (TSFL) of friction stir spot welded AA6061 aluminum and copper alloys is a function of the parameters, such as tool rotational speed (N), tool plunge rate (R), dwell time (T) and tool diameter ratio (D), and can be expressed as

$$TSFL = f(N, R, T, D) \quad (2)$$

The second order polynomial equation used to represent the response surface Y is given by

$$Y = b_o+\sum b_i x_i+\sum b_i x_i^2 + \sum b_{ij} x_i x_j \quad (3)$$

Table 4. Design matrix and experimental results

Exp. No.	Coded value				Actual Value				TSFL (kN)
	N	R	T	D	N (rpm)	R (mm/ min)	T (s)	D	
1	-1	-1	-1	-1	1800	6	20	3.0	3.07
2	+1	-1	-1	-1	2200	6	20	3.0	3.65
3	-1	+1	-1	-1	1800	8	20	3.0	3.39
4	+1	+1	-1	-1	2200	8	20	3.0	3.89
5	-1	-1	+1	-1	1800	6	30	3.0	3.59
6	+1	-1	+1	-1	2200	6	30	3.0	4.1
7	-1	+1	+1	-1	1800	8	30	3.0	3.85
8	+1	+1	+1	-1	2200	8	30	3.0	4.34
9	-1	-1	-1	+1	1800	6	20	4.0	3.44
10	+1	-1	-1	+1	2200	6	20	4.0	3.91
11	-1	+1	-1	+1	1800	8	20	4.0	3.69
12	+1	+1	-1	+1	2200	8	20	4.0	4.14
13	-1	-1	+1	+1	1800	6	30	4.0	3.88
14	+1	-1	+1	+1	2200	6	30	4.0	4.35
15	-1	+1	+1	+1	1800	8	30	4.0	4.1
16	+1	+1	+1	+1	2200	8	30	4.0	4.52
17	-2	0	0	0	1200	7	25	3.5	2.99
18	+2	0	0	0	2200	7	25	3.5	3.92
19	0	-2	0	0	2000	5	25	3.5	3.79
20	0	+2	0	0	2000	9	25	3.5	4.18
21	0	0	-2	0	2000	7	15	3.5	3.44
22	0	0	+2	0	2000	7	35	3.5	4.38
23	0	0	0	-2	2000	7	25	2.5	3.88
24	0	0	0	+2	2000	7	25	4.5	4.42
25	0	0	0	0	2000	7	25	3.5	4.74
26	0	0	0	0	2000	7	25	3.5	4.72
27	0	0	0	0	2000	7	25	3.5	4.75
28	0	0	0	0	2000	7	25	3.5	4.71
29	0	0	0	0	2000	7	25	3.5	4.79
30	0	0	0	0	2000	7	25	3.5	4.76

The selected polynomial could be expressed as,

$$TSFL = \{b_o+b_1(N)+b_2(R)+b_3(T)+b_4(D)+b_{12}(NR) +b_{13}(NT)+b_{14}(ND)+b_{23}(RT)+b_{24}(RD) +b_{11}(N^2)+b_{22}(R^2)+b_{33}(T^2) +b_{44}(D^2)\} \text{ kN} \quad (4)$$

Table 5. ANOVA test results

Source	Sum of Squares (SS)	Degree of Freedom	Mean Square (MS)	F ratio	p-value (Prob > F)	Signifi-cant or not
Model	7.56	14	0.54	849.90	< 0.000	Yes
Tool rotatio-nal speed	1.38	1	1.38	2169.46	< 0.0001	Yes
Plunge rate	0.31	1	0.31	481.90	< 0.0001	Yes
Dwell time	1.23	1	1.23	1934.70	< 0.0001	Yes
D	0.43	1	0.43	684.57	< 0.0001	Yes
NR	0.001	1	0.0018	2.84	0.1124	--
NT	0.007	1	0.00075	1.19	0.2924	--
ND	0.004	1	0.004	7.18	0.0172	Yes
RT	0.001	1	0.001	2.21	0.1574	--
RD	0.0025	1	0.0025	3.55	0.0790	--
TD	0.0027	1	0.0027	4.34	0.0547	--
N^2	2.87	1	2.87	4518.67	< 0.0001	Yes
R^2	1.00	1	1.00	1574.75	< 0.0001	Yes
T^2	1.21	1	1.21	1899.22	< 0.0001	Yes
D^2	0.61	1	0.61	967.83	< 0.0001	Yes
Resid-ual	0.009	15	0.006	-	-	Yes
Lack of fit	0.005	10	0.0005	0.65	0.7391	No
Pure error	0.0041	5	0.0008	Pred. R- squared		0.995
Cor. total	7.57	29		Press		0.037
Std.deviation			0.025	Mean		4.05
R-squared			0.9987	C.V		0.62
Adj. R- squared			0.9976	Adeq. precision		99.50

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. The values of co-efficient were calculated using Design Expert 8 software at 95% confidence level. The significance of each co-efficient was calculated from student t-test and p values, which are listed in Table 6. A value of "Prob>F" less than 0.05, indicates that the terms in the model are significant. If the values are greater than 0.10, it indicates that terms are not significant. In this case, N, R, T, D, ND, N^2, R^2, T^2, and D^2 are the significant terms. The final empirical relationship was constructed using only these significant factors, and the developed final empirical relationship is given below.

$$TSFL = \{4.75 + 0.24(N) + 0.11(R) + 0.23(T) + 0.13(D) - 0.017(N*D) - 0.32(N^2) - 0.19(R^2) - 0.21(T^2) - 0.15(D^2)\}\ \text{kN} \quad (5)$$

Table 6. Estimated regressions co-efficients

Factors	Cofficient
Intercept	4.75
N-Tool rotational speed	0.24
R-plunge rate	0.11
T-dwell time	0.23
D-Tool diameter ratio	0.13
NR	-0.011
NT	-0.006
ND	-0.017
RT	-0.003
RD	-0.012
TD	-0.013
N^2	-0.32
R^2	-0.19
T^2	-0.21
D^2	-0.15

The adequacy of th model is tested by ANOVA. The results of ANOVA are given in Table 6, at the desired level of confidence of 95%. The relationship may be considered to be adequate provided that the calculated value of the F ratio and the calculated value of R ratio of the developed relationship do not exceed the tabulated value of R ratio for a desired level of confidence, and, in this case, the model is found to be adequate. The model F value of 849.98 implies that the model is significant. 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 0.65 implies that the lack of fit is insignificant. There is only 73.91% chance that a lack of fit F values this large could occur due to noise. Each predicted value matches its experimental value well, as shown in Figure 4.

The Fisher's F test with very low probability value demonstrates a very high significance for the regression model. The goodness of fit of the model is checked by the determination coefficient (R^2). The coefficient of determination was calculated to be 0.998 for response which implies that 99.8% of the experimental values confirm the compatibility with data as predicted by the model. TheR^2 value should always be between0 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 adjusted R^2= 0.998 is also high and indicates high significance of the model. The predicted R^2 value is 0.9951 which implies that the model could explain 99% of the variability in prediction. This is in reasonable agreement with the Adj.R^2 of 0.9976. The value of coefficient of variation is low at 0.62 which indicates that the deviation between experimental and predicted values is low. A ratio greater than 4 is desirable, to indicate that the signal is adequate. In this investigation, the ratio is 99.498, which indicates an adequate signal. So, this model can be used to navigate the design space.

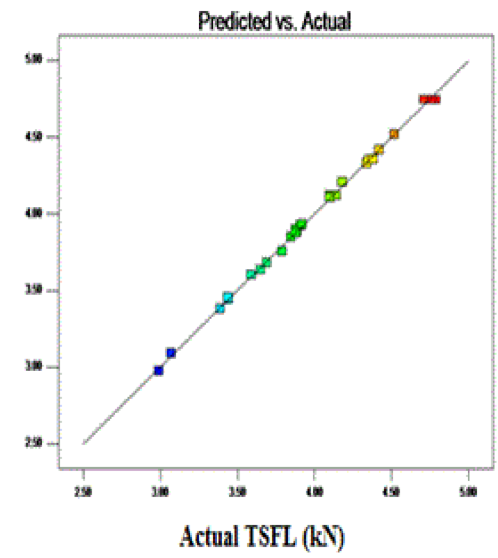


Fig.4 Correlation graph

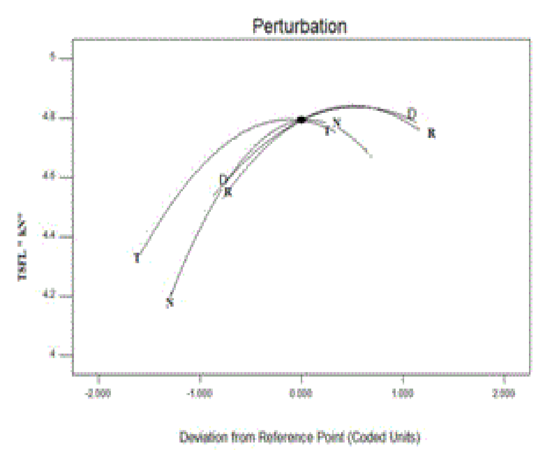
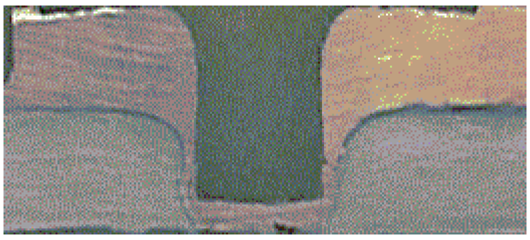


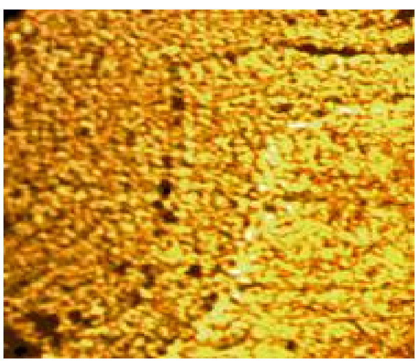
Fig.5 Perturbation plot for the effect on the TSFL

The perturbation plot for the response TSFL of joints is illustrated in Figure 5. This plot provide a silhouette view of the response and shows the change of TSFL when each FSSW parameters moves from the reference point, with all other parameters held constant at the reference value. Design of experiment sets the reference point default at the middle of the design space.

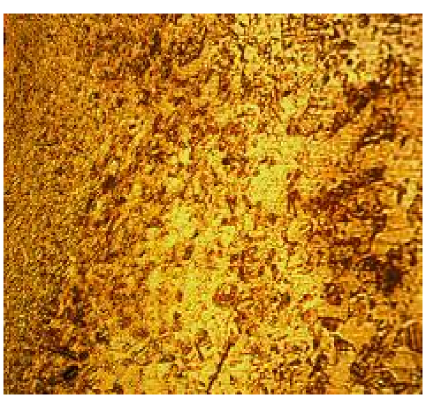


(a) Macrostructure

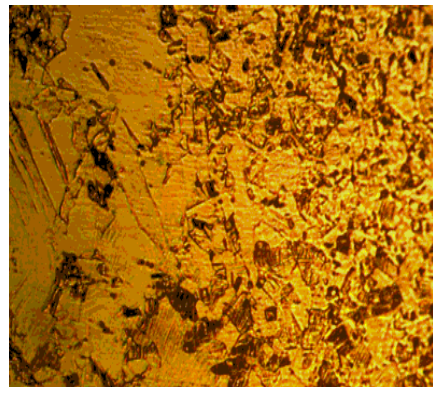
(b) Stir zone on AA6061



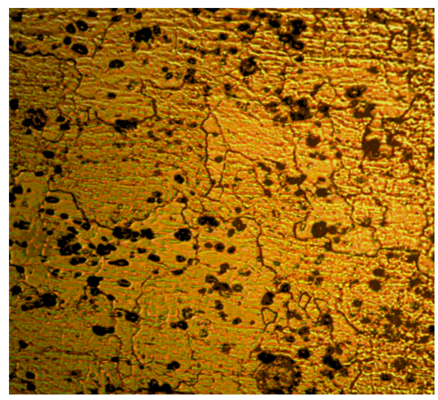
(c) Stir zone on copper



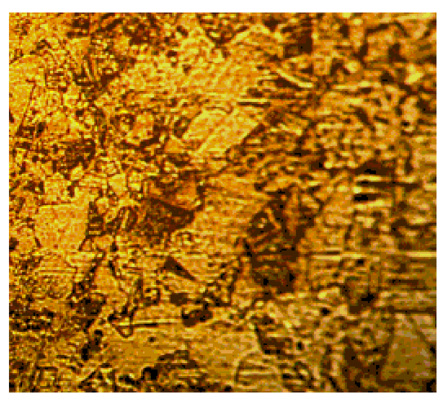
(d) TMAZ -AA6061



(e) TMAZ copper



(f) HAZ –AA6061



(g) HAZ copper

Fig.6 Optical macrograph and micrograph of FSSW joint

Figure-6 (a-f) indicates the response surface and contour plots, and presents the interaction effect of any two input parameters on the TSFL. The maximum TSFL is obtained for higher tool rotational speed and dwell time, with lower plunge rate and tool diameter ratio. This combination produces sufficient heat for metallurgical phenomena such as grain coarsening [22], and so the maximum TSFL was obtained at these levels. The macrograph and micrograph of the joint fabricated using the optimized parameters are displayed in Figure 6 to demonstrate the feasibility of mechanically sound and metallurgical compatible bimetallic joints can be made using FSSW process. The developed empirical relationship is validated by fabricating FSSW joints using three random combinations of parameters in the test range; the actual response was calculated as the average of three measured results. Table 7 summarizes the experimental values, the predicted values and the percentage of error. The validation results revealed that the empirical relationship developed is quite accurate as the errors in prediction are within ± 5%.

Table 7. Confirmation of test results

Sl. No	N (rpm)	R (mm /min)	T (sec)	(D	TSFL (kN)		Error (%)
					Actual	Predicted	
01	2036	7.0	28.0	3.50	4.8	4.79	+0.02
02	2095	7.25	27.4	3.75	4.88	4.85	+0.61
03	2013	6.8	26.5	4.0	4.82	4.84	-0.41

4. Conclusions

i. An empirical relationship was developed using statistical techniques such as Design of Experiments, Analysis of variance and RSM to predict the tensile lap shear strength of friction stir spot welded dissimilar joints of AA6061 aluminum and copper alloys incorporating important process parameters (at 95% confidence level).

ii. Maximum tensile lap shear strength of 4.79 kN was obtained at a tool rotational speed of 2000 rpm, a plunge rate of 7 mm/min, a dwell time of 25 s and tool diameter ratio of 3.5 (as per the experimental results)

iii. Of the four process parameters investigated, the tool rotational speed was found to have the greatest influence on tensile shear fracture load, followed by dwell time, tool diameter ratio and plunge rate (as per the F ratio)

Acknowledgement

The authors are grateful to the Department of Manufacturing Engineering, Annamalai University, for extending the facilities of Material Testing Laboratory to carry out this investigation. The authors also wish to record their sincere thanks to Mr. C. Rajendran, Research scholar, Annamalai University, for rendering support to carry out this investigation.

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