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Prediction of Optimum Welding Parameters for FSW of Aluminium alloys AA6063 and A319 using RSM and ANN☆

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Abstract

Friction stir welding is an innovative solid state joining technique and has been employed in aerospace, rail, automotive and marine industries for joining aluminum, magnesium, zinc and copper alloy. The FSW process parameters such as tool, rotational speed, welding speed, axial force, etc play major role in deciding the weld quality. This method focuses three methods such as Taguchi methodology, Response Surface Methodology and Artificial neutral network, are used to predict the tensile strength of friction stir welded aluminum alloy. The experiments were conducted based on three factors, three level and central composite technique and mathematical model is developed using Artificial neural network methodology. The result obtained through ANN technique is compared with RSM technique. It was found the error rate predicted the regression ANN was smaller than predicted by the other ANN methods.

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Keywords: Friction Stir Welding ; Aluminum alloy; Response surface methodology.

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1. Introduction

Friction stir welding (FSW) is a solid state welding process invented and patented by The Welding Institute (TWI) in 1991[1]. Unlike the conventional fusion welding process, where the material to be joined is melted and re-solidified, FSW works on the principle of severe material deformation. This avoids the melting of the material to be joined which is considered to be the source of the welding defects. However, the material is joined in the solid state by the heat generated in the interface by the friction and by the flow of materials due to intense stirring action. The required heat input is given by applying compressive forces across the joint.

FSW comprises a non-consumable rotating tool with a specially designed pin and shoulder which is inserted into the abutting edges of the plates to be joined. The rotating tool is then traversed along the line of joint. The work surface to be joined has to be suitably clamped in a specially designed fixture by arresting all degrees of freedom of movement to prevent the abutting joint faces from being forced apart. The length of the pin is designed to be slightly less than the required weld depth i.e. less than the thickness of the work surface. The tool is stopped when the tool shoulder touches the surface of the job.

Design of experiment is a structured and organized method used to determine the relationship between the different factors affecting a process and output of that process [2]. Optimization problems focused in the literature for FSW, in general, are obtained by considering a set of process parameters (in most cases, the translational welding speed and the rotational speed) and few constraints and objective functions [3]. Trial and error approaches improve the welding process parameters in FSW of 2000 series aluminium alloys [4]. The welding speed is optimized so that the material in front of the tool is softened to allow easy tool traversing. Taguchi approach to is used to determine the most influential control factors which yield better tensile strength of the joints of FSW of RDE-40 aluminium alloy [5]. Through this approach, the optimum level of process parameters (tool rotational speed, traverse speed and axial force) is determined. The results indicate that the rotational speed, welding speed and axial force are the significant parameters in deciding the tensile strength of the joint. FSW of AA6351 aluminium alloy is based on three factors, five level and central composite rotatable design with full replications technique [6]. The process parameters chosen are welding speed, tool rotational speed and axial force. Mathematical model is developed for the effect of three process parameter at five levels using response surface methodology (RSM). Analysis of variance (ANOVA) technique is used to check the adequacy of the developed mathematical model. The effect of FSW process parameter on mechanical properties of AA6351 aluminium alloy show that the increase in the tool rotational speed, welding speed and axial force lead to the increase in the ultimate tensile strength and reaches to the maximum value and then decreases. This trend is common to yield strength and percentage of elongation. The effect of welding parameters such as tool rotational speed, traverse speed and probe geometries on various mechanical properties of AA1100 aluminium alloys are studied to determine the ultimate tensile strength, percentage of elongation and hardness[7]. In recent years, Artificial Neural Networks (ANN) gains increased importance among the researched owing to its ability to solve complex optimization problems. This chapter presents a detailed study of the effect of FSW process parameters on desired responses using the design of experimental approach. It investigates an understanding about the relationship of various FSW process parameters selected for study and their effect on weld characteristics like ultimate tensile strength, yield strength, percentage elongation and hardness were discussed on the development of mathematical models. Artificial Neural Network (ANN) was used to develop regression equations relating to response characteristics and process parameters. Results of the models are presented in the tabular column for better understanding.

2. Experimentation

AA6063 belongs to a group of heat treatable 6xxx series which contains Al-Si-Mg as major composition. AA6063 is procured as roller plates of 6mm thickness. The required welding sizes of 100mm x 50 mm x 6mm were taken from the sheet. A319 belongs to a group of cast aluminum alloys of Al-Si-Cu or Al-Si-Cu-Mg which are heat treatable. A319 is procured from the supplier as ingots and is machined to obtain the required dimensions. The composition and mechanical properties of AA6063 and A319 alloys are given in Table 1 and Table 2 respectively.

Table 1. Composition of AA6063-T6 and A319.

BM	Si	Cu	Mg	Mn	Ti	Zn	Fe	Al
AA6063	0.3	0.1	0.5	0.1	0.1	0.1	0.3	Bal
A319	6.2	3.4	0.1	0.5	0.3	0.1	0.7	Bal

Table 2. Mechanical properties of AA6063 and A319 aluminium alloys.

BM	UTS (MPa)	YS (MPa)	Elongation (%)	Hardness (Hv)
AA6063	245	214	2.5	80
A319	186	124	12	85

FSW experiments are carried out on Friction stir welding machine of R.V machine tools limited, India. For the current experimentation of friction stir welding of AA6063 and A319 dissimilar alloys square tool pin profile is selected. The material identified for the tool making is high speed steel material hardened to 60HRc. Feasible working limits of FSW process parameters are calculated using trial runs.

In the present investigation, experimental investigations are designed on the basis of RSM method. A 3 factor, five level central composite circumscribed (CCC) design consist of 20 sets of coded conditions. CCC designs provide high quality predictions over the entire design space, but require factor settings outside the range of the factors in the factorial part. The design composed of a full factorial $2^3 = 8$, plus 6 centre points and 6 star points as shown in Table 3.The upper and lower values are coded as +1.682 and -1.682 respectively. Based on the results mentioned above, the friction stir welding parametric window was developed for the welding of aluminium alloys AA6082-T651. This window was used to decide the defect-free working range of the welding parameters. For determining the working range for the process parameters, the upper limit of the variables is coded as +1.682 and the lower limit as –1.682. The intermediate levels are calculated from the relationship

$$Xi=1.682\ [2X - (Xmax + Xmin)] / (Xmax - Xmin) \quad (1)$$

where Xi is the required coded value of a variable X, and X is any value of the variable from Xmin to Xmax, Xmin is the lower level of the variable, Xmax is the upper level of the variable.

Table 3. Working Range of FS welding parameters of AA6063 and A319.

Process Parameters	**Unit**	**Symbol**	**Levels**				
			-1.682	**-1**	**0**	**1**	**1.682**
Tool rotational speed	rpm	*N*	800	901	1050	1198	1300
Welding Speed	mm/min	*S*	20	24	30	36	40
Axial Load	kN	*F*	3	4	5.5	7	8

.

In central composite design, the process parameters identified for the experimentation are tool rotational speed, welding speed, axial load and the effect of these parameters on ultimate tensile strength, yield strength, percentage of elongation and hardness are carried out in this work. The selected factor’s working ranges are fixed based on conducting trial runs, wherein one of the factors is varied and the remaining factors are at constant values. The experiment is performed according to the run order design as given in Table 4. The experiments for 20 runs are conducted as per design matrix at random order, to avoid the possibility of systematic errors infiltrating in to the system. The FSW specimens are shown in Fig.1. The design results are observed using MINITAB -16 statistical software package

3. Prediction model from DOE

3.1 Response Surface Analysis:

Mathematical models of response surface analysis were developed to predict the effect of the individual input parameters and their interaction effect on the responses like tensile strength and hardness. Various response surfaces created using MINITAB software shows a reasonable acceptance of the actual and predicted responses. Ultimate tensile strength, yield strength, percentage of elongation and hardness of the FSW joints are functions of rotational speed, axial force and welding speed, and it can be expressed as

$$Y = f\,(N, F, S) \quad (2)$$

Table 4. Design Matrix.

	Design matrix			Estimated Mechanical parameters			
Run No	FSW Process parameters			UTS	YS	E	Hardness
	N	F	S	(MPa)	(MPa)	%	(Hv)
1	-1	-1	-1	90	73	6.2	71
2	1	-1	-1	160	140	12.0	76
3	-1	1	-1	104	85	6.6	81
4	1	1	-1	172	152	14.0	111
5	-1	-1	1	87	66	6.1	68
6	1	-1	1	144	123	8.6	58
7	-1	1	1	102	80	6.5	74
8	1	1	1	150	132	9.1	96
9	-1.682	0	0	75	52	5.8	70
10	1.682	0	0	166	147	13.0	85
11	0	-1.682	0	121	102	7.0	67
12	0	1.682	0	138	119	7.6	98
13	0	0	-1.682	144	126	11.4	93
14	0	0	1.682	114	95	6.8	79
15	0	0	0	132	112	9.3	90
16	0	0	0	133	113	9.4	93
17	0	0	0	134	114	9.7	94
18	0	0	0	135	115	9.8	92
19	0	0	0	136	116	10.0	95
20	0	0	0	137	117	9.6	96

For the two factors, the selected polynomials can be expressed as

$$Y = b0+ b_1N + b_2F + b_3S + b_{11}N^2 + b_{22}F^2 + b_{33}S^2+ + b_{12}NF + b_{13}NS +b_{23}SN \tag{3}$$

where b_1, b_2 and b_3 are linear terms, b_{12}, b_{13} and b_{23} are interactive terms, b_{11}, b_{22} and b_{33} are the quadratic terms of the polynomial The coefficients b_0, b_1, b_2, b_3 ,b_{11}, $b_{22,}$ b_{33},b_{12} ,b_{13} and b_{23} are the least square estimates of true polynomial, representing the response surface. The strength of the respective process parameters and their interactions are represented by these coefficients. The p value of regression analysis indicates the linear, square and interaction of the FSW process parameters with the response functions and these *p* values are used to identify the significant parameters on the response functions.

$$UTS = 134.492+28.97(N) +5.428(S) - 6.90852(F) - 4.8964(N^2) - 1.68875(S^2) - 1.83544(F^2) -1.33(NS) - 4.08(NF)- 0.58(SF) \tag{4}$$

$$YS = 114.5 +29.4906(N) + 5.53468(S) -7.40520(F) - 5.301(N^2) -1.41287(S^2) - 1.41287(F^2) - 0.625(NS) - 3.125(NF) - 0.125(SF) \tag{5}$$

$$\%E = 7.37152 + 2.63390(N) + 0.129797(S) - 1.32061(F) + 1.04037(N^2) – 0.02(S^2) + 0.580864(F^2) - 0.0625(NS)- 1.23750(NF) +0.037500(NS) \tag{6}$$

$$Hv = 93.3957+5.28838(N) + 10.338(S) -4.87237(F) - 6.00587(N2) – 4.23854(S2) - 3.00141(F2) + 7.12500(NS) – 2.875(NF) -0.125(SF) \tag{7}$$

Table 5 Comparison of R^2 and adjusted R^2 for responses.

Responses	S Value	R^2	Adjusted R^2
UTS	2.00199	97.56	95.36
YS	1.632250	98.40	96.96
%E	0.352354	97.12	95.00
Hv	2.53	97.22	95.00

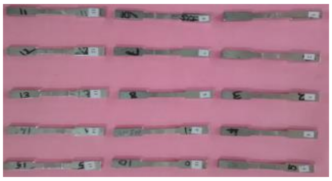


Fig.1. FSW specimens

3.2 Checking the adequacy of the developed models using ANOVA

Table 6. ANOVA test results for UTS,YS,%E and HV

Analysis of variance for UTS

Source	DF	Sum of Squares	Adj Mean Square	F Value	P Value
Regression	9	1599.87	177.763	44.35	0.000
Linear	3	1236.10	412.033	102.80	0.000
Square	3	349.43	116.476	29.06	0.000
Interaction	3	14.34	4.781	1.19	0.361
Residual Error	10	40.08	4.008		
Lack of Fit	5	37.58	7.516	15.03	0.005
Pure Error	5	2.50	0.500		
Total	19	1639.95			

Analysis of variance for YS

Source	DF	Sum of Squares	Adj Mean Square	F Value	P Value
Regression	9	1641.05	182.339	68.44	0.000
Linear	3	1327.39	442.462	166.07	0.000
Square	3	306.38	102.126	38.33	0.000
Interaction	3	7.28	2.428	0.91	0.470
Residual Error	10	26.64	2.664		
Lack of Fit	5	24.93	4.987	14.60	0.005
Pure Error	5	1.71	0.342		
Total	19	1667.69			

Analysis of variance for % of E

Source	DF	Sum of Squares	Adj Mean Square	F Value	P Value
Regression	9	41.8640	4.65155	37.47	0.000
Linear	3	24.9935	8.33116	67.10	0.000
Square	3	14.8855	4.96183	39.97	0.000
Interaction	3	1.9850	0.66167	5.33	0.019
Residual Error	10	1.2415	0.12415		
Lack of Fit	5	0.9015	0.18031	2.65	0.154
Pure Error	5	0.3400	0.06800		
Total	19	43.1055			

Analysis of variance for Hv

Source	DF	Sum of Squares	Adj Mean Square	F Value	P Value
Regression	9	2236.74	248.50	38.83	0.000
Linear	3	1544.88	514.96	80.46	0.000
Square	3	606.00	201.99	31.56	0.000
Interaction	3	85.86	28.62	4.47	0.031
Residual Error	10	64.01	6.401		
Lack of Fit	5	62.30	12.459	36.47	0.001
Pure Error	5	1.71	0.342		
Total	19	2300.74			

To check the adequacy of the developed models, Analysis of Variance (ANOVA) is used to test the fit and goodness of the predicted models. The statistical significance of the goodness of fit is analyzed by ANOVA test. The R-Sq, adjusted R-Sq (Adj. R-Sq) and standard Error (SE) of the final model are estimated and presented in Table 5. It can be observed that the calculated values of ‘F-ratio’ are greater than the tabulated value at 95 % confidence level and hence the models are adequate. In the decision-making process for a hypothesis test that is based on the p-value, it indicates the probability of falsely rejecting the null hypothesis when it is really true. If the p-value is less than or equal to a predetermined significance level (also known as alpha or α), then the null hypothesis is rejected. If the p-value is greater than α, the null hypothesis cannot be rejected. Using α equal to 0.05, the p-value (0.000) in the Analysis of Variance provides enough evidence to conclude that the obtained models are adequate.

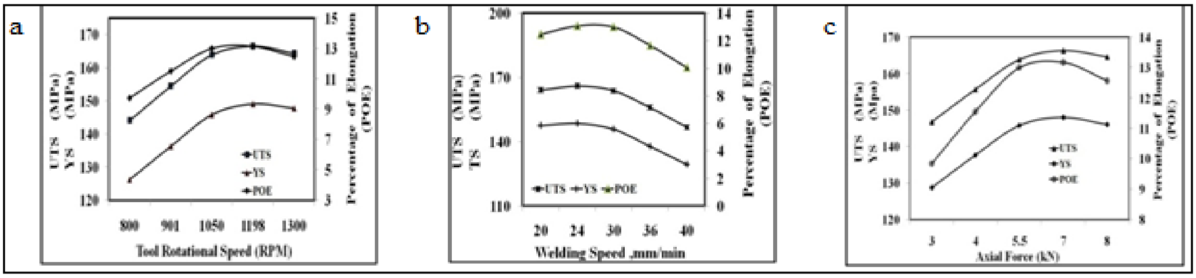


Fig.2. Direct Effects of Friction Stir Welding Process Parameters on mechanical parameters of UTS, YS and % E with respect to (a) Tool rotational speed b) Axial Load c) Welding speed

4. Direct effects of FS welding process parameters

The direct effect of the process parameters on mechanical properties of the FS welds are given below in Table 6 and also in Figure 2(a) to (c). The direct effects are considered by keeping one of the process parameter as variable and other two parameters as the center value.

Table 6. Direct Effects of Process Parameters.

Direct effects of Tool Rotational Speed		
Lower Parameter Value	Optimum Parameter Value	Higher Parameter Value
• Frictional Heat generated is lower. • Higher cooling rate decreases the plastic flow and inadequate bonding • Coarser Grain	• Optimum heat input resulting in finer grains with the increased plastic flow Adequate bonding	• Higher heat input • Slow cooling rate • Metallurgical transformation such as solubilisation, reprecipitation and coarsening of the precipitates.
Direct effects of Welding Speed		
• Heat input in SZ is high. • Frictional heat generated per unit length is very high • Coarse grains developed in SZ	• Tool-work interaction is improved. • Frictional heat generation per unit length gets reduced. • Sufficient plastic flow of material in SZ • Fine grains formed	• Material receives less frictional heat • Insufficient plastic flow of material in SZ • Coarse Grains formed • Plasticized material is cooler and less easily forged by the tool shoulder resulting in lack of bonding
Direct Effects of Axial Load		
• Insufficient heat due to escape of heat from the upper surface of base plate. • Shoulder was not capable of confining the material within the SZ, a part of material is lost as flash	• Plasticized material from leading edge to trailing edge is confined within the weld cavity. • Heat generation is more • Loss of heat is diminished due to confinement of material within the weld cavity.	• Increased frictional heat generated • Material is lost as flash due to excessive rubbing of tool shoulder and base plate resulting decreased cross sectional area. • More heat loss due to removal of material from base plate with the decreased availability of heat for weld formation • Severe clustering of precipitates

5. Optimization of Process Parameters for the Final Model

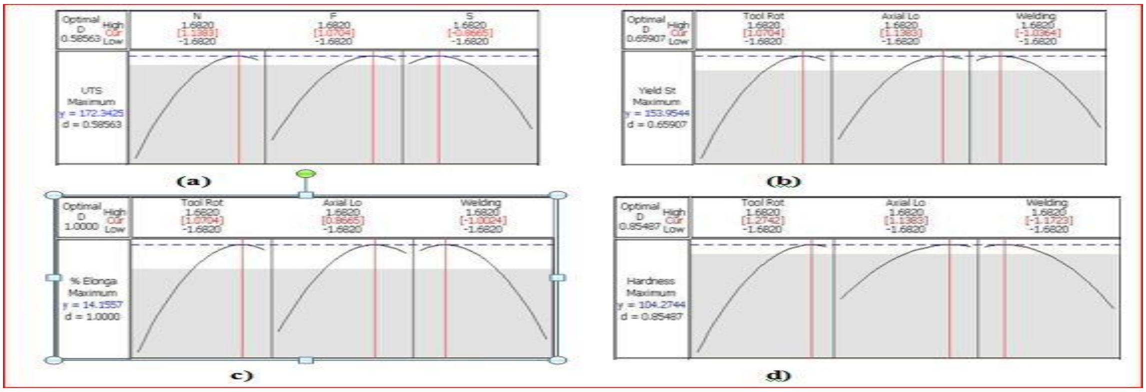


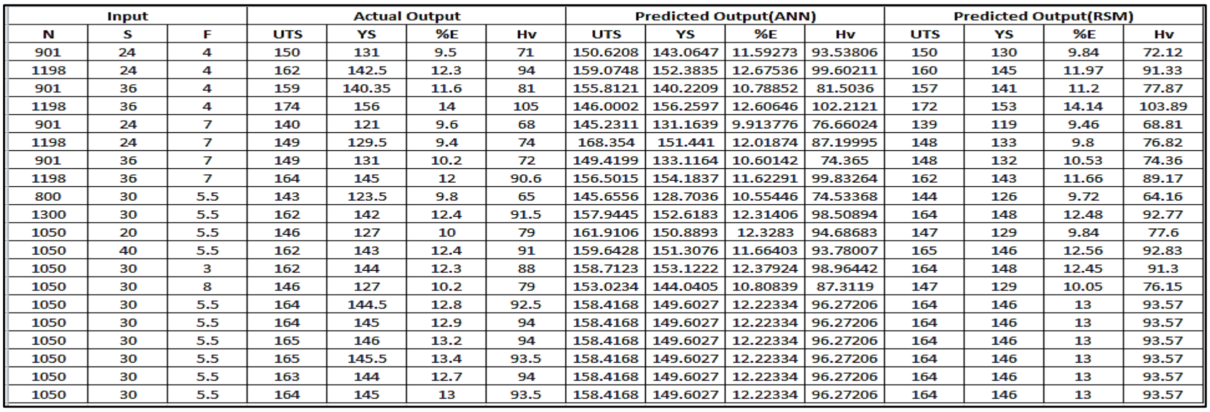
Fig. .3 Optimization plot using response optimizer for a) Ultimate Tensile Strength b) Yield Strength c) % Elongation d) Hardness

Response optimizer setup in Minitab software is used to identify the optimum process variables for the desirable responses which help to identify the combination of input variable settings that jointly optimize a single response or a set of responses. The optimization plot for the input variables obtained for the ultimate tensile strength, yield strength percentage of elongation and hardness explains the process from Fig.3(a-d)

6. Artificial Neural Network Method

ANNs composed of biological network of neurons used to solve complex functions in various optimization methods. Neural networks are inspired from biological network systems that consist of synchronous processing elements called neurons. Input layer, hidden layer and output layer are the three layers used for the ANN used here for the current problem. Back-propagation (BP) algorithm is one of the most popular learning-algorithms in ANN and in this present study, BP algorithm is used with a single hidden layer improved with numerical optimization techniques. Mathematical models of artificial neural network were developed to predict the effect of the individual input parameters and their interaction effect on the responses like tensile strength and hardness. Table 8 provides the actual and predicted results for the inputs on each process. The architecture for training parameters used for ANN is 3-12-4, 3corresponding to input nodes,12 to hidden nodes (feed forward) and 4for the number of output nodes.The number of epochs used are 500. Matlab version 7 is used to train the ANN module.

Table 8. Actual and Predicted reports of ANN & RSM



Input			Actual Output				Predicted Output(ANN)				Predicted Output(RSM)			
N	S	F	UTS	YS	%E	Hv	UTS	YS	%E	Hv	UTS	YS	%E	Hv
901	24	4	150	131	9.5	71	150.6208	143.0647	11.59273	93.53806	150	130	9.84	72.12
1198	24	4	162	142.5	12.3	94	159.0748	152.3835	12.67536	99.60211	160	145	11.97	91.33
901	36	4	159	140.35	11.6	81	155.8121	140.2209	10.78852	81.5036	157	141	11.2	77.87
1198	36	4	174	156	14	105	146.0002	156.2597	12.60646	102.2121	172	153	14.14	103.89
901	24	7	140	121	9.6	68	145.2311	131.1639	9.913776	76.66024	139	119	9.46	68.81
1198	24	7	149	129.5	9.4	74	168.354	151.441	12.01874	87.19995	148	133	9.8	76.82
901	36	7	149	131	10.2	72	149.4199	133.1164	10.60142	74.365	148	132	10.53	74.36
1198	36	7	164	145	12	90.6	156.5015	154.1837	11.62291	99.83264	162	143	11.66	89.17
800	30	5.5	143	123.5	9.8	65	145.6556	128.7036	10.55446	74.53368	144	126	9.72	64.16
1300	30	5.5	162	142	12.4	91.5	157.9445	152.6183	12.31406	98.50894	164	148	12.48	92.77
1050	20	5.5	146	127	10	79	161.9106	150.8893	12.3283	94.68683	147	129	9.84	77.6
1050	40	5.5	162	143	12.4	91	159.6428	151.3076	11.66403	93.78007	165	146	12.56	92.83
1050	30	3	162	144	12.3	88	158.7123	153.1222	12.37924	98.96442	164	148	12.45	91.3
1050	30	8	146	127	10.2	79	153.0234	144.0405	10.80839	87.3119	147	129	10.05	76.15
1050	30	5.5	164	144.5	12.8	92.5	158.4168	149.6027	12.22334	96.27206	164	146	13	93.57
1050	30	5.5	164	145	12.9	94	158.4168	149.6027	12.22334	96.27206	164	146	13	93.57
1050	30	5.5	165	146	13.2	94	158.4168	149.6027	12.22334	96.27206	164	146	13	93.57
1050	30	5.5	165	145.5	13.4	93.5	158.4168	149.6027	12.22334	96.27206	164	146	13	93.57
1050	30	5.5	163	144	12.7	94	158.4168	149.6027	12.22334	96.27206	164	146	13	93.57
1050	30	5.5	164	145	13	93.5	158.4168	149.6027	12.22334	96.27206	164	146	13	93.57

7. Fractography

The SEM fractrographs of FS welded Al alloys AA6063-T6 and A319 results show that the tensile failure occurs mostly at stir zone or towards base metal region where the low strength Al alloy A319 was placed in the advancing side. The high magnification of the SEM images revealed the tensile fracture surfaces as an array of randomly distributed fine macroscopic cracks. Also the presence of voids of varying size and shape are found throughout the fracture surface. The SEM fracture image shown in Figure 5(b) shows the presence of brittle failure.

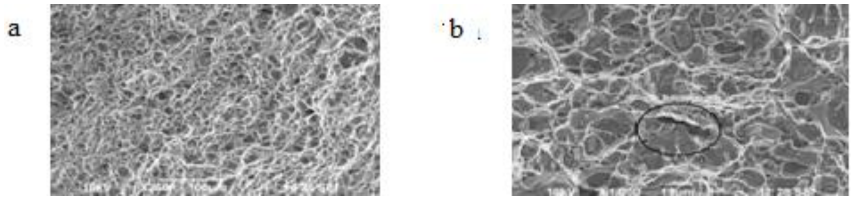


Fig.4. Fractography of FSW samples (a) Ductile Failure (b) Brittle failure

The overall surface texture is rough and macroscopic failure occurred in the weld zone in a direction normal to the field stress axis. Also fine dimples seen in Figure 4(a) are the characterization of the ductile failure which indicates the tensile specimen elongates before failure. Thus the overall failure mode of the joint is a combination of ductile and brittle failures.

8. Conclusions

Friction stir welding tool of square pin profile was developed successfully which is identified to be suitable for the dissimilar welding of aluminium alloys. The important process parameters that affect the quality of the joint are identified. The working range of process parameters that give defect free joints are developed for the dissimilar FS welding by trial experiments. Dissimilar FS joints were successfully developed as per Central Composite Circumscribed design matrix using square tool pin profile. Regression modeling equations of the dissimilar FS welded AA6063-T6 and A319.0 aluminium alloys were developed based on the experimental values of Ultimate tensile strength, yield strength, percentage elongation and hardness and the developed models were validated for 95% confidence level. The increase in tool rotational speed and axial load increases the responses to a certain level .All the values decreases after reaching a maximum value. But, the increase in welding speed has negative impact on the responses. The process parameters were optimized for maximum tensile strength characteristics and hardness. For the dissimilar joints fabricated using FSW shows a decrease in hardness for high heat input joint. The SEM images of the fractography of the weld zone revealed the combination of ductile and brittle fracture during tensile testing.

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