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Optimization Parameters of Friction Stir Lap Welding of Aluminum Alloy AA6061-T6

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ABSTRACT

Friction stir welding as a new method of joining is getting more popular whereas the statistical approach as an advanced method of quality management is widely used. Here, a full factorial design 2^2 (two factors at two levels) with replicates was conducted to investigate the influence of the factors rotational speed (900 and 1200 rpm) and the welding speed (40 and 60 mm min^{-1}) in the Friction Stir Lap Welding (FSLW) process for the purpose of UTS-AS, UTS-RS, grain size-WZ, grain size-HAZ and EPT. The study used plates of Al-alloys AA6061-T6. The factors rotational speed and welding speed were significant and an increase in the welding speed and a decrease in the rotational speed contributed to all the responses in FSLW. Effect of interaction was not significant for all responses such as UTS-AS, grain size-WZ, grain size-HAZ and EPT and the contribution of this effect to the UTS-RS were positive, but less than 18%. The response surface analysis and table of ANOVA indicate that the most effective level of factors for FSLW process in this study was achieved using a 900 rpm and 60 mm min^{-1} solution of rotational speed and a welding speed, respectively.

Key words: Frictions stir lap welding, full factorial design, ANOVA

INTRODUCTION

Friction stir welding is a solid state welding process; this remarkable up-gradation of friction welding was invented in 1991 by The Welding Institute (TWI). It shows extreme potential for aluminum alloys since it can perform without any toxic fumes and since the base metal does not reach melting point, defects that normally coming from melting are not seen in this process. Among these alloys, AA6061-T6 is one of the most popular alloys that increasingly used in different industries (Liu *et al*., 1997; Mishra and Ma, 2005). In addition to welding in a butt shape, friction stir welding is also, widely used in lap joints but there are a few effort about friction stir lap welding (Mishra and Ma, 2005; Cederqvist and Reynolds, 2001; Cantin *et al*., 2005). Figure 1 shows a lap joint as illustrated; two metal plates are overlapped by a certain width. The process starts with clamping the plates to be welded to a backing plate so that the plates do not fly away during the welding process.

A rotating wear resistant tool is plunged on the upper plate to a predetermined depth (passing the interface between upper and lower plate) and moves forward to form the weld (Fig. 1). The tool consists of two features, shoulder and pin. Intensive contact frictional heat is generated between the rotating tool and the work pieces. Heat is also generated by plastic deformation of the material. The generated heat results in softening of the material (without reaching the melting point) which then flows around the tool pin and deposits at the back of the pin during welding. There are two sides with respect to the welding tool during FSLW. The Advancing Side (AS) is the side where the tool rotational motion and traverse direction are in the same direction and the Retreating Side (RS) is the

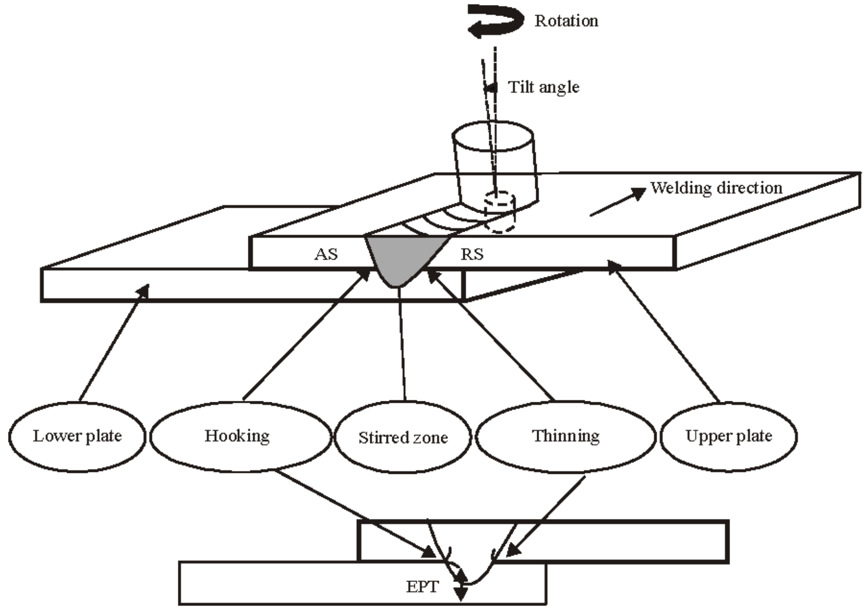

Fig. 1: Schematic of friction stir lap welding (Fadaeifard *et al*., 2014a)

side where the tool rotational motion is opposite to the traverse direction (Mishra and Ma, 2005; Cederqvist and Reynolds, 2001). The tool usually is tilted relative to the work piece and this allows the material to be consolidated behind the tool as it is swept from the advancing to the retreating side.

During friction stir lap welding, plastic flows on the two sides of the welding tool are asymmetric: On the Advancing Side (AS) the tool rotation and translation make available the forces for plastic flow along the same direction (both are the driving forces), whereas on the Retreating Side (RS) they prepare the forces in opposite directions. Frictions stir lap welding, for the reason that the tool was made to penetrate into the lower plate to a certain depth, the original plate interface on either side of the weld slightly bends upwards or downwards (up to tool geometry and welding parameters) to provide somewhere to stay the tool penetration and translation, that called hook effect (Cantin *et al*., 2005). This wavy flaw in advancing side called hooking whiles in retreating side called thinning. Also, the hook and plate thinning geometries show dissimilarity (Cantin *et al*., 2005; Fadaeifard *et al*., 2014a; Babu *et al*., 2012).

The existence of hook and thinning decreases the effective plate thickness in one of plates (upper or lower). The EPT known as a minimum plate thickness which is determined by measuring the smallest distance between hooking flaw (hooking or thinning) and the top of the upper plate if the flaw located in top plate and the bottom of the lower plate (if the flaw located in the bottom) (Fadaeifard *et al*., 2014b). Even though the microstructure and grain size of Weld Zone (WZ) and Heat Affected Zone (HAZ), have impact on strength (Yazdanian *et al*., 2012; Ma, 2008) of a lap joint, the effective thickness (EPT) has an emotional effect on welding strength.

Tensile behavior of welded sample can be affected by the location of EPT in Advancing Side (AS) or Retreating Side (RS). Therefore, the Ultimate Tensile Strength (UTS) when the advancing side of a lap welds was loaded on the upper workpiece (UTS-AS) indicates different results compare with while; the retreating side of a lap joint was loaded on the upper workpiece (UTS-RS).

Importance of statistical analysis of the result of testes on friction stir welding was given in previous studies (Karthikeyan and Mahadevan, 2012).

Based on the above facts, a statistical approach based on the full factorial and ANOVA techniques was adopted in this present study to determine the degree of importance of each process parameter on the UTS-AS, UTS-RS, grain size-WZ, grain size-HAZ and EPT of friction stir lap joint processed aluminum alloy.

MATERIALS AND METHODS

Sampling: Plates of Al-alloys AA6061-T6, 5 mm thick, 220 mm long and 140 mm wide were selected for both the top and bottom plates of lap joints. The chemical compositions in wt% of parent metals AA6061-T6 are shown in Table 1. The mechanical properties of this alloy are shown in Table 2. Figure 2 indicates the FESEM image of microstructure of AA6061-T6 (perpendicular to rolling direction).

The longitudinal direction of the plates was parallel to the plate rolling direction. The overlap along the linear direction of the plates was 50 mm wide. The designed tool for friction stir lap welding is a two-fold pin was modeled from multistage pins (for top plate was cylindrical and bottom plate was conical). The cylindrical part is (Ø8×5 mm) and the

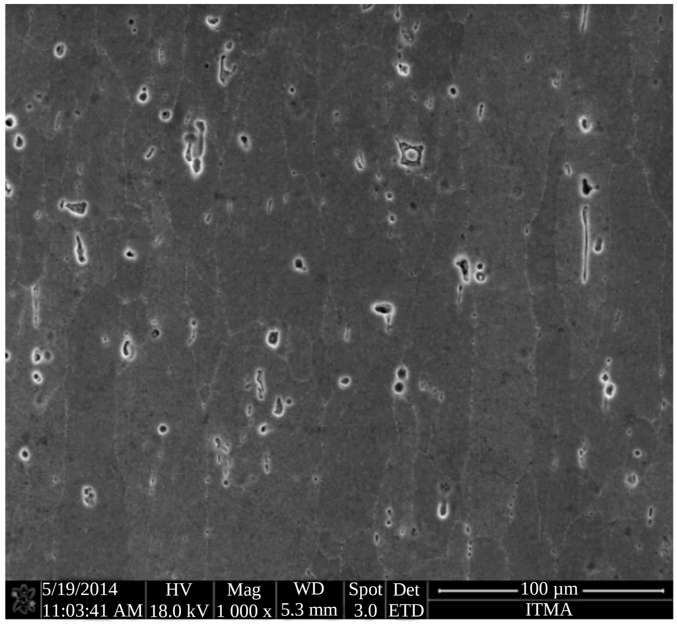

Fig. 2: Microstructure of AA6061-T6 (perpendicular to rolling direction)

Table 1: Chemical composition of parent metals AA6061-T6 (wt%)

Elements	wt (%)
Mg	1.00
Si	0.66
Cu	0.27
Fe	0.30
Mn	0.03
Ti	0.02
Zn	0.05
Cr	0.18

Table 2: Mechanical properties of the 6061-T6 aluminum alloy (as received)

Parameters	Values
Plate thickness (mm)	5
Yield strength (Mpa)	280
Ultimate strength (Mpa)	310
Elongation (%)	15
HV	105

sub-conical headpin is (Ø8×3 mm) having standard left-hand threads and a cylindrical shoulder (Ø20 mm) which was made from hardened high-speed tool steel (AISI H13).

This FSLW was performed at welding speeds of 40 and 60 mm min^{-1} in various rotation speeds (900 and 1200). The rotation direction of tool pin was chosen in clockwise. The tool was tilted at 3° in the backward of driving tool direction during welding. In addition, the tool shoulder was plunged into the upper work-piece by a depth of around 0.15 mm.

As-welded samples were cut perpendicular to welding direction. Microstructural investigations were conducted on the cross-section of the as-welded samples. For metallographic study, samples were exposed to mechanical grinding using different abrasive papers and then polished with 1 µm diamond paste. The samples were then etched with Keller's reagent. A Lecia light microscope joined with a Qwin image analyzer was employed to observe the microstructure. Samples were investigated by field-emission scanning electron microscope (FE-SEM, FEI, NovaNanoSEM 230). Grain sizes of samples were measured on the image obtained from 4 mm under the upper surface of upper plate in WZ and HAZ by Heyn method (standard test method for determining average grain size: E112, 2012).

Strength of welds loaded technically in lap shear test was inspected. The dimensions of lap shear test's samples were according to AWS D17.3 which is an American National Standard for FSLW of aluminum alloys for aerospace hardware. Due to the asymmetric feature of FSLW, two welding locations were considered, thus resulting in two different loading forms. Figure 3 shows a schematic of shear testing arrangement; type A is when the advancing side of a lap weld was loaded on the upper workpiece while in type B, the retreating side of a lap joint was loaded on the upper workpiece. Room temperature lap shear tests were done using a 100 KN Instron mechanical testing machine with the cross-head speed of 2.0 mm min^{-1}. The average of three test specimens is taken to find average weld strength in each particular rotational speed.

FSLW analysis: According to analysis of the FSLW performance, two factors were tested: The rotational speed of the tool holder (900 or 1200 rpm) and the speed of tool movement on the work-piece called as welding speed (40 or 60 mm min^{-1}) in the FSLW process.

Experimental design: A 2^2 full factorial design (two factors with two levels) with replicates was performed to investigate the influence of two factors on the FSLW performance. The factors were Rotational speed (900 or 1200 rpm) and welding speed (40 or 60 mm min^{-1}), as shown in Table 3. The responses used were content the UTS-AS, UTS-RS, grain size-WZ, grain size-HAZ and EPT as shown in Table 4.

Statistical analysis: In statistical, analysis of variance (ANOVA) is employed to recognize the process parameters that are statistically significant. The dispersion of a characteristic value is obtained by experiments and expressed as the sum of squares. In addition, the method decomposes the sum of squares into components classified by factors. In this case, the value of the ANOVA was obtained for all the responses as shown in Table 3.

Response Surface Methodology (RSM) was applied to evaluate the effect of independent variables on the responses. The second order modeling contains all terms of first order with some extra terms such as quadratic terms and interaction terms were developed as shown in Table 4. The general equation of the second order models can be expressed as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \quad (1)$$

where, y is the true modeled response, β_0 is a constant, β_1, β_2, β_{11}, β_{22} and β_{12} are the regression coefficients and x_1, x_2 are the levels of independent variables.

But in this case we ignore the quadratic terms, so the final equation can be expressed as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 \quad (2)$$

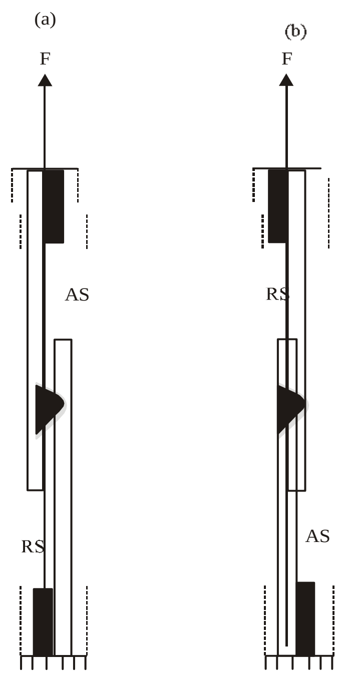

Fig. 3(a-b): Overlap shear testing methods, (a) Type A and (b) Type B (Fadaeifard *et al.*, 2014b)

Table 3: Effective factors with their levels

			Levels	
Factors	Symbol	Type	-1	1
Rotational speed (rpm)	A	Numeric	900	1200
Welding speed (mm min^{-1})	B	Numeric	40	60

RESULTS AND DISCUSSION

Table 4 indicates the circumstances of the 2^2 full factorial design with replicate that applied to the experiments of this study and the values found for all the responses studied: UTS-AS, UTS-RS, grain size-WZ, grain size-HAZ and EPT.

The residual graphs of each response demonstrate that the data presented normality and uniformity of variance in an acceptable way, indicates that the models are significant and showing that there is no significant lack of fit. The F value and the coefficient of regression R^2 for all models which are presented by ANOVA, indicate the significance of the models that shown in Table 5 and 6, respectively. The regression equations (Table 6) were modeled by analyzing the data which were belongs to level of factors and the responses.

Table 5 presents the values obtained by ANOVA in terms of 2^2 full factorial design with replicate for each of the responses. Response surfaces graph were built for factors versus each responses, as shown in Fig. 4. Figure 5 depicts the effects of the individual factors and their interaction for all responses analyzed using the half normal plots.

Table 4: The 2^2 full factorial design (in replicate) for FSLW and the responses obtained in the study

	Independent factors levels		Responses				
Trial	Rotational speed	Welding speed	UTS-AS (Mpa)	UTS-RS (Mpa)	Grain size-WZ (μm)	Grain size-HAZ (μm)	EPT (mm)
1	900	40	132.0	137.0	37.6	92.9	4.83
2	900	40	133.4	136.2	36.8	92.5	4.68
3	1200	40	124.0	94.1	31.4	93.8	3.15
4	1200	40	123.0	95.0	31.2	93.9	3.26
5	900	60	137.0	136.0	28.6	88.7	4.88
6	900	60	136.3	135.0	29.7	89.0	4.89
7	1200	60	126.0	122.1	26.6	90.9	4.01
8	1200	60	126.4	121.0	27.0	90.7	3.95

Table 5: ANOVA table for the responses considered in the 2^2 factorial model

Source	Degree of freedom	Sum of square	Mean square	F-test	p-value
Response 1 = UTS-AS					
Regression	3	215.954	71.9846	159.52	0.000
A = Rotational Speed	1	193.061	193.061	427.84	0.000
B = Welding Speed	1	22.111	22.111	49.00	0.002
A×B = Interaction	1	0.781	0.7812	1.73	0.259
Pure error	4	1.805	0.4512		
Total	7	217.759			
Response 2 = UTS-RS					
Regression	3	2298.21	766.07	1674.47	0.000
A = Rotational Speed	1	1568.00	1568.00	3427.32	0.000
B = Welding Speed	1	335.41	335.41	733.13	0.000
A×B = Interaction	1	394.8	394.80	862.96	0.000
Pure error	4	1.83	0.46		
Total	7	2300.04			
Response 3 = Grain size WZ					
Regression	3	119.084	39.6946	154.91	0.000
A = Rotational speed	1	34.031	34.031	132.80	0.000
B = Welding Speed	1	78.751	78.751	307.32	0.000
A×B = Interaction	1	6.301	6.3010	24.59	0.008
Pure error	4	1.025	0.2562		
Total	7	120.109			
Response 4 = Grain size HAZ					
Regression	3	28.93	9.64333	257.16	0.000
A= Rotational Speed	1	4.805	4.8050	128.13	0.000
B = Welding Speed	1	23.805	23.805	23.805	0.000
A×B = Interaction	1	0.320	4.8050	8.53	0.043
Pure error	4	0.150	0.0375		
Total	7	29.08			
Response 5 = EPT					
Regression	3	3.6310	3.6310	252.81	0.000
A = Rotational Speed	1	3.0135	3.0135	629.45	0.000
B = Welding Speed	1	0.4095	0.4095	85.54	0.001
A×B = Interaction	1	0.2080	0.2080	43.45	0.003
Pure error	4	0.0192	0.0048		
Total	7	3.6502			

Table 6: Mathematical equations for all the responses by means of the response surface model

Response	Equation	R^2 (%)
UTS-AS	UTS-AS = 139.5-0.02 A+0.55 B	99.35
UTS-RS	UTS-RS = 433.550-0.33 A-4.27 B+0.005 A×B	99.92
Grain size WZ	Grain size WZ = 92.3-0.0433A-0.935 B+0.00059A×B	99.15
Grain size HAZ	Grain size HAZ = 101.75-0.0015A-0.3125B+0.000133A×B	99.48
EPT	EPT = 13.935-0.01023A-0.11325B+0.000127 A×B	98.48

Table 5 shows the ANOVA results, described that for all responses the main factors were very significant and in all cases the interaction between the main factors were significant except for the response UTS-AS. Figure 5a, can confirm the result for UTS-AS, the interaction point is located exactly next to the normal line which is indicate that the interaction point has no significance in case of UTS-AS.

Figure 5a, b and e make it obvious that the factor which has most influence to the responses UTS-AS, UTS-RS and EPT was the rotational speed, because the points in accordance with the main effect, for these three responses, are further away from the normal line. According to the results demonstrated by the ANOVA test (Table 5), the contribution percentage of the rotational speed for the responses UTS-AS, UTS-RS and EPT was 84.06, 68.17 and 82.56%, respectively. The percentage of welding speed was the next most significant factor for these three responses, with a percentage of 10.15% for UTS-AS and 11.21% for EPT. The interaction effect on UTS-RS was more than effect of welding speed on it; it was 17.16% in comparison with 14.58%.

Figure 5c and d make it obvious that the factor which has most influence to the responses grain size-WZ and grain size-HAZ was the welding speed, because the points in accordance with the main effect, for these two responses, are further away from the half normal line. The grain size of the WZ and HAZ are indicated in Fig. 6 and 7, respectively.

According to the results demonstrated by the ANOVA test (Table 5), the contribution percentage of the welding speed for the responses grain size-WZ and grain size-HAZ was 65.57 and 81.86%, respectively. The percentage of rotational speed was the next most significant factor for these two responses, with a percentage of 28.33% for grain size-WZ and 16.52% for grain size-HAZ. Moreover, the ANOVA showed a contribution percentage of 5.24 and 1.1% of the interaction for the responses grain size-WZ and grain size-HAZ, respectively.

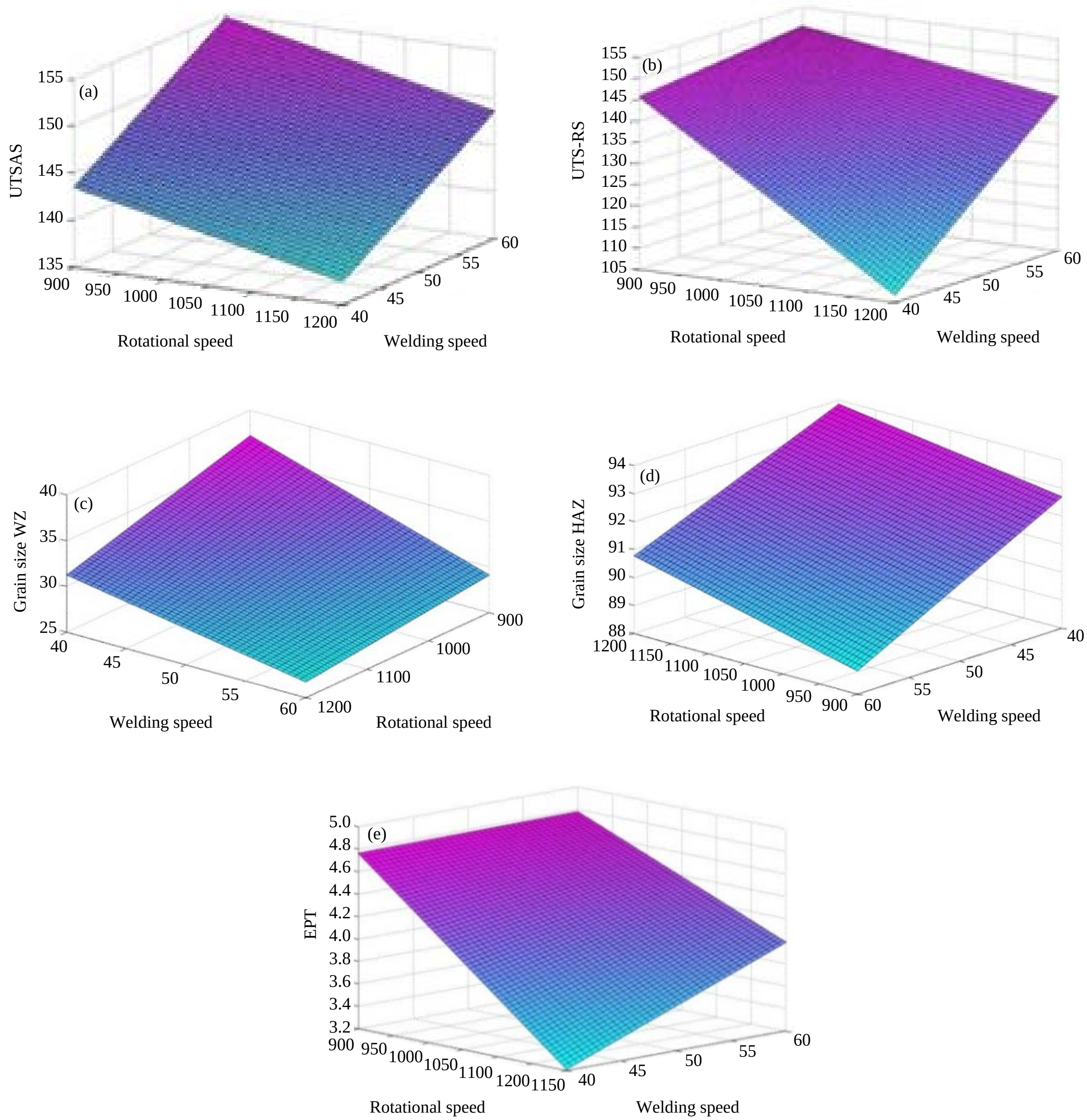

Fig. 4(a-e): Surface response of the 2^2 full factorial design variables presented in Table 4 for the responses, (a) UTS-AS (b) UTS-RS, (c) Grain size-WZ, (d) Grain size-HAZ and (e) EPT

The response surfaces prescribed in Fig. 4a-e indicated that the increase in welding speed from 40-60 (mm min^{-1}) and the decrease in the rotational speed solution, from 1200-900 rpm, caused increase in the values of all responses UTS-AS, UTS-RS and EPT. Thus, increasing the rotational speed and decreasing the welding speed negatively influenced the determination of grain sizes in WZ and HAZ.

Therefore, the response surfaces (Fig. 4a-e) achieved by the 2^2 factorial design demonstrate that the minimum values of rotational speed (rpm) and maximum values of welding speed provided more efficient determination of all FSLW responses.

In addition we compare this study with the previously researches as shown in the Table 7.

The results of Table 7 shows that the optimization level of each parameter for each research is stand in deferent level, for instance the optimization level of rotational speed in these three studies is located in low level, high level and medium level, respectively from left to right. Moreover, the

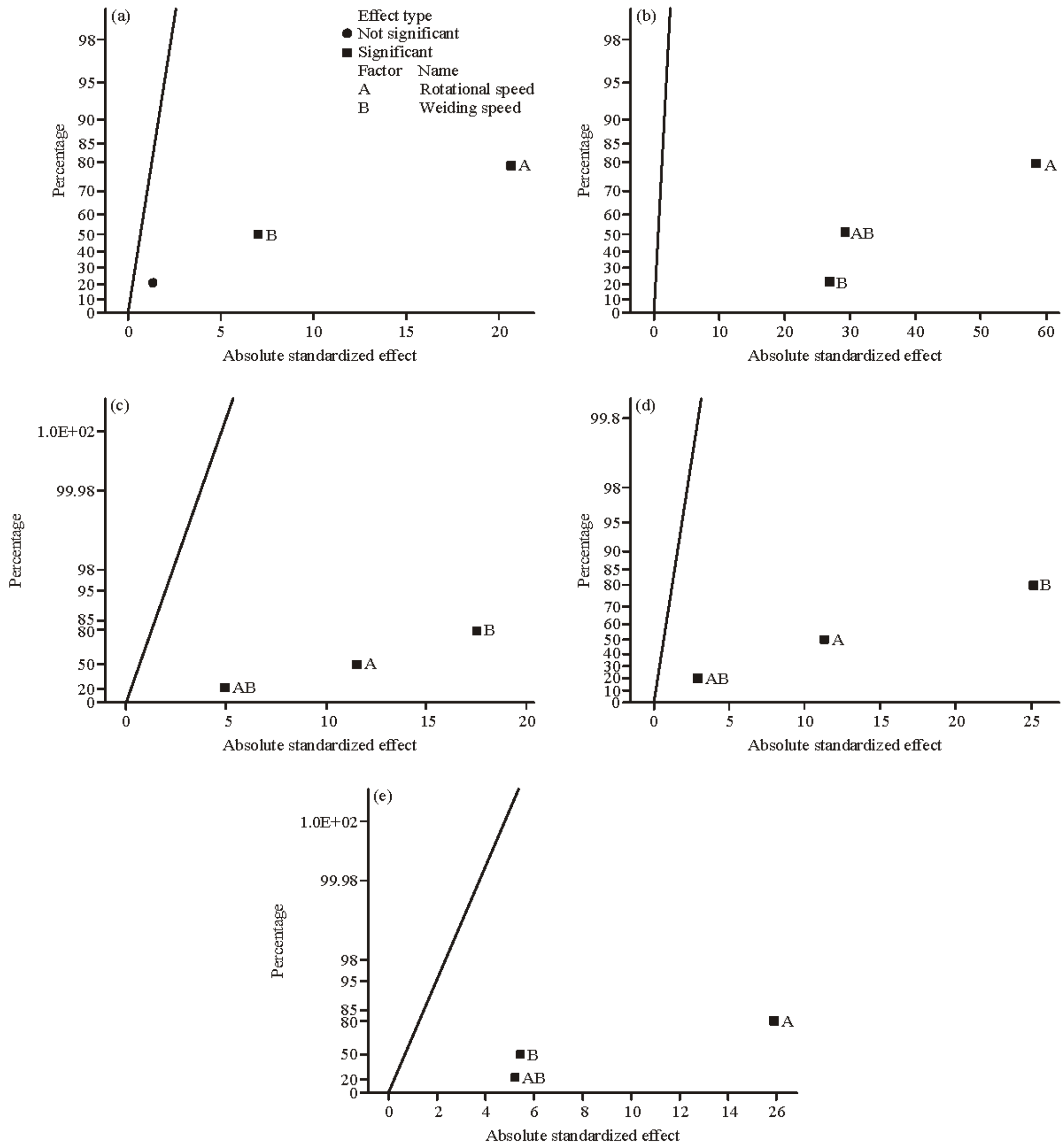

Fig. 5(a-e): Half normal probability of the 2^2 full factorial design variables presented in Table 4 for the responses (a) UTS-AS, (b) UTS-RS, (c) Grain size-WZ, (d) Grain size-HAZ and (e) EPT, $\alpha = 0.05$

Table 7: Comparison of present study with previous researches

Variables	Present study		Ahmadi *et al*. (2014)			Li and Liu (2014)		
Parameter studied	A^1	B^2	RS^1	WS^2	TA^3	R^1	W^2	r^4
Parameter levels	2	2	3	3	3	3	3	3
Optimize value	900	60	1250	25	1	1075	225	550
Optimize level	Low	High	High	High	Middle	Middle	Middle	Middle
Optimization method	Full factorial		Taguchi			Box-Behnken		
Material	Aluminum alloy AA6061-T6		PP composites			Aluminum alloy 2219-T6		

1: Rotational Speed (rpm), 2: Welding Speed (mm min^{-1}), 3: Tilt Angle (degree), 4: Rotation speed of the assisted shoulder (rpm)

optimization level of each parameter is related to so many factors such as type of materials, tools, plate thickness and pin. Furthermore one of important issues in FSW is the ratio of rotation speed to welding speed. With increasing the ratio of rotation speed to welding speed (ω/v) the micro hardness of the joints decreases. The value of ω/v also has impact on the fracture mode of the joints as well as the elongation (Li *et al*., 2013).

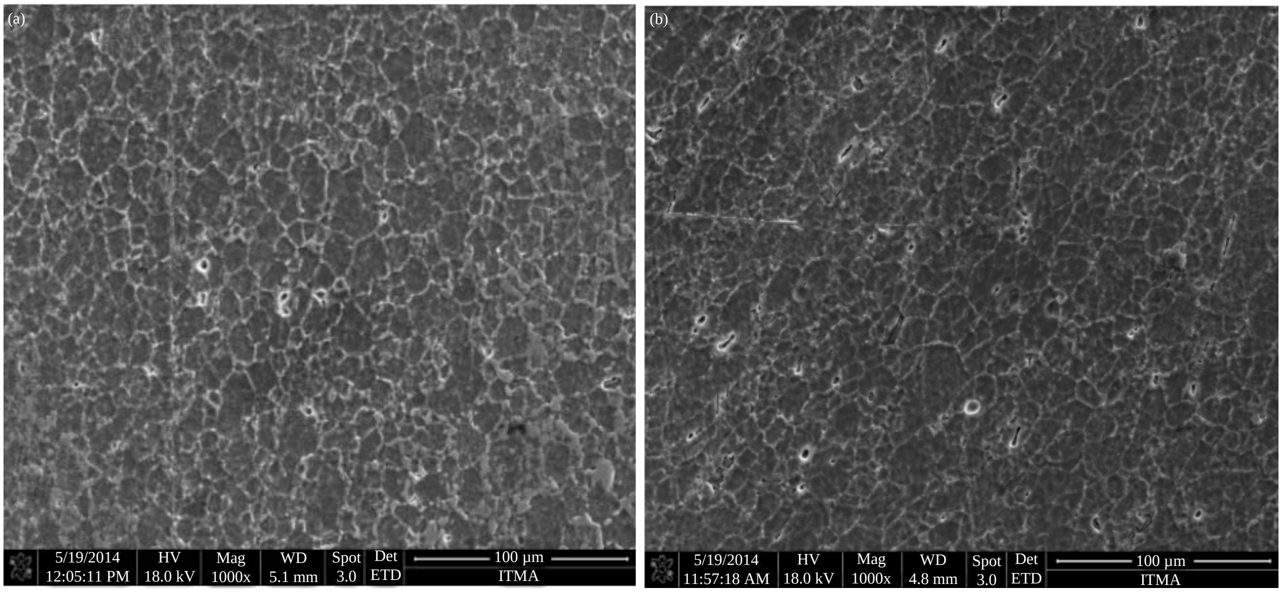

Fig. 6(a-b): FESEM image of weld zone-WZ (a) 1200 rpm-40 mm min^{-1} and (b) 1200 rpm-60 mm min^{-1}

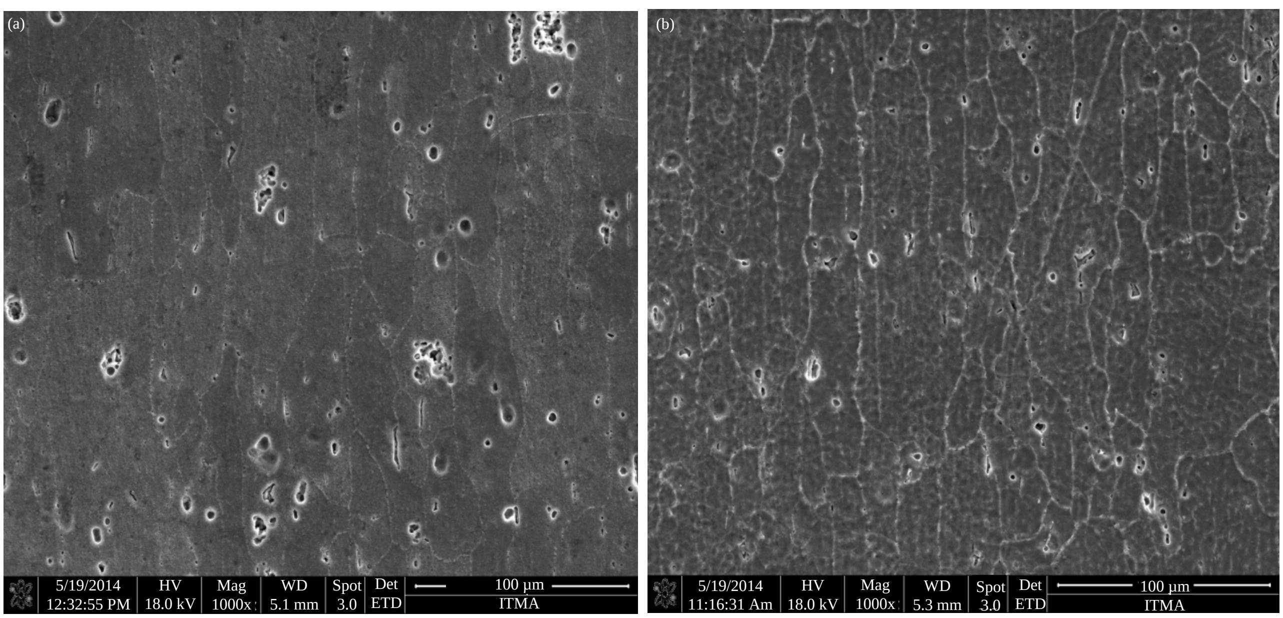

Fig. 7(a-b): FESEM image of heat affected zone-HAZ (a) 900 rpm-40 mm min^{-1} and (b) 900 rpm-60 mm min^{-1}

CONCLUSION

A 2^2 full factorial design with replicate carried out to optimize the methodology of samples for FSLW process. We concluded that the effect of factors rotational speed and welding speed were significant on the FSLW responses and increasing the ratio of rotation speed to welding speed the micro hardness of the joints decreases.

Effect of interaction was not significant for most of responses such as UTS-AS, grain size-WZ, grain size-HAZ and EPT and the contribution of this effect to the UTS-RS were positive but less than 18%. The response surface analysis and table of ANOVA indicate that the most effective level of factors for FSLW process was achieved using a 900 rpm and 60 mm min^{-1} solution of rotational speed and a welding speed, respectively.

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