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WELDING PARAMETERS EFFECT ON THE MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

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ABSTRACT

In this work, the Taguchi technique has been applied to optimize the welding parameters to detect the better mechanical attributes of friction stir welded AA6061, AA1050, AA5049, and AA5754 joints. L16 orthogonal array is used by considering the welding parameters, such as rotational speed, transverse speed, and tool pin profile. The best welding parameters for the greatest tensile strength and hardness of the joints were detected by studying the signal/noise (S/N) ratio and analysis of variance (ANOVA) results. The optimum levels for tensile strength were found to be 800 rpm rotational speed , materials 1050-H24 aluminum alloy, 25 mm/min transverse speed and pin profile is conical .Also, the optimal levels for hardness were found to be 600 rpm rotational speed, materials 1050-H24 aluminum alloy, 32 mm/min transverse speed and pin profile is conical . Besides, the fractured surface microstructure was examined of the friction stir welded joints.

KEYWORDS

Aluminum alloys, Tensile Strength, Hardness, Taguchi method, microstructure, friction stir welding,

INTRODUCTION

Aluminum alloys have neat ductility and deformability, regrettably, they experience from a great coefficient of thermal expansion and relatively humble strength. These humble characteristics declare their applications in various fields needing better thermal and mechanical properties, [1 - 2]. Ascribable their excellent characteristics such great strength to weight ratio, bigger fatigue life, and large corrosion resistance, [3 - 4]. However, the hot-crack, defects as well as tacky microstructures are expected to be formed through a fusion bonding process of the Aluminum alloy joint, which exceedingly limited the applications, [5 - 7]. Aluminum alloys are attempted to friction weld and the effect of various process parameters on mechanical properties is experimentally investigated, [8].

Friction stir welding (FSW) is one of the established and smart methods over the conventional fusion welding processes to provide defect-free joints in non-ferrous alloys. FSW succeeds in the arc welding process and sound joints are possible between aluminum and high strength low alloy steels, [9]. Moreover less welding defects are provided as the process will not reach red hot condition through welding, [10]. FSW technique finds fast industrial purposes, such as shipbuilding, aerospace, and automobile, [11]. FSW method

is conducted at lower temperatures, it doesn't experience much distortion and residual stresses. This technique also exposes great dimensional stability. Unlike the conventional welding processes, FSW doesn't lack any filler material or shielding gas. Due to innumerable such qualities and advantages of FSW over conventional joining processes, it has enhanced a rapidly emerging solid-state joining process, [12]. Commin et al., [13] presented FSW of AZ31 magnesium alloy and noticed that the heat generation increased due to the increase in shoulder diameter and tool rotational speed, whereas the increase in weld speed decreased the heat generation in the weld zone. Vijay and Murugan [14] achieved that straight square pin profiles produced high strength joints after investigating FSW of Al –10 wt. % TiB_2 metal matrix composite. Sivakumar and Vignesh Bose, [15] studied at the simple ideas of FSW are represented, including metal flow and thermal records, earlier than explaining how process parameters influence the weld microstructure and the chance of defects. The range of mechanical properties that may be carried out is considered. It is confirmed that FSW of aluminum is turning into a frequently mature era with numerous manufacturing applications.

The influence of FSW parameters on the mechanical properties of aluminum weld joints is evaluated. The report does the collection of different researcher conclusions to state the different viewpoint of the advantage of the friction stir processing and welding technique for the different materials joining for unlimited applications, [16, 17]. Aluminum alloy AA 2014-T6 of 5 mm thickness is friction stir welded by changing pin profile geometries and other factors to state the influences of the chosen experimental condition on tensile properties and microstructure are exhibited utilizing response surface methods [18]. Taguchi design utilized to optimize a set of friction stir welding parameters in terms of total crack energy, crack initiation energy, and crack propagation energy in weldments, [19]. Ismail et al., [20] presented full penetration FSW of 6063 aluminum pipes and gathered that a high tool rotational speed of 1500 rpm and a welding speed of 144 mm/min produced defect-free welds.

Tool pin profile represents a significant role in the microstructure, material flow, welding loads, and mechanical properties of the joints in friction stir welding, [21 - 23]. In special, a cylindrical or conical pin with threads and/or flats has been extensively utilized in the experiments for its prominent efficiency of improving the material flow in the stirring zone, decreasing the traverse force and enhancing the mechanical properties, [21, 22, 24]. Zhao et al., [25, 26] observed that a tapered pin with threads spurred more vertical material flow and reduced the defects in the weld. Lorrain et al., [27] found that a tapered cylindrical pin with three flats developed the material flow formed by the shoulder and produced more change of the material velocity than the straight cylindrical pin.

Some factors impact the honesty of the welds performed in FSW. These factors involve among others, tool rotational speed, tool geometry, travel speed, the spindle tilt angle, axial force, and plunge depth, [28]. Several researchers have recorded the influence of these factors on mechanical properties and microstructures of welds, [29-31]. Hence, optimizations of these factors become important to economize time and cost of experiments and to get high-quality welds. Researchers have utilized several methods of optimizing these factors, [32, 33] outstanding among them is the Taguchi method which has found enormous purpose for optimizations. The present study is an attempt to utilize the Taguchi method of experiment with L16 orthogonal array for optimizing the different parameters such as the rotation speed, the profile of the pin, the feeding speed, the type of material for the friction stir welding.

EXPERIMENTAL

Materials and Methods

Friction stir welding of butt joints is performed of 1050-H24, 5754, 5049 and 6061-T6 aluminum alloys. The chemical composition of these alloys are listed in Table 1. The weld samples are made using 6 mm thick, 100 mm wide, and 200 mm long cut from aluminum plates. Tools were made from steel CK45 with Two different pin profiles (conical and cylindrical) were utilized to perform FSW, while the shoulder diameter was 20 mm and the probe length and diameter were 5.7mm and 6 mm, respectively.

Table 1 Chemical composition of aluminum alloys (mass fraction, %)

Materials	Al	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti
1050-H24	Bal	0.08	0.3	0.02	0.01	0.01	0.02	–	0.02
5754-Al alloy	Bal	0.40	0.40	0.10	0.50	2.6	0.20	0.30	0.15
5049-Al alloy	Bal	0.17	0.35	0.08	0.80	1.9	–	0.12	0.05
6061-T6	Bal	0.62	0.33	0.28	0.06	0.9	0.02	0.17	0.02

Design of Experiments for Taguchi Method

The Taguchi approach is powerful in targeting quality enhancement in product development. It utilizes a fractional factorial experimental design, announced an orthogonal array (OA), to decrease the number of experiments under permissive reliability. A primary component of the Taguchi method is parameter design. The parameters are defined such that the product's functional characteristics are optimized, with minimum sensitivity to noise, [34]. The influence of the input welding parameters on the mechanical properties of friction stir welding aluminum alloys was predicted by the Taguchi approach, [35 - 37]. In the Taguchi design, the examinations of experimental results have three basic objectives. Firstly, examining the main effects of each parameter provides the general influence of each parameter. Secondly, knowing whether higher or lower values produce the preferred result, the best levels of factors can be predicted. Three functions may be employed based on the signal to noise (S/N) ratio: ‘‘larger the better’’, ‘‘nominal the best’’ and ‘‘smaller the better’’, [25]. Finally, the contribution of each parameter is confirmed by the analysis of variance (ANOVA was utilized to conclude the relative percent influence and significance of each parameter, [38].

In this research, four parameters chosen for this welding process are tool pin profile, materials type, rotational speed, and travel speed. Table 2 shows the values chosen for the welding parameters and their levels. L16 (4^4) orthogonal array (OA) design was used to investigate the four processing parameters, as given in Table. 3.

3.2 Analysis of variance (ANOVA)

The analysis of variance aims to identify the significance of design parameters on the process response [40]. The ANOVA results can determine very clearly the impact of each parameter on tensile strength and hardness as shown in Tables 7 and 8 respectively. The percentage contributions using ANOVA is used to compensate for the effect of individual parameters on the process response. The parameter with a higher percent contribution, a small variation will have a high impact on the performance. The results of ANOVA observed that the type of the material (31.44% contribution) has the highest impact on the tensile strength followed by the transverse speed (18.44% contribution), rotational speed (16.02% contribution), and pin profile (0.38% contribution) respectively. Also, the type of the material (81.7% contribution) has the largest effect on the hardness followed

by the rotational speed (3.68% contribution), transverse speed (1.82% contribution), and pin profile (0.79% contribution) respectively.

Table 2 Experimental welding parameters and levels.

Parameters	Units	Symbol	Levels			
			1	2	3	4
Tools pin profile	Shape	PP	Conical	Cylindrical	Conical	Cylindrical
Materials	-	M	5754	5049	1050	6061
Rotational speed	rpm	RS	400	600	800	1000
Travel speed	mm/min	TR	25	32	42	52

Table 3 L16 orthogonal array (OA) design for the experiments

Experiment number	PP	M	RS	TS
1	Conical	5754	400	25
2	Conical	5049	600	32
3	Conical	1050	800	42
4	Conical	6061	1000	52
5	Cylindrical	5754	400	25
6	Cylindrical	5049	600	32
7	Cylindrical	1050	800	42
8	Cylindrical	6061	1000	52
9	Conical	5754	400	25
10	Conical	5049	600	32
11	Conical	1050	800	42
12	Conical	6061	1000	52
13	Cylindrical	5754	400	25
14	Cylindrical	5049	600	32
15	Cylindrical	1050	800	42
16	Cylindrical	6061	1000	52

RESULTS AND DISCUSSION

3.1 Mechanical properties performance

In this research, the results of the mechanical properties (Tensile strength and Hardness) obtained from each trial were statistically analyzed by employing S/N ratio equations. Since higher mechanical properties are wished during optimum process parameters. The S/N ratios were calculated based on the larger the better quality characteristic employing the following equation, [39]:

$$\boldsymbol{Larger\ the\ better\ S/N\ (db) = -10\log\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}} \qquad (1)$$

Where yi is the performance characteristic value for the i_{th} test and n is the number of data points in each test. The tensile strength, hardness (experimental results), and computed S/N ratio values are listed in Table 4. The response to mean and signal-to-noise ratio (S/N) assessed applying the larger is a better approach. Furthermore, the estimated S/N ratio response of tensile strength and hardness for each parameter for all levels is presented in Tables 5 and 6 respectively. Based on the highest values of the S/N ratio, it

can be concluded that the optimal values of tensile strength could be achieved at 800 rpm rotational speed (level 3), materials 1050-H24 aluminum alloy (level 3), 25 mm/min transverse speed (level 1) and pin profile is conical (level 1).Also, the optimal values of hardness at 600 rpm rotational speed (level 2), materials 1050-H24 aluminum alloy (level 3), 32 mm/min transverse speed (level 2) and pin profile is conical (level 1).

Table 4 Experimental results of the four parameters in the L16 orthogonal array (OA)

Experiment number	Tensile strength (Mpa)	S/N ratio (db)	Hardness (HV)	S/N ratio (db)
1	173.2	44.7710	95	39.5545
2	189.7	45.5613	110	40.8279
3	180.2	45.1151	35	30.8814
4	174.0	44.8110	64	36.1236
5	190.2	45.5842	94	39.4626
6	89.0	38.9878	73	37.2665
7	91.0	39.1808	31	29.8272
8	167.8	44.4958	59	35.4170
9	119.6	41.5546	107	40.5877
10	110.3	40.8515	63	35.9868
11	81.7	38.2444	33	30.3703
12	182.0	45.2014	62	35.8478
13	205.6	46.2605	91	39.1808
14	201.4	46.0812	67	36.5215
15	81.0	38.1697	36	31.1261
16	161.7	44.1742	82	38.2763

Table 5 S/N response table for Tensile strength

Levels	Parameters			
	PP	M	RS	TS
1	43.26	40.18	41.24	43.81
2	42.72	42.87	43.63	43.64
3	-	44.54	44.31	43.63
4	-	44.37	42.78	40.88
Delta	0.55	4.37	3.07	2.93
Rank	4	1	2	3

Table 6 S/N response table for Hardness

Levels	Parameters			
	PP	M	RS	TS
1	36.27	30.55	36.37	35.44
2	35.88	37.65	36.82	36.45
3	-	39.70	35.85	36.15
4	-	36.42	35.28	36.28
Delta	0.39	9.15	1.54	1.01
Rank	4	1	2	3

3.2 Analysis of variance (ANOVA)

The analysis of variance aims to identify the significance of design parameters on the process response [40]. The ANOVA results can determine very clearly the impact of each parameter on tensile strength and hardness as shown in Tables 7 and 8 respectively. The percentage contributions using ANOVA is used to compensate for the effect of individual

parameters on the process response. The parameter with a higher percent contribution, a small variation will have a high impact on the performance. The results of ANOVA observed that the type of the material (31.44% contribution) has the highest impact on the tensile strength followed by the transverse speed (18.44% contribution), rotational speed (16.02% contribution), and pin profile (0.38% contribution) respectively. Also, the type of the material (81.7% contribution) has the largest effect on the hardness followed by the rotational speed (3.68% contribution), transverse speed (1.82% contribution), and pin profile (0.79% contribution) respectively.

Table 7. Analysis of variance (ANOVA) results for tensile strength.

Factor	SS	DF	MS	F-ratio	Contribution %
PP	121	1	121	0.06	0.38
M	9891	3	3297	1.55	31.44
RS	5038.9	3	1679.6	0.79	16.02
TS	5802	3	1934	0.91	18.44
Error	10622.4	5	2124.5		33.77
Total	31457.3	15			100

Table 8. Analysis of variance (ANOVA) results for hardness.

Factor	SS	DF	MS	F-ratio	Contribution %
PP	81	1	81	0.33	0.79
M	8412.8	3	2804.25	11.37	81.7
RS	379.2	3	126.42	0.51	3.68
TS	187.2	3	62.42	0.25	1.82
Error	1233.5	5	246.7		11.98
Total	10293.7	15			100

3.3 Influence of welding parameters on Tensile Strength.

Fig. 1 presents the influence of different welding parameters such as rotational speed, traverse speed, and pin profile on tensile strength. The rotational speed increases, the tensile strength will increase and decrease with an increase in transverse speed, [41 - 44].

As explained from this figure increasing the rotational speed (RS) and decreasing traverse speed (TS) increased in tensile strength. A lower tool rotational speed (400 rpm) provided a lower heating condition as well as poor stirring action by the tool pin and improper consolidation of work material by the tool shoulder, [45]. The increase in rotational speed increased the heat input per unit length of the joint, which produces a greater uniform grain refinement resulting in enhanced tensile strength. The other point produced from Figure 1 states that an input heat larger than the optimized limit will generate a soft joint that lacks the demanded strength.The tool pin profile is an important part, which plays a crucial role in material flow and mixing, [22]. In a conical profiled pin, with the tapered probe, the greater frictional heat increases the plastic deformation because of the larger contact area of the probe with the work piece. Hence a larger tensile strength was concerned.

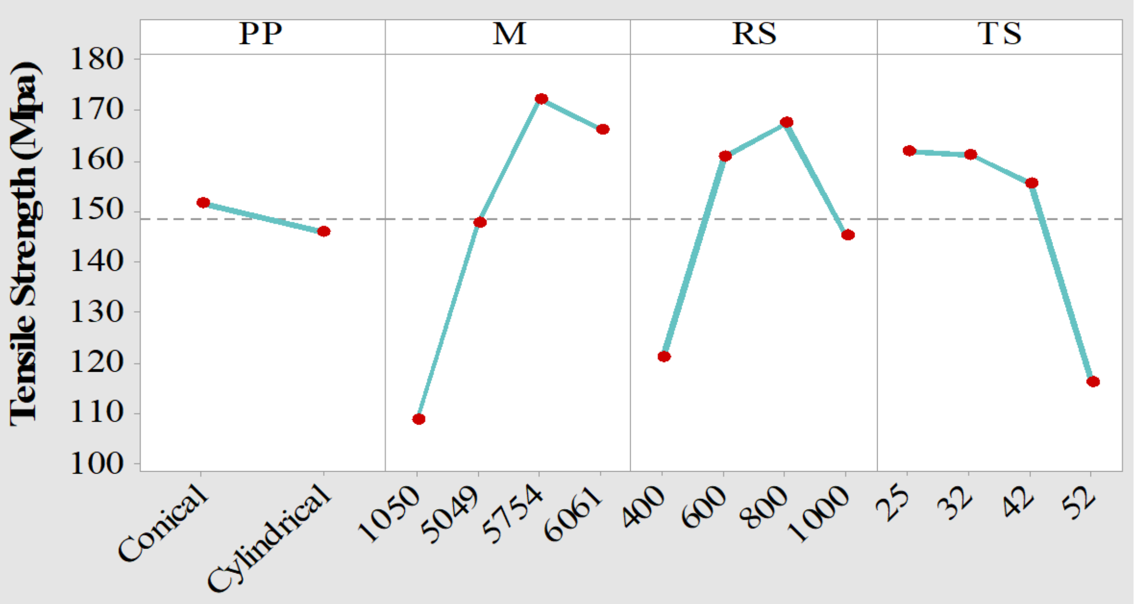


Fig.1 influence of process parameters on tensile strength.

Influence of welding parameters on hardness

Fig. 2 represents the influence of different welding parameters such as rotational speed, traverse speed, and tool pin profile on hardness. The hardness of weld nuggets displays increment and decrement trends concerning tool rotation speed. Tool rotation speed was considered as a sensitive parameter In the FSW process since heat generation near the weld zone was mainly depends on the tool rotation speed. Here heat generation is minimal at low tool rotation this results in lower plastic deformations and inadequate material flow near the weld zone thus decreases the hardness However, at higher tool rotation speed the heat generation is increased that induces turbulent flow that forms rough grain results the lower hardness The hardness values decrease at the higher welding speed. As result to lower heat input because of the higher cooling rate near the weld nugget leads to rough grain structure formations [46].As shown from this figure increasing rotational speed (1000 rpm) and decreasing traverse speed (25 mm/min) resulted in decreasing in hardness due to increase in the heat input. The hardness of the weld joint is maximum for tool conical pin profile, rotation speed of 600 rpm and traverse speed of 32 mm/min.

3.4 Fractography of the Weld Joint

Essential information about the nature of the fracture can be achieved by utilizing scanning electron microscope (SEM). As a result of the complex interaction between the materials as well as the processing parameters, different fracture modes were examined. As it is clear in Fig. 3 (a, b, and c). However, under certain conditions (material and properties), a complete dimpled structure was seen in Fig. 3 (d, e, f, and g). It is clear from the above figures that the dominant fracture mode can be ascribed as partially dimpled and cleavage type. Furthermore, these various modes can be observed in a single specimen which further makes a reliable discussion is not simple. Close testing of the nugget zone, which has been described as the part of thermo-mechanically affected zone (TMAZ), has undergone the rest severe plastic deformation. The width of the nugget is normally similar to, but slightly greater than, the diameter of the pin. The structure of which differs from the rest of the TMAZ. The material is dynamically recrystallized during processing and described by a fine relatively equiaxed grains, normally between 5~15 µm in diameter, which appears to vary as a function of the alloy composition and

welding parameters. However, there is a controversy regarding the recrystallization mechanism (continuous or discontinuous). But we can safely say that the significant enhancement in mechanical properties of FSW Al alloys is connected to microstructural refinement, homogenization, and elimination of porosity.

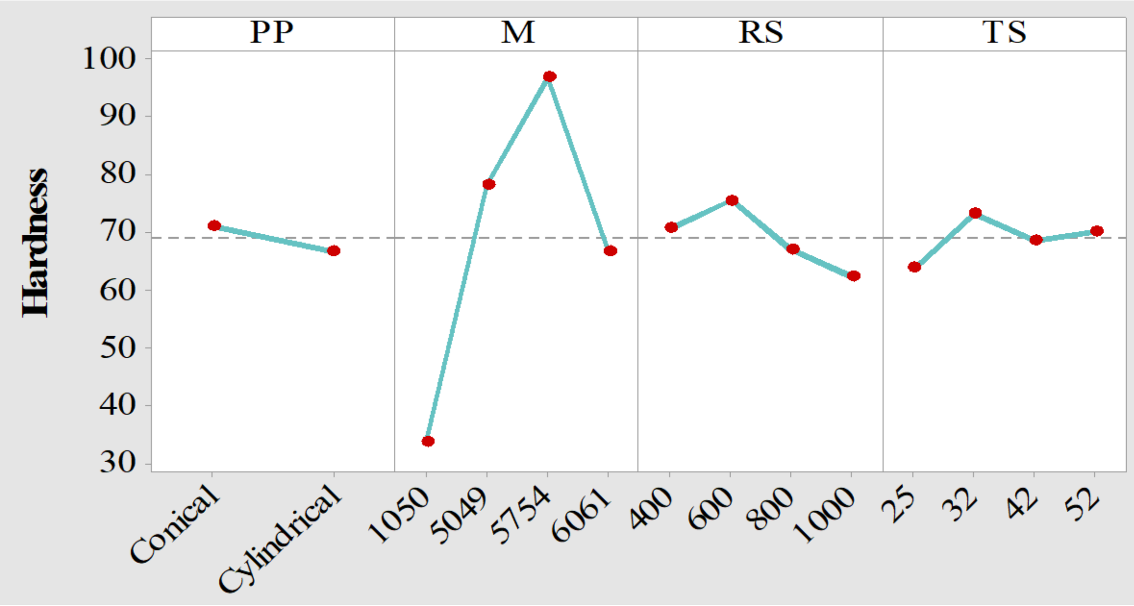
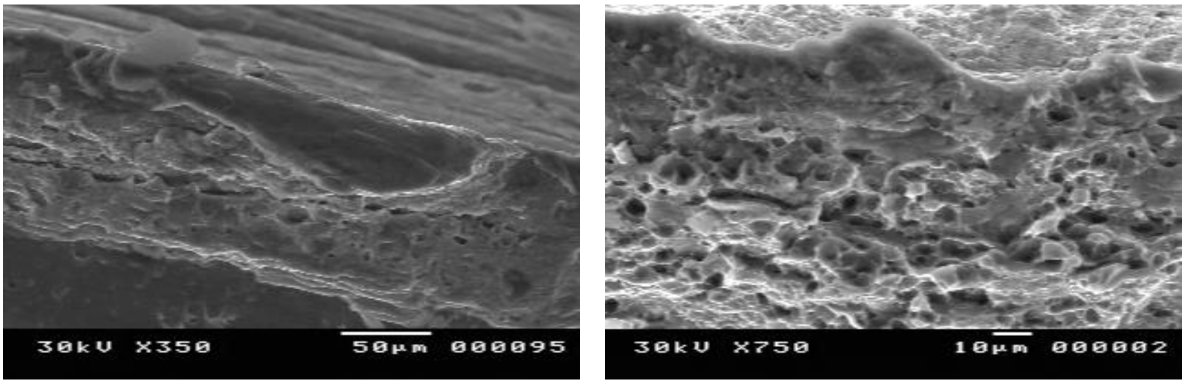
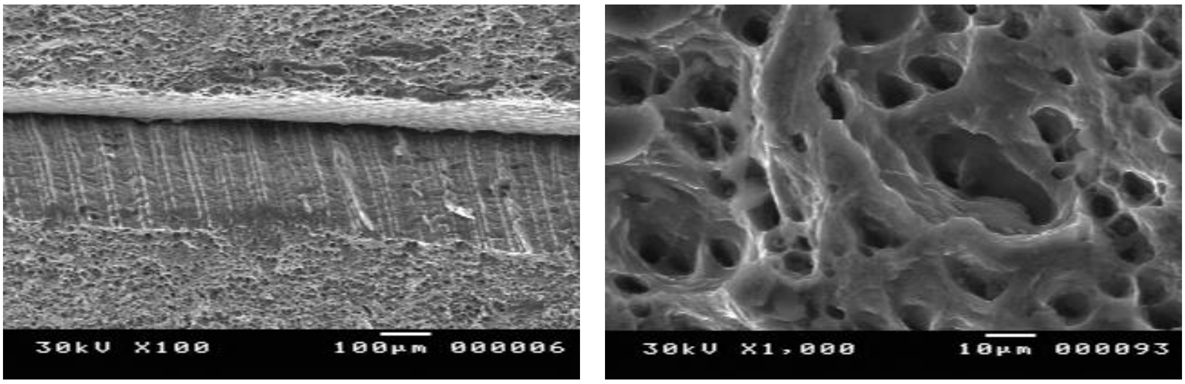


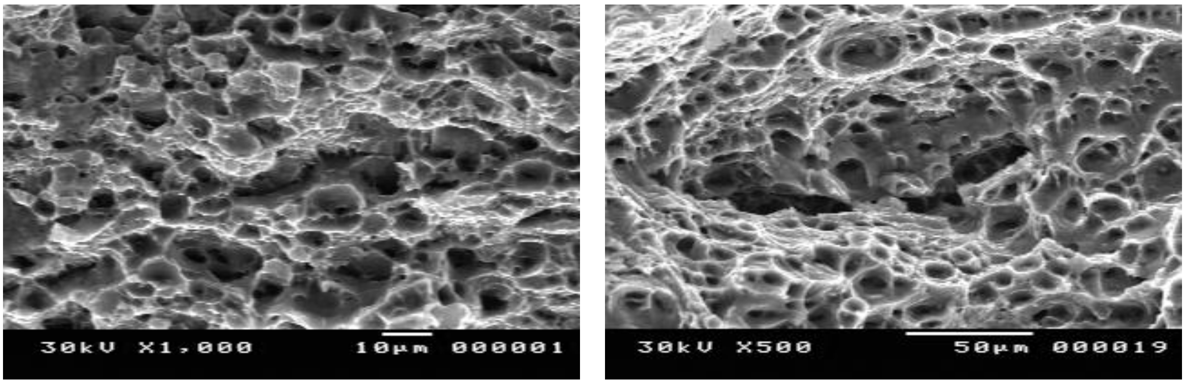
Fig. 2 influence of process parameters on hardness.



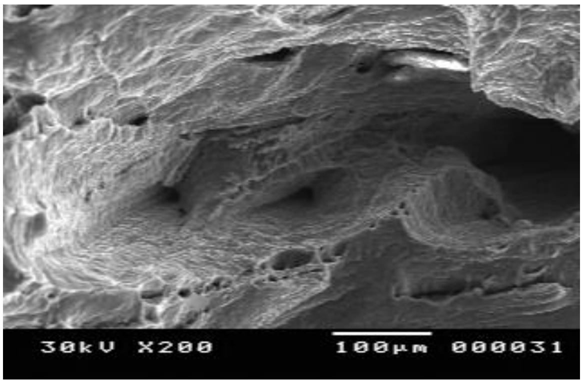
(a) Al 5754, conical tool, 400 rpm and 25 mm/min. **(b) Al 6061, conical tool, 1000 rpm and 52 mm/min.**



(c) Al 5754, conical tool, 800 rpm and 32 mm/min. **(d) Al 5754, conical tool, 400 rpm and 25 mm/min.**



(e) Al 6061, conical tool, 1000 rpm and 52 mm/min. **(f) Al 6061, conical tool, 600 rpm and 25 mm/min (cleavage).**



(g) Al 1050, cylindrical tool, 600 rpm and 52 mm/min: dimple fracture.

Fig. 3 fracture surfaces of bonded regions of the FSW joints.

CONCLUSIONS

The welding process parameters of a friction stir welding AA6061, AA1050, AA5049, and AA5754 aluminum alloy have been optimized to maximize the tensile strength and hardness of the joints by using the Taguchi L16 orthogonal array. The following conclusions can be summarized from the present study:

1. **The higher tensile strength was obtained at optimal combination of welding parameters were found to be 800 rpm rotational speed, materials 1050-H24 aluminum alloy, 25 mm/min transverse speed and pin profile is conical.**
2. **The higher hardness was obtained at optimal combination of welding parameters were found to be 600 rpm rotational speed, materials 1050-H24 aluminum alloy , 32 mm/min transverse speed and pin profile is conical**
3. **The tensile strength of the friction stir welded joints increased with the increase of tool rotational speed and welding speed up to a maximum value, and then decreased**

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