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Optimization of Friction Stir Processing Parameters for Aluminum Alloy (AA6061-T6) Using Taguchi Method

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ABSTRACT

This work is devoted toward optimization of the parameters of the friction stir processing (FSP) which effect on tensile strength of aluminium alloy AA6061-T6 of 6mm thick plate by applying a certain number of tests utilizing the Taguchi method. Design of experiment (DOE) has been applied for the determination of the most important parameters influencing ultimate tensile strength. FSP was achieved under three different rotation speeds (800,1000 and 1250) rpm, different transverse speeds (16,25 and 32) mm\min, and number passes(1,2 and 3) in the same direction and tool tilt angle was 2° with using threaded cylindrical pin profile. The best FSP parameters were 1250 rpm and 32 mm\min and two passes. It was found that the higher hardness value was 75HV in stir zone center and then decreases toward the TMAZ, HAZ and the base metal.

1. Introduction

Aluminum alloys are important for many applications such as aerospace and automotive industries etc…., because of their light weight and high strength to weight ratio [1]. Because of the good properties of aluminum alloy 6061-T6, light weight, good strength, good erosion and corrosion properties, it is widely used in marine areas, cars and aircraft [2]. Homogenising and refining the grain structure of the alloy get better mechanical properties. Its ability be carried out via an assortment of processes such as high pressure-torsion (HPT), thermo mechanical treatment (TMT), accumulative roll-bonding (ARB), equal channel-angular process (ECAP), and so on. This process exhaustion time and complex [3]. Recently Friction Stir Processing (FSP), an innovative approach was developed for grain refinement and fabrication of surface composite materials. Its basic principles are the same as those of FSW. FSP is quite a promising method for the enhancement of metal properties [4]. This process causes high strain rates and intensive plastic deformation [5]. Through (FSP) a rotational tool pin sticks to the metal's surface that will be processed, then traversed along the paths. Heat will be produced via the friction between the rotating shoulder, the tool pin, and the surface of the metal. The metals' temperature doesn't reach its point of melting and only plastic-deformations appear in the region of processing. Recrystallization placed in the severely distorted metals, because of the homogeneous and refined structure of the grain in the stirred-area [6]. FSP has many benefits. FSP is a short route solid state process which has a single step processing which reaches homogeneity and micro-structural refinement. Also, the heat input through FSP come from plastic deformation and friction, and that refers to the fact that FSP is environment-friendly and energy-efficient approach with no radiation, noise and deleterious gas. FSP localizes modifications and controls of micro-structures in the near-surface layers of

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the processed components of the metal [7].The Taguchi method has been applied in a large scale to engineering analysis and is widely used in designing systems with high quality to investigate the effect of the FSP factors with using a small number of tests [8]. Kwon et al. [9] noticed that after applied FSP on 1050 aluminum alloy mechanical characteristics like hardness and tensile strength improved when decreasing the speed of the tool rotation. At 560rpm, those properties increased due to grain enhancement by nearly 37% and 46% respectively in comparison with the base alloy.Elangovan and Balasubramanian [10] studied the impact of the parameters of FSP (pin profile and speed of rotation) on AA2219 aluminum alloy has 6mm thickness. Using five various tool pin-profiles (tapered cylindrical, straight cylindrical, threaded cylindrical, square and triangular) utilized three various tools rotational speed to manufacture weld. They have discovered that the square tool pin profile mechanically generates sound and metallurgically defects free welds in comparison with other tool pin profiles. Shafiei Zarghani et al. [11] used the FSP to create very small grained materials via strict plastic deformations. FSP has been performed for extruding 6082-T4 aluminum alloy for producing very small grained micro-structure with a grain of a size between 0.5µm and 3µm. The FSPed aluminum alloy hardness considerably increases with the decrease in the speed of tool rotation. Elangovan and Balasubramanian [12] have proved that the impact of the FSP parameters (speed of rotation and pin profile) on AA6061 aluminum alloy. Using 5 various tool pin-profiles (threaded cylindrical, tapered cylindrical, straight cylindrical, square and triangular) utilized 3 different tools rotational speed to manufacture weld. They have discovered that the square pin profiled tool produced mechanical sounds and metallurgically defected free welds in comparison with other tool pin profiles. Magdy et al. [13] applied FSP on 6082-T6 aluminum alloy for improving the mechanical properties and modifying the micro-structure. At the fixed speed of rotation (850rpm) and 3 various traverse speeds (90,140,224) mm/min was utilized for processing. Strength and hardness increased with the increase of traverse speed, increasing the number of passes resulted in lowering the ultimate tensile strength and softening.

The current study aims at obtaining the best parameters of FSP which are the speed of tool rotation, travel speed and a number of passes. The identification of the most effective parameters of friction stir processing is made by using L9 Taguchi orthogonal array. Furthermore, ANOVA is used to find out how much each parameter contributes to the process.

2. Experimental work

Aluminum alloy plate AA6061-T6 employed in this study. This plate was prepared into dimensions of (150×100×6) mm by using cutting machine. The chemical structure of this alloy has been performed with the use of spectro-meter analysis apparatus that has been presented in the "General Company for Examination and Rehabilitation Engineering ", as listed in **Tables 1.** The mechanical properties of the alloy listed in **Table 2.**

Table1: Chemical composition of the as-received AA6061-T6 alloy (weight %)

Element wt.%	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Other	Al
Nominal (value) [1]	0.8 max	0.7 max	0.4 max	0.15 max	1.2 max	0.35 max	0.05 max	0.25 max	0.15 max	0.05 max	Bal.
Measured (value)	0.636	0.586	0.258	0.105	0.916	0.183	0.0032	0.0357	0.051	0.0147	Bal.

T6: Solution heat treatment and artificial aging.

Table 2: Mechanical properties of AA6061-T6 alloy

Base Alloy AA6061-T6	Yield strength YS (MPa)	Tensile strength TS (MPa)	Elongation %	Hardness HV Kg/mm^2
Measured value	160	314	28	58
Standard value *	276	310	12	95

*Datasheet for ASM Aerospace Specification Metals Inc.

The FSP has been performed on a vertical milling machine (type: WMW-HECKERT-Germany). The specimens are prepared and fixed in a specially designed and fabricated fixture and clamped firmly in order to ensure that the plates remain in their places and don't fly away because of the welding forces as shown in **Fig. 1** and tool has been plunged into the chosen sheet area. A non-consumable cylindrical-shouldered and threaded pin made of high speed steel (HSS) with a shoulder diameter of 16 mm and 6 mm pin diameter of length 3.2 mm has been utilized as shown in **Fig. 2** and tool tilt angle 2°.

3. Orthogonal Array Selection

The experimental design suggested by Taguchi covers the use of orthogonal arrays to arrange in order the parameters of FSP and the levels at which they must differ. In terms of the L9 orthogonal array suggested by Taguchi, three experiments were carried out on each set of parameters of the process. The three parameters which were used in this work were the speed of rotation (rpm), transverse speeds (mm\min), and a number of passes (1,2 & 3) in same direction. **Table 3** shows the parameters and levels of the process. The tilt angle (2º) remains constant. A total of "nine experimental" runs were made, a set of levels was utilized for each control factor as shown in **Table 3**.

Figure 1: Sample after frictions stir processing

Figure 2 : The tool used in this work

Table 3: Parameters and their levels of FSP

parameters	Level 1	Level 2	Level 3
Rotation speed RS (rpm)	800	1000	1250
Welding speed WS (mm\min)	16	25	32
Number of passes	1	2	3

Table 4: Experimental results of DOE Taguchi L9 Orthogonal array

Experiment Number	RS (rpm)	TS (mm/min)	No. of passes
1	800	16	1
2	800	25	2
3	800	32	3
4	1000	16	2
5	1000	25	3
6	1000	32	1
7	1250	16	3
8	1250	25	1
9	1250	32	2

After friction stir processing tensile tests have been performed to estimate the tensile strength of FSP at all processing parameters. Tensile specimens were cut parallel to the FSP in the longitudinal direction by CNC milling machine type (C-TEK). **Fig. 3** shows the dimensions with the geometry of the tensile sample according to the properties specified in the ASTM standard E8M- 011 for specimens of sub-size [14].

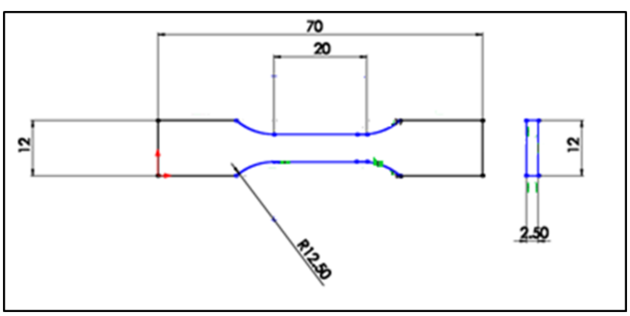

Figure 3: Sample of ASTM- E8M Sub-Size for Tensile Test, all dimensions in mm

4. Microstructure Examination and Microhardness Test

An optical microscope was used to examine the specimens which were made from a cross-section of the FSP in sequences steps. The operation of wet grinding was made using water and emery paper of SiC in various grits of 320, 500, 600, 800, 1000 and 1200. The process of polishing was made on the samples using 0.5µm diamond paste and special cloth for polishing and lubricant. The process of etching was carried out on the specimens by utilizing etching solution Keller's reagent (composed of 95 ml H_2O, 2.5 ml HNO_3, 1.5 ml HCL, 1.0 ml HF). They were washed and dried. Optical micro-scope is utilized to supply information concerning the micro-structure of processing specimens. Digital micro-hardness tester type (Laryee, Mode HVS-1000) was utilized to conduct the Vickers hardness test. A 200 gm load applied cross-section of SZ of the FSP direction, for 15 sec.

5. Results and Discussion

5.1. Signal to Noise Ratio: (S\N) Ratio

Tensile strength is an important property taken into consideration in this study. For the estimation of the FSP parameters impact on tensile strength, values of means and S/N ratio for every one of the direct factors (rotational speed of the tool, travel speed and a number of passes) have been considered. A suitable S/N ratio has been selected utilizing previous knowledge, experience, and process understanding. Concerning this study, the S/N ratio has been carefully chosen in terms of the standard of the higher is better, for the sake of maximizing the response. The method of Taguchi is utilized for determining the difference of the quality properties from the wanted value is achieved by using the S/N ratio. In this study, the data of tensile strength have been analyzed to decide the influence of FSP parameters. **Table 5** depicts the 3 levels of parameters of the process as "per L9 orthogonal array", the means of tensile strength and the matching S/N ratio. Analyzing the mean for every experiment will result in better parameter combination level so that tensile strength at a high level is made certain in terms of experimental data. The plots as in **Figures** (4 and 5) may be utilized for identifying the highest level of process parameter conformity to the biggest S/N ratio and tensile strength respectively. The tensile strength is assessed to be the highest with speed of rotation of 1250 rpm and travel speed 32 mm/min and two passes which is optimal from the plots obtained.

Table 5: Tensile strength and S/N Ratio for experiments.

Experiment number	RS (rpm)	TS (mm\min)	No. of passes	Mean tensile strength MPa	S\N ratio
1	800	16	1	162	44.19
2	800	25	2	158	43.97
3	800	32	3	152	43.63
4	1000	16	2	159	44.02
5	1000	25	3	138	42.79
6	1000	32	1	165	44.34
7	1250	16	3	160	44.08
8	1250	25	1	170	44.60
9	1250	32	2	215	46.64

5.2. Analysis of Variance (Anova)

This test is applied for studying the significance regarding the FSP's parameters affecting the tensile strength related to processing with FSP. To determine which one of the processes significantly impact the tensile strength, the F-test which is termed after Fisher might be applied. Generally, the process parameter's difference holds a considerable impact on the quality characteristics related to the tensile strength of the processing, in the case when F is considered high. The ANOVA test results indicate that the process's parameters are very important factors which influence the tensile strength with FSP in the order of a number of passes, travel and rotation speeds. From Table 6 it was shown that the ANOVA of tensile result display that the rotation speed is considered as the utmost effective parameter having a percentage of 38.68% after that comes the number of passes 31.9% and travel speed 22.55%.

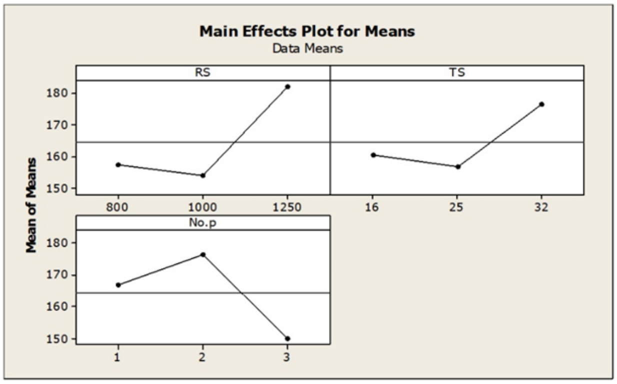

Figure 4 :Main effect plot for S/N ratios

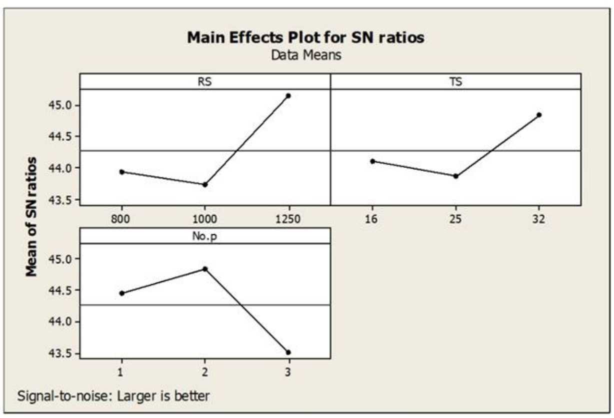

Figure 5: Main effect plot for mean tensile strength

Table 6: ANOVA for FSP parameters

Parameters	DF	Seq SS	Adj SS	Adj MS	F	PA%
Rotation speed RS (rpm)	2	1368.7	1368.7	684.3	5.64	38.68
Travel speed TS(mm/min)	2	798.0	798.0	399.0	3.29	22.55
Number of passes	2	1128.7	1128.7	564.3	4.65	31.9
Error	2	242.7	242.7	121.3	-	6.87
Total	-	-	-	-	-	100%

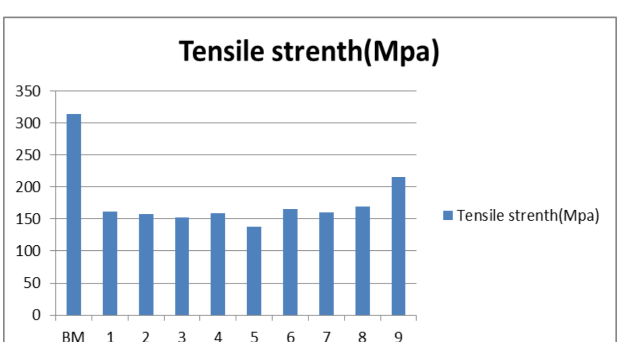

Figure 6: The tensile strength of base alloy AA6061-T6 and FSPed samples

5.3. TENSILE TEST RESULTS

The tensile results indicated the fact that the tensile strength regarding the base alloy has been greater than that of all friction stir processing tested as shown in **Fig. 6**. According to the test results, the increment in the travel and rotations speeds will lead to an increment in the tensile strength.

At a tool rotation speed of (1250 rpm), the tensile strength had its highest value. In comparison to un processing alloy, it has been discovered that the tensile strength will decrease with increased tool rotation speed, the is because of the extra heat that is generated in the stir zone because of the high rotational speed for the tool, and thus increasing stirring influence which is related to the pin, however it could create extra explosion or flash of metal flow outside causing imperfections in stir-zone. Similarly, elevated heat inputs will cause an increase in peak temperature and triggers grain-growth, that will cause a reduction in the tensile strength.

At FSP speeds of (16mm\min) and (25mm\min), it has been spotted that the tensile strength has been lesser than of speed (32mm\min), this is considered as the result of the elevated frictional heat and dissipation most of the heat created regardless of tool rotations speed as well as the number of passes. The minimum rotational speed leads to decrease the FSP's tensile strength because of the higher heat input in processing samples, whereas the maximum rotation speed causes an increase in tensile strength which will result in short exposure time to frictional heating.

The FSP at two passes has higher tensile strength than that of one or three passes. This is because the FSP at 2 passes created a pronounced effect in refining the stir zone microstructure and the break-up of inter metallic compound. The best value of tensile strength of FSP (215MPa) was achieved at (1250rpm) rotating speed (32 mm/min) rotation speed and two passes. The acquired results are consistent with the results obtained by the researcher Magdy et al. [13].

5.4. Microhardness Results

Microhardness distribution along FSP cross section is displayed in **Fig. 7**, Vickers- micro-hardness apportionment on cross section vertical to the tool traverse direction regarding the FSP sample formed at a tool rotational speed of 1250 rpm and travel speed32mm/min with two passes. The stir-zone showed a higher hardness than the unaffected zone. The maximum hardness was 75HV in center of stir zone. This is due to refining grain and dynamic recrystalline stir zone and presence of precipitates 2[nd] phase particles of Al_3Mg_2 phase in α-Al. Several researchers [15,16] proved these outcomes in their studies of FSW welding aluminum alloys.

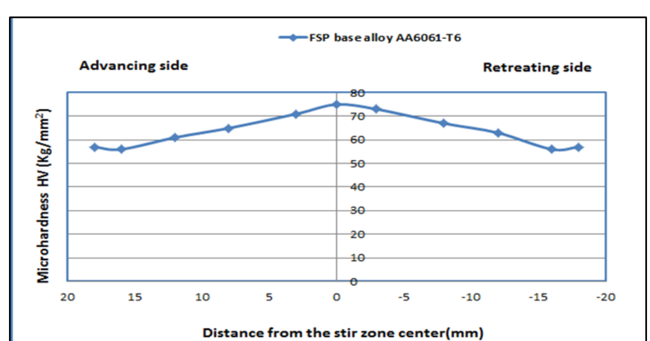

Figure 7 : Microhardness distribution across the transverse cross section of FSP for base metal at rotation speed 1250 rpm, travel speed 32 and two passes

5.5. Microstructure Results

Fig. 8 (a,b,c &d) shows the microstructural characterization of a cross section of friction stir processing at best parameters (1250 rpm,32mm/min and 2 passes). It is seen that the FSP sample has four distinct regions: stir zone (SZ) is the region that is thermo-mechanically processed zone where the grain size is very fine and equaxed grains or homogenized structure (**Fig. 8a**), friction stir processed zone (FSP zone) (**Fig. 8c**), the thermo mechanically affected-zone (TMAZ) in which the grain is elongated due to the fact that it has been deformed in a thermo- mechanical way with observation of union rings (**Fig. 8b**), heat affected-zone (HAZ) which is considered to have the same grain structure of base metal (BM) and the base metal or AA6061-T6 alloy (unaffected metal) considered as the region which is not influenced through the FSP process. This microstructure contains very fine precipitates 2nd phase particles of Al_3Mg_2 phase distributed uniformly in α-Al.(**Fig. 8d**).

6. conclusions

- It was found that optimum or best friction stir processing (FSP) parameters were 1250 rpm of rotation speed, 32mm/min of travel speed and two passes for a number of passes.
- Tensile strength of FSP ed sample increases as the rotation speed and travel speed increase.
- It has been indicated that the stir zone of FSP exhibited microhardness higher than TMAZ and HAZ because of grain refinement and existence of precipitates (Al3Mg2) distributed in the aluminum matrix.
- It was shown from ANOVA analysis of tensile strength that the rotation speed has contribution percentage (38.68%) which is the most effective parameter followed by a number of passes was 31.9% and then travel speed was 22.55 %.

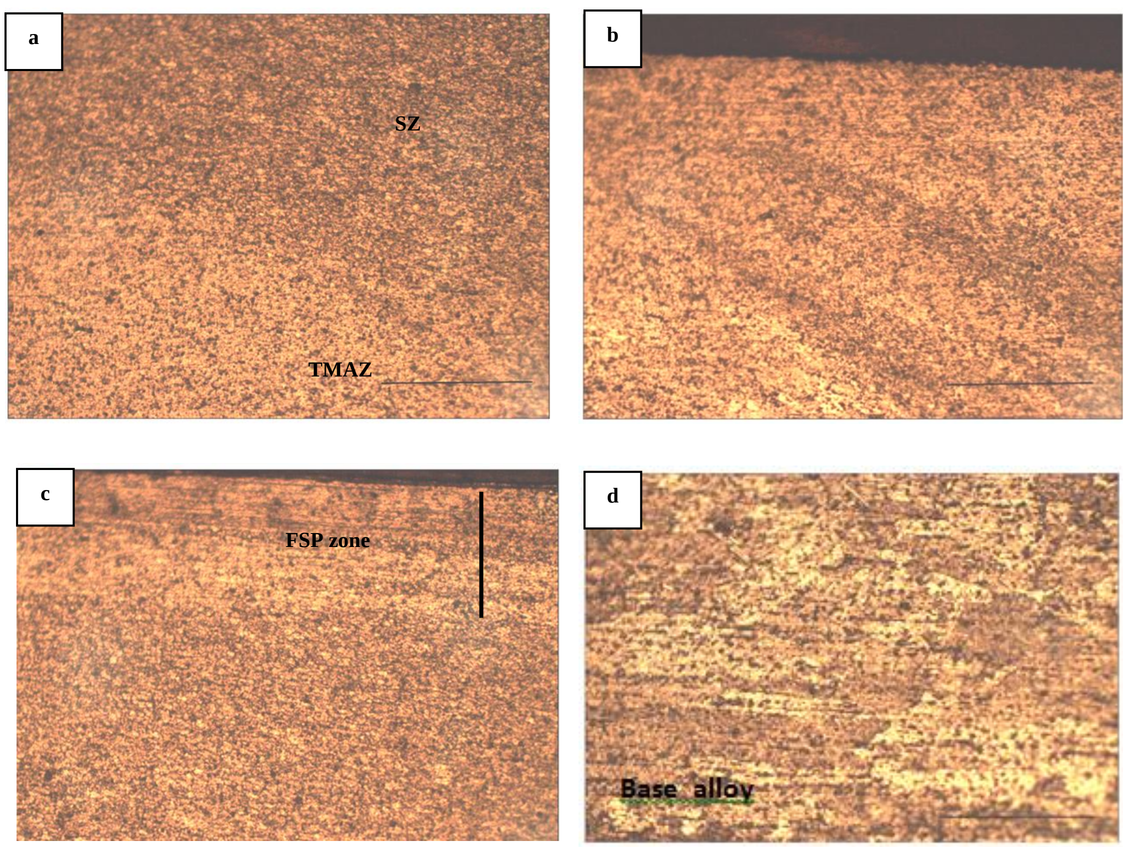

Figure 8: Microstructure of friction stir processed (FSP) sample at optimum conditions 1250 rpm , 32mm/min and 2 pass in same direction at 100x. (a) SZ and TMAZ , (b) Union rings in TMAZ , (c) FSP zone , (d) Base alloy AA6061-T6.

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