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PARAMETRIC OPTIMIZATION OF FRICTION STIR WELDING OF Al-Mg-Si ALLOY: A CASE STUDY

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Abstract: Al-Mg-Si alloys have wide applications in industries such as aerospace, marine, automobile, construction. In this work, newly developed friction stir welding (FSW) was utilized for joining of AA6082-T6 alloy. The effect of major FSW process variables like rotational speed, traverse speed, and shoulder diameter of tool is studied over microstructural and mechanical characteristics of friction stir welded (FSWed) joints. Experimental design was done using Taguchi method (L9 orthogonal array). Three factors viz. rotational speed, welding speed, and diameter of tool shoulder were taken at three levels each. Mathematical modelling was developed in order to optimize the tensile strength of weld joints. Analysis of variance (ANOVA) was utilized to determine the percentage contribution of input variables. The results of present study exhibits that shoulder diameter, rotation, and welding speed of tool significantly affect the mechanical strength of FSWed joints.

Keywords: Friction Stir Welding, Mechanical Properties, Al-Mg-Si Alloy, Process Parameters, Optimization, Taguchi Technique.

MSC: 90C29, 90C31.

1. INTRODUCTION

Friction stir welding (FSW) offers great suitability for joining aluminium with other light weight metallic alloys owing to their solid state nature [1, 2, 3]. FSW has proved itself as the most significant joining process, especially for aluminium alloys, in the past decade, and as a "green" method of joining. It was invented in 1991 [4] and its applications have now extended to aerospace, automobile, marine, and some other critical industries. The application of FSW has been extended to its derivatives such as friction stir processing [5, 8], friction based additive manufacturing [7, 6], etc. and are gaining popularity. Several studies have been reported on FSW of different aluminium alloys [9, 10, 11, 12, 13]. Yan *e*t al. [11] [11] investigated the effects of process parameters such as axial force, welding speed, and speed of rotation on mechanical characteristics and microstructural evolution of FSW of AA2524 alloys. Sameer *e*t al. [12] reported the FSW of AA 6082-AZ91 dissimilar materials by varying the materials towards advancing side and retreating side. Rahmatian *e*t al. [13] investigated the effect reinforcement particles during FSW of AA5083 alloys and found tensile strength 84% to base matrix. Kadaganchi *e*t al. [14] studied the effect of important process parameters such as welding speed, tool speed, angle of tilt, and geometry of tool during FSW of AA2014 alloy using RSM technique.

Thus, it can be concluded from the literature that several studies on FSW of aluminium alloys have been reported, so far, investigating the individual as well as combined effect of FSW process parameters. However, reported works on FSW of AA6082 alloys are limited. In this work, parametric effect of chosen process parameters is evaluated for determining the mechanical strength of FSWed AA6082 alloy plates.

2. MATERIALS AND METHODS

In this work, AA6082 alloy in T6 condition was used as the base metal (BM). Table 1 depicts the composition of BM. The BM was initially cut in plate form of dimensions 200mm × 50mm (length × width). The thickness of plates was kept at 5mm and joined using butt configuration. The flatness and cleaning of all plates was ensured using CNC machining and washing with acetone. H-13 tools of varying shoulder diameters and a threaded conical pin of 5.5mm root diameter and 3.5 mm tail diameter were utilized to perform FSW runs. FSW was performed on a modified vertical milling machine as illustrated in Fig.1.

We utilized Design of experiment (DOE), a reliable technique to reduce the number of experiments and to optimize the obtained results [15], to design and perform our experiments, i.e., Taguchi's technique (L_9 orthogonal array design) was selected to design and conduct the experimental runs. Three input parameters are: rotational speed of tool (RST), welding speed of tool (WST), and shoulder diameter of tool (SDT). The selection of input parameters was done in the following way: initially, a lot of trials runs were conducted to choose the fixed and variable parameters; after deciding the fix parameters and their values, trial runs were

Table 1: Composition of AA6082-T6 (wt %)

Element	Mg	Si	Cu	Zn	Ti	Mn	Cr	Al
Amount (wt %)	0.75	1.11	0.055	0.05	<0.05	0.54	0.03	Balance

performed again to obtain a process window for variable parameters. Process window for three parameters, i.e., RST, WST, and SDT was finalized on the basis that all the experiments performed in between this window were defect free. The values of fixed parameters and variable parameters are presented in Table 2 and Table 3, respectively.

(a) (b)

Figure 1: (a) Image of FSW set-up; (b) visual appearance of a particular FSW joint

After identification of process window, experimental runs were performed as per L_9 design matrix shown in Table 4. After completion of all the FSW runs (single pass), samples for microstructural characterization were machined from the welded region using wire EDM. Tensile samples were cut as per ASTM: E8/E8M-011 standard in the traverse direction to FSW. Analysis of tensile strength was done on average values of two samples for each FSW run.

Table 2: FSW parameters (which were kept constant)

Process parameters	Value taken
Profile of pin of tool	Conical threaded
Profile of shoulder	Flat
Tilt angle	2.5°
Tool pin length	4.8 mm
Depth tool plunge	0.25mm

Table 3: Variable process parameters (working window)

Notation	Input variables	Working range	Levels		
			(1)	(2)	(3)
A	RST (rpm)	710-1120	710	900	1120
B	WST (mm/min)	50-80	50	63	80
C	SDT (mm)	20-24	20	22	24

Table 4: Designed L9 OA and results of tensile strength

Experiments	Variables			Mechanical properties	
	RST	WST	SDT	UTS (MPa)	S/N
1	710	50	20	210	46.444
2	710	63	22	213	46.5676
3	710	80	24	199	45.9771
4	900	50	22	237	47.4950
5	900	63	24	226	47.0822
6	900	80	20	202	46.1070
7	1120	50	24	244	47.7478
8	1120	63	20	226	47.0822
9	1120	80	22	221	46.8878

*Note: Average of two reading were taken for analysis

3. RESULTS & DISCUSSIONS

3.1. Analysis of variance

Table 4 presents the values of UTS for each FSW run. MINITAB 15^{TM} was utilized to analyze the results of Taguchi's method in the current study. Signal to

Noise (S/N) ratios were obtained for each run. Analysis of variance (ANOVA) was utilized to draw conclusions of experiments. Table 5 presents ANOVA for UTS of FSWed joints. The effect of chosen parameters on the output response (UTS) is discussed in subsequent sections.

Table 5: ANOVA results for UTS

Variables	DOF	Squares, sum (SS)	Adj. mean sum of squares (MSS)	F-ratio	P-value	% contribution
b) For UTS Regression	3	1749.0	582.99	28.41	0.001	
A	1	782.6	782.60	38.14	0.002	42.2
B	1	806.2	806.2	39.29	0.002	43.54
C	1	160.2	160.2	7.81	0.038	8.7
Error	5	102.6	20.52			5.5
Total	8	1851.6				100

3.2. Effect of RST on UTS

Fig. 2 illustrates graphical plot of S/N ratio for UTS. It can be observed from the figure that when RST increases from level 1 to level 2, UTS of welded joints increases, and also, with further increase of RST, UTS further increases. This is mainly due to the enhancement of heat generation owing to increase of RST. Also, stirring effect of tool increases, which improves the material mixing and materials flow. That means, at lower level of RST (i.e., level 1, 710 rpm), heat generation and material mixing are insufficient, resulting in low strength of welded joint. The heat generation increases with the increase of RST from level 1 to level 2, which leads to better deformation and mixing of material and higher joint strength. However, contrary factors are involved that govern UTS while increasing the values of RST. These mainly involve: material flow and softening effect owing to high heat generation. It can be explained as: with the enhancement of RST material, mixing and material flow improve, which tends to increase UTS. However, at the same point, with increase of RST, heat generation and softening effect increase, which tends to decrease UTS. Here, it is interesting to note that the effect of better material flow and material mixing dominates the softening effect, which results in enhancement of UTS. However, this increment is more sharp during level 1 to level 2.

3.3. Effect of WST on UTS

Fig. 2 shows the effect of WST on UTS. It can be seen from the figure that UTS decreases with increase of WST. The main reason behind this can be explained as: WST is responsible for dispersion of generated heat, it implies that with the higher WST, the propagation of heat, for the same length, takes place for a shorter interval of time. This reduces the overall heat input, owing to which the chances of

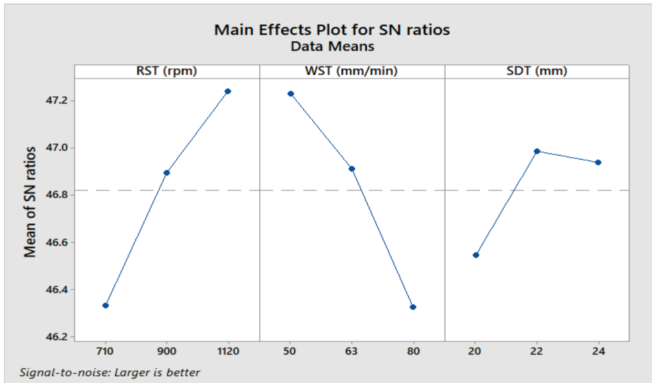


Figure 2: S/N ratio graphical plot- ultimate tensile strength

grain growth reduces leading to higher UTS. On the other hand, at higher WST, owing to lower overall heat input and higher rates of tool traverse poor material mixing can take place, which may result in lower UTS. In this study, the overall heat was adequate to acquire sufficient material mixing at level 1 of WST. Due to this reason, UTS decreases from level 1 to level 2 and level 2 to level 3 of WST.

3.4. Effect of SD on UTS

Fig. 2 depicts the effect of SDT on UTS of welded joints. It is evident from the figure that UTS enhances with enhancement of SDT from level 1 to 2. However, UTS decreases as SDT further increases from level 2 to 3. This can be understood as: SDT is one of the major tool variable responsible for heat generation and forging of material under it [16]. The increase of SDT, keeping other parameters constant, results in the increase of heat input, forging action, and volume of material to be stirred, which tends to enhance UTS. The increment in heat input beyond an adequate value may lead to dissolution of precipitates and grain growth, ultimately, leading to lower weld joint strength. With further increase of SDT, increment in heat input causes softening effect that dominates the effect of previous phenomena. Thus, UTS decreases during level 2 to level 3 of SDT. Thus, it can be concluded from the above discussion, that higher UTS can be obtained at level-3 of RST, level-1 of WST, and level-2 of SDT. Then, confirmation tests were conducted at these optimum parameters, and the average values of two readings are presented in Table 6.

3.5. Microstructural analysis

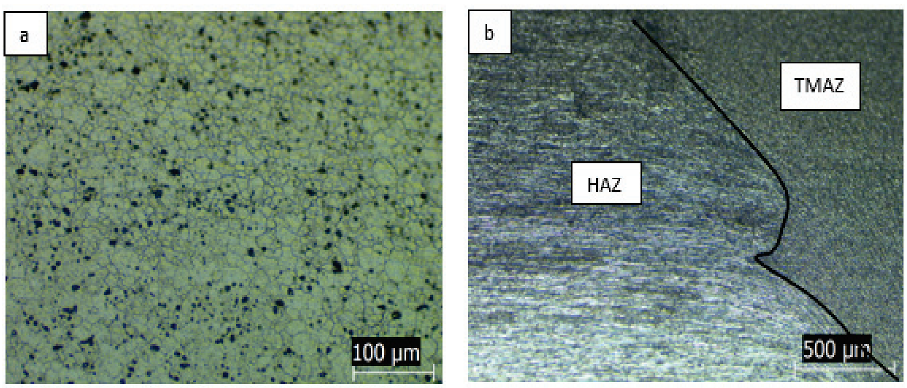
Fig. 3. depicts the micrographs of FSWed sample at optimum parameters combination, i.e., A3B1C2. Fig. 3(a) depicts the welded zone (WZ), while Fig. 3 (b) is showing thermo-mechanical heat affected and heat affected zone of the same FSWed sample. It is visible from the figure that the grain size is smallest

Table 6: Results of confirmation tests

Output	Optimum parameter combination	Experimental value*
UTS (MPa)	Level-3 of RST, level-1 of WST and level-2 of SDT	247

* Average of two values were taken

for WZ and is different for WZ, TMAZ, and HAZ. This is mainly owing to the recrystallization mechanism that occurs in WZ. A large number of precipitates were found present in stir zone (SZ) of FSWed sample developed at optimum process parameters. The dispersion of strengthening precipitates and grain size refinement defines the UTS of metals.



(a) (b)

Figure 3: Optical micrographs of FSWed sample at optimum process parameters combination (a) WZ; (b) TMAZ-HAZ region.

4. CONCLUSION

The conclusions of present work on FSW of AA6082 alloys can be summarized as:

1. FSW was successfully utilized to obtain sound weld joints of AA6082 alloy and optimum process parameter combination was analyzed.
2. Among the chosen process parameters, WST has maximum contribution (43.54%), then RST (42.2), and then SDT (8.7).
3. The highest value of UTS obtained at optimum parameters was 247 MPa, which is equivalent to 0.80 times the UTS of BM.

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