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Experimental Study of Double Sided Friction Stir Welding of AA 6061 Plates Using Hexagonal Tool Tip

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Abstract- In current scenario, the application of aluminium alloys in oil tanker and ship building industries has increased. Friction stir welding (FSW) is the emerging technique for joining of aluminium and its alloys. This process is widely used because it does not have common problems such as solidification and liquifaction cracking associated with the fusion welding techniques. The objective of present work is to study the double sided friction stir welding of AA6061 plates of 12mm thickness using hexagonal tool tip. For joining of AA6061 plates, two process parameters namely tool rotational speed (TRS) and weld speed (WS) are varied in three levels. Strength analysis is carried out on the AA6061 welded joints. TOPSIS method is employed to identify the optimal process parameters set for joining AA 6061 plates with 12 mm thickness. From the TOPSIS method, the optimal set of process parameters was found at tool rotational speed of 1400 rpm and 28 mm/min weld speed to achieve maximum ultimate tensile strength and maximum percentage of elongation of welded joint.

Keywords- AA 6061; Friction stir welding; Hexagonal tool tip; Optimization; TOPSIS method

1. INTRODUCTION

FSW is a solid state thermo mechanical metal joining process that has become a viable manufacturing technology of metallic sheet and plate materials for applications in various industries, including ship building and marine construction industries. In Friction stir welding, welded joints are achieved by the heat due to friction between two surfaces. The friction is developed by rubbing action between two surfaces, usually by rotation of one-part relative to the other. In previous, researchers are trying to analyze and optimize process parameters in friction stir welding process for effective joining of materials, some of them are given below:

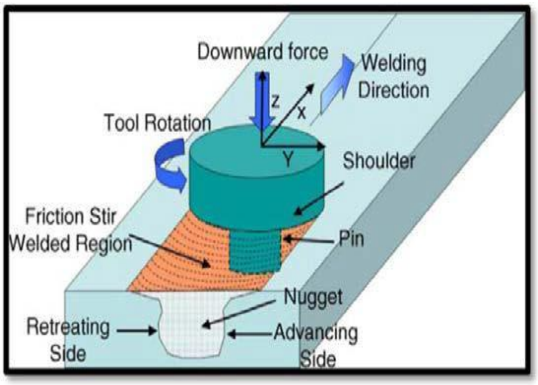

Fig. 1. Schematic diagram of FSW

N.A. McPherson et. al. [1] has compared single sided and double sided friction stir welding while joining of DH36 steel with 8 mm thickness. It was observed that high strength, toughness and hardness exhibited by the welded joints in double sided FSW are more than that of single pass FSW. Sunny Mehra et al. [2] has studied the effect of tool on tensile strength in single and double sided friction stir welding while joining of AL19000 H12 plates have thickness of 6mm. It was concluded that joints obtained by double passes have shown high UTS, percentage elongation and joint efficiency values. Deepthi Anil Kumar et al. [3] studied on friction stir welding of 12mm thick aluminum alloy plates. It was concluded that higher tool rpm with low welding speed resulted in finer grain structure leading to higher strength as well as higher ductility values. Y. M. Zhang and C. Pan et al. [4] investigated on improved microstructure and prosperities of 6061 aluminum alloy elements using a double-sided arc welding process. From the study, variable arc plasma arc welding was compared with double sided arc welding and it was concluded that the percentage of equiaxied grains has been increased and the hot cracking sensitivity was also reduced because of the symmetrical temperature profile produced during double sided welding. H.K. Mohanty et al. [5] investigated on the effect of tool shoulder and pin profiles in friction stirred aluminum welds. In this study, it was observed that weld bead cross sectional area varies proportionally with the tensile strength of the joint. Indira Rani. M, Marpu R N and A.C.S. Kumar et al. [6] studied on process parameters of friction stir welding while joining 6.6 mm AA6061 in

O and T6 conditions. It was concluded that in annealed condition TRS of 800rpm and WS 10mm/min and 15mm/min are the optimal parameters. TRS of 1000rpm and 10mm/min WS are the optimal parameters in T6 condition. P.Prasanna et. Al. [7] investigated, the effect of four different tool profiles used at tool rotational speed of 1200rpm and weld speed of 14mm/min and axial force of 7kN on the mechanical properties of AA6061.

Mohammad Hasan Shojaeefard et. Al. [9], studied the influence of rotational and traverse speed on the friction stir weldir

It can be stated from the previous works that FSW is one of the most successful joining method for aluminium and its alloys. The joints formed by FSW have exhibited superior properties like less distortion, high tensile strength and hardness values. Most of the previous works concentrated on conducting FSW for joining metal plates with thickness below 7 mm. But in the marine industry and ship building industries the thickness of the plates to be joined is more than 10mm. In joining of these plates with single pass has shown less strength at the joint. From literature survey on double sided arc welding and other techniques it is observed that welding on double sides for a plate has resulted in increase of several physical characteristics like ultimate tensile strength, ductility, joint efficiency and hardness. In this research work, an attempt was made to identify a set of double sided friction stir welding process parameters to join AA 6061 plates of 12 mm thickness which will give higher maximum ultimate tensile strength and maximum percentage of elongation

2. EXPERIMENTAL SETUP

2.1 Material Selection:

Aluminium is replacing various metals in many of the applications. In recent years, aluminium alloy 6XXX series are widely used in aerospace and ship building industries. Therefore, AA6061 is used as the base metal in the experimentation. The chemical composition is as shown in Table 1.

Table 1. Chemical Composition of AA6061

Alloying Element	Percentage by weight
Mg	1.1
Mn	0.12
Fe	0.35
Si	0.58
Cu	0.22
Cr	0.35
Zn	---
Al	Remaining

The mechanical properties like ultimate tensile strength, yield strength, elongation percentage, and hardness of base metal AA6061 are shown in Table 2.

Table 2. Mechanical Properties of AA6061

Mechanical Property	Value
Ultimate Tensile Strength (MPa)	310
Yield Strength (MPa)	276
Elongation Percentage	12
Hardness (BHN)	34

In present work, the experiments were carried out to join the AA6061 plates of 150 mm (length) × 90 mm (width) × 12 mm (height) in size.

2.2 Tool Design:

The design of tool and material used in its preparation are critical factors as a good tool can improve the quality of the weld. It is desirable that the tool material should be sufficiently strong, tough, and hard wearing at the welding temperature. So, selection of tool dimensions and material play vital role in forming sound joints. Hot worked tool steel H13 is proven perfectly for welding aluminium alloys of thickness ranging 0.5−50mm. Chemical composition of H13 steel is given in Table 3.

Table 3. Chemical composition of H13 steel

Alloying Element	Percentage by Weight
C	0.35
Mn	0.30
Si	0.88
Cr	5.0
Ni	0.3
Mo	1.5
V	1.0
Cu	0.25
P	0.03
S	0.03

Hexagonal tip tool is used to conduct experiments by varying different parameters. The hexagonal tip tool used for experimentation is shown in Fig. 2.

Fig. 2. Hexagonal tip tool during experimentation

2.3 Process parameters Selection:

Friction stir welding is affected by many parameters like tool rotation speed, weld speed, tilt angle, plunge depth and axial force. Tool Rotational Speed and Weld Speed are the most important parameters which influence the joint in FSW. In the experimentation two process parameters namely, tool rotational speed (TRS) and weld speed (WS) are varied in three levels.

Table 4. Process parameters and their ranges

Process Parameters	Units	Levels		
		1	2	3
Tool Rotational Speed	rpm	1000	1400	2000
Weld Speed	mm/min	20	28	40

By varying two parameters at three levels, nine combinations are conducted in the present work. Milling machine is used for the carrying out the experiment. To withstand the forces which separate the work pieces during welding, a special clamping arrangement is made on the machine bed as shown in Fig. 3.

Fig. 3. Experimental setup used in study

3. RESULTS AND DISCUSSION

The joints obtained after welding are tested for strength analysis is carried out on the 9 welded joints. The 9 joints are obtained by varying the process parameters. Strength analysis is carried out to know the ultimate tensile strength, elongation percentage and yield stress of welded joints of welded joints.

3.1. Strength Analysis:

In the present work for the conduction of strength analysis, the welded plates are machined to standard dimensions following ASTM norms and these specimens are taken for tensile test on the universal testing machine. The dimensions of the tensile specimen are as shown in Fig. 4.

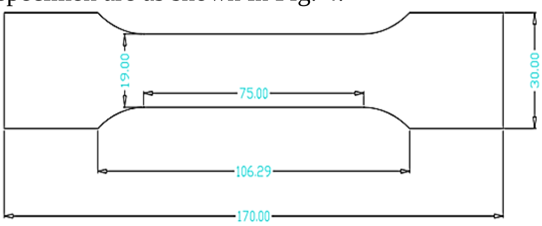

Fig. 4. ASTM Standard for Specimen

The most common testing machines are universal testers, which test materials in tension, compression, or bending. In the study, tension testing is carried. For the conduction of tensile testing samples are numbered from 1 to 9. Fig. 5 shows the fracture specimens of the welds formed by using Hexagonal tip tool.

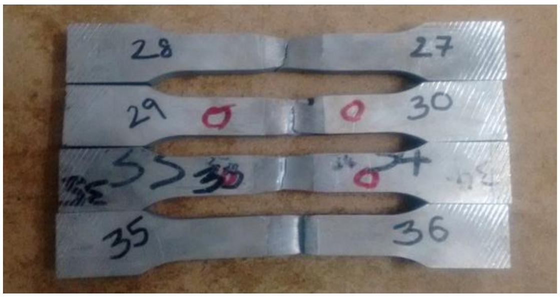

Fig. 5. Fractured specimens of weld joints formed from Hexagonal tip tool

The tensile test gives the values of ultimate tensile strength, elongation percentage and yield stress of all the 9 samples. Their values are shown in Table 5. It is observed that weld obtained from Hexagonal tool at 1000rpm tool rotational tool and 40 mm/min weld speed has showed maximum tensile strength value of 185.298 N/mm^2.

3.2. Joint Efficiency

Joint efficiency is the ratio of the ultimate tensile strength of the welded joint to the ratio of ultimate tensile strength of the base metal. In calculating the joint efficiency, the ultimate tensile strength of base metal i.e., AA6061 is taken as 310MPa. Joint efficiency for each weld sample is calculated.

$$\textbf{Joint Efficiency}=\frac{\textit{Ultimate tensile strength of welded joint}}{\textit{Ultimate tensile strength of base metal}}$$

Table 5. Experimental Design with Ultimate Strength Results

Sample number	TRS (rpm)	WS (mm/min	UTS (N/mm^2)	% of Elongation	YS (N/mm^2)
1	1000	20	173.403	14	134.987
2	1000	28	181.965	14.1	172.661
3	1000	40	185.298	10.8	184.080
4	1400	20	177.273	14.2	160.816
5	1400	28	184.135	14.24	157.041
6	1400	40	156.39	9	144.057
7	2000	20	164.609	11.14	145.797
8	2000	28	181.729	12.4	125.688
9	2000	40	147.091	8.6	85.309

Table 6. Joint efficiency values of all samples

Sample Number	UTS of Joint (N/mm^2)	Joint Efficiency Value	Joint Efficiency in percentage
1	173.403	0.55	55
2	181.965	0.58	58
3	185.298	0.6	60
4	177.273	0.57	57
5	184.135	0.59	59
6	156.390	0.5	50

7	164.609	0.53	53
8	181.729	0.59	59
9	147.091	0.47	47

Maximum joint efficiency of 60% is obtained by using hexagonal tool at 1000 rpm tool rotational tool and 40 mm/min weld speed.

4. OPTIMIZATION

There are a variety of multiple criteria techniques to aid selection in conditions of multiple alternatives. Using multiple attribute decision making methods, the set of input parameters which maximize the output parameters can be obtained. TOPSIS was initially presented by Hwang and Yoon in 1981. TOPSIS is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution.

4.1 TOPSIS Method:

TOPSIS method is carried out in five steps. Initially an evaluation matrix consisting of m alternatives and n criteria, with the intersection of each alternative and criteria given as (x_{ij}) is created and a matrix $(x_{ij})_{m\times n}$ is obtained. The evaluation matrix is shown in Table 7.

Table 7. Output parameter values used in the TOPSIS method

Sample number	Tool Rotational Speed (rpm	Traverse Speed (mm/min	Ultimate Tensile Strength (N/mm^2)	Elongation %
1	1000	20	173.403	14
2	1000	28	181.965	14.1
3	1000	40	185.298	10.8
4	1400	20	177.273	14.2
5	1400	28	184.135	14.24
6	1400	40	156.39	9
7	2000	20	164.609	11.14
8	2000	28	181.729	12.4
9	2000	40	147.091	8.6

Step 1: Calculation of the normalized decision matrix. The matrix $(x_{ij})_{m\times n}$ is then normalized to form the matrix $R=(r_{ij})_{m\times n}$, using the normalization method. For normalizing UTS and % of elongation values Equ. (1) is used. The normalized values of UTS and % of elongation are shown in Table 8.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, i = 1,2,\dots,m, j = 1,2,\dots,n \text{ ----- Eq. (1)}$$

Where, i = number of alternatives (trials)
j = number of criteria (Output responses)

X_{ij} = represents the actual value of the i th value of j th experimental run.

Table 8. Normalized values of output parameters

Sample Number	Ultimate Tensile Strength	Elongation %
1	0.334296	0.381217
2	0.350802	0.38394
3	0.357227	0.294082
4	0.341756	0.386663
5	0.354985	0.387752
6	0.301497	0.245068
7	0.317342	0.30334
8	0.350347	0.337649
9	0.28357	0.234176

Step 2: Calculation of the weighted normalized decision matrix.
The weighted normalized value (t_{ij}) is calculated by multiplying the normalized value by its associated weights and is shown in Equ. (2). Here, equal weightage is given to all the responses. Therefore, w_j = 0.50 [8].

$$T = (t_{ij})_{m\times n} = (w_j r_{ij})_{m\times n,}\ i = 1,2,\dots,m \text{ ----- Eq. (2)}$$

Table 9. Weights of the output parameters for all samples

Sample Number	(t_{ij}) UTS	(t_{ij}) Elongation
1	0.167148	0.190609
2	0.175401	0.19197
3	0.178614	0.147041
4	0.170878	0.193332
5	0.177493	0.193876
6	0.150749	0.122534
7	0.158671	0.15167
8	0.175174	0.168825
9	0.141785	0.117088

Step 3: In this step, the worst alternative (t_{wj}) and the best alternative (t_{bj}) are determined. From the weighted normalized values (t_{ij}). These values are used to determine the separation measures. Table 10 shows the Best and worst values of output parameters.

Table 10. Best and worst values of output parameters

Output parameter	t_{bj}	t_{wj}
UTS	0.177493	0.141785
Elongation %	0.193876	0.117088

Step 4: In step 4, separation measures of each sample are calculated. The distance between the target alternative i and the worst condition (t_{wj}) is calculated using Equ. (3) and the distance between the alternative

i and the best condition tbj is calculated using Equ. (4). The separation measures are shown in Table 11.

$$d_{iw} = \sqrt{\sum_{j=1}^{n}(t_{ij} - t_{wj})^2}\ , i = 1,2, \dots\dots, m \text{ ----- Eq. (3)}$$

$$d_{ib} = \sqrt{\sum_{j=1}^{n}(t_{ij} - t_{bj})^2}\ , i = 1,2, \dots\dots, m \text{ ----- Eq. (4)}$$

Table 11. Separation measures of all samples

Sample Number	d_{ib}	d_{iw}
1	0.01085	0.07779
2	0.00283	0.08208
3	0.04684	0.04747
4	0.00663	0.08161
5	0	0.08468
6	0.07619	0.01048
7	0.04621	0.03848
8	0.02515	0.06157
9	0.08468	0

Step 5: Finally, relative closeness to the ideal solution (S_{iw}) is calculated and maximum S_{iw} gives the most suitable parameter set. The relative closeness to ideal solution is calculated using Equ. (5). The relative closeness to ideal solution values and corresponding values are given in Table 12.

$$S_{iw} = \frac{d_{iw}}{d_{iw} + d_{ib}}, where\ i = 1,2, \dots.9 \text{ ----- Eq. (5)}$$

Table 12. Final values obtained from TOPSIS method

Sample Number	$S_{iw}=d_{iw}/(d_{iw}+d_{ib})$	Rank
1	0.877585	4
2	0.96667	2
3	0.503302	6
4	0.924784	3
5	0.98911	1
6	0.121002	8
7	0.454377	7
8	0.709937	5
9	0.00211	9

From the final values of Table 12, it is observed that using hexagonal tip tool at tool rotational speed of 1400 rpm and 28 mm/min weld speed has showed the highest rank of 0.9811. More over the final values of sample 9 i.e., weld joint at 2000rpm TRS and 40 mm/min WS is the least so it can be concluded that high TRS and high WS results in poor joints. The optimal parameters set for joining AA 6061 plates with 12 mm thickness was found that hexagonal tip tool at tool rotational speed of 1400 rpm and 28 mm/min weld speed.

CONCLUSIONS

In present study, AA6061 plates of 12mm thickness were joined using double-sided friction stir welding. For joining of AA6061 plates, two process parameters namely tool rotational speed and weld speed are varied in three levels. Tensile test is carried out on the AA6061 welded joints. TOPSIS method was used to find the optimal process parameters for joining AA 6061 plates with 12 mm thickness and the following conclusions are drawn:

- When compared to higher tool rotation speed like 4000rpm, superior quality welds are obtained at speed of 1400 rpm at 28 mm/min weld speed.
- For hexagonal tool, joint efficiency values are maximum at tool rotational speed of 1000rpm at weld speed of 40 mm/min.
- From the final values table of TOPSIS and output parameters table it is observed that for joining AA 6061 plates with 12 mm thickness the optimal set of process parameters are tool rotational speed of 1400 rpm and 28 mm/min weld speed to achieve maximum ultimate tensile strength and maximum percentage of elongation of welded joint.

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