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Experimental Study And Optimization of Double Sided Friction Stir Welding of AA 6061 Plates

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Abstract — *Friction stir welding (FSW) is relatively a new welding method where heat generated by friction is used to forge components together under an axial force. In this method, the generated heat does not exceed the material melting point, instead the material is heated to its forging temperature and is stirred together by a rotating tool. Since the invention of FSW, this technique has been mainly used for welding aluminium plates together for butt and lap joint configurations. In this work, double sided friction stir welding was performed on AA 6061 plates of 12 mm thickness at rotational speeds (1000, 1400, 2000 rpm), weld speed (20, 28, 40 mm/min) with the conical tip tool. Tensile strength analysis has been carried out on nine sets and process parameters are optimized by using TOPSIS method. The most suitable set of parameters is found at tool rotational speed (TRS) of 1000 rpm and weld speed (WS) of 40 mm/min*

Keywords*-AA 6061; Conical tip; Friction stir welding; Tensile strength; Joint efficiency;*

I. 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, aerospace industry and automobile 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:

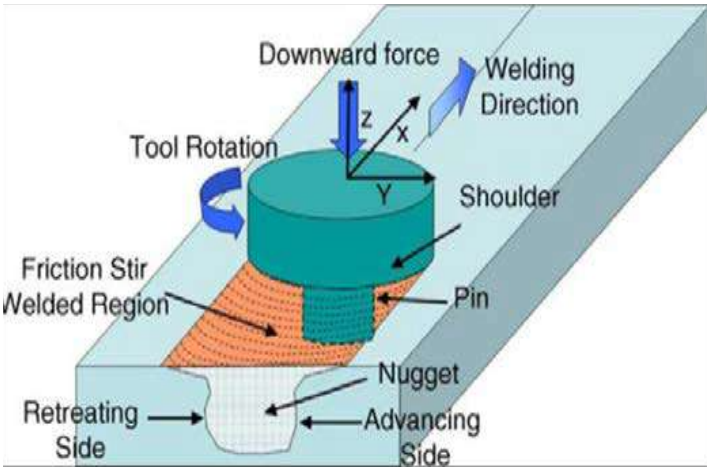

Fig. 1. Schematic diagram of FSW

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.

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.

II. 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. AA6061 was selected for double sided friction stir welding. The chemical composition of AA6061 is given in Table 1.

Table 1 Chemical Composition of AA6061

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

MechanicalProperty	Ultimate Tensile Strength (MPa)	Yield Strength(MPa)	ElongationPercentage	Hardness (BHN)
Value	310	276	12	34

In present work, the plates of 150 mm X 90 mm X 12 mm are prepared for experimentation as shown in Fig. 2.

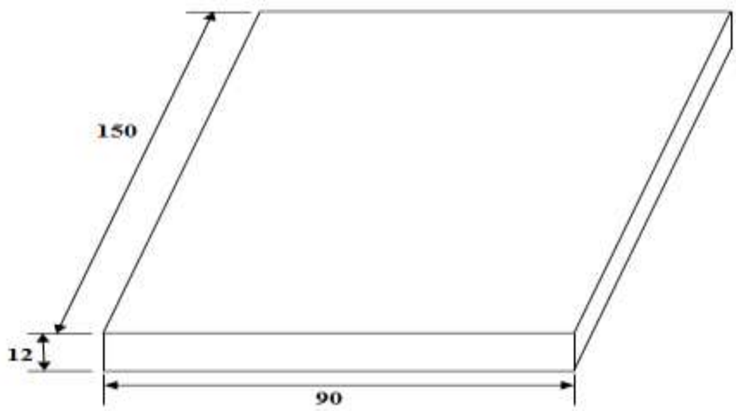

Fig. 2. Dimensions of work piece used in experimentation

2.2 Tool Design:

In friction stir welding, design of tool and tool material are critical factors to 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. Hot worked tool steel H13 is proven perfectly for welding aluminium alloys of thickness ranging 0.5−50mm. Chemical composition of H13steel is mentioned in Table 3.

Table 3 Chemical composition of H13 steel

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

Conical tip tool is used to conduct experiments by varying different parameters. From literature survey, it is observed that tools with shoulder-to-pin diameter ratio 3 has shown superior weld characteristics like ultimate tensile strength and hardness. The conical tool used for experimentation is shown in Fig. 3.

Fig. 3. Conical 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. 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**	**Level 1**	**Level 2**	**Level 3**
Tool Rotational Speed (TRS)	rpm	1000	1400	2000
Weld speed (WS)	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. 4.

Fig. 4. Experimental setup used in study

III. RESULTS AND DISCUSSION

The joints obtained after welding are tested for strength analysis was carried out on the 9 welded joints. Strength analysis is carried out to find the UTS, elongation percentage and yield stress of welded joints of welded joints. 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. 5.

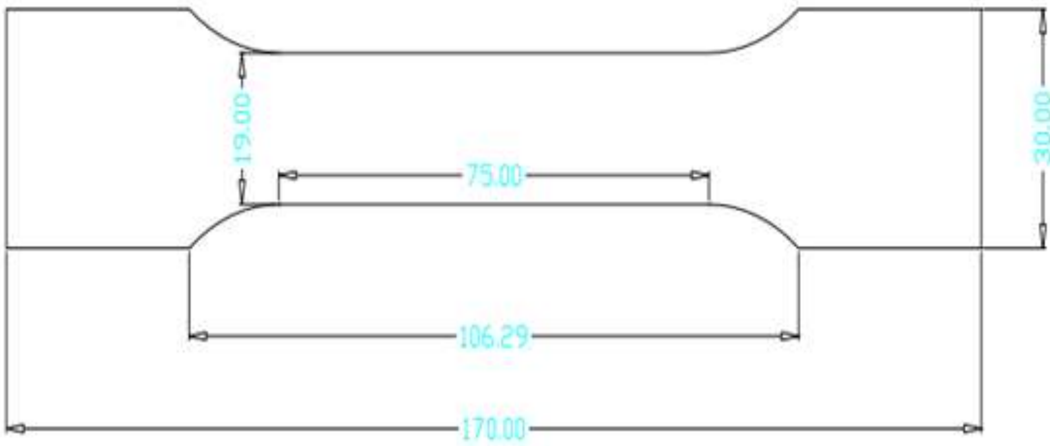

Fig. 5. Tensile specimen used (All dimensions are in mm)

Tensile test gives the values of ultimate load, UTS, elongation, yield stress. By this, the values under which the joints can be used safely are recorded. For the conduction of tensile testing samples are numbered from 1 to 9. Fig. 6 shows the fracture specimens of the welds formed by using conical tip tool.

Fig. 6. Fractured specimens of weld joints formed from conical tip tool

The tensile test gives the values of ultimate tensile strength, elongation percentage and yield stress of all the 9 samples and the output values are given in Table 5.

Table 5 Experimental Design with Ultimate Strength Results

Sample number	Tool Rotational Speed (rpm)	Weld Speed (mm/min)	Ultimate Tensile Strength (N/mm^2)	Elongation %	Yield Stress (N/mm^2)
1	1000	20	170.513	6.8	163.175
2	1000	28	146.772	3.6	146.772
3	1000	40	157.215	3.2	88.667
4	1400	20	180.029	5.2	133.081
5	1400	28	156.226	5.16	129.627
6	1400	40	146.76	5.1	124.264
7	2000	20	172.75	6.6	162.812
8	2000	28	173.773	4.94	165.379
9	2000	40	162.745	4	152.585

It is observed that weld obtained from conical tool at 1400rpm tool rotational tool and 20 rpm weld speed has showed maximum tensile strength value of 180.029 N/mm^2.

3.1 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. While 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.

$$\text{Joint efficiency} = \frac{\text{Ultimate tensile strength of welded joint}}{\text{Ultimate tensile strength of base metal}}$$

Table 6 Joint efficiency values of all samples

Sample Number	UTS of Joint (N/mm^2)	Joint Efficiency Value	Joint Efficiency in percentage
1	170.513	0.55	55
2	146.772	0.47	47
3	157.215	0.5	50
4	180.029	0.58	58
5	156.226	0.5	50
6	146.76	0.47	47
7	172.75	0.55	55
8	173.773	0.56	56
9	162.745	0.52	52

Maximum joint efficiency of 58% is obtained by using conical tool at 1400 rpm tool rotational tool and 20 rpm weld speed.

IV. OPTIMIZATION

4.1 TOPSIS Method

TOPSIS is a simple and effective multi criteria decision making tool used in many applications corresponding to sustainable concept selection, location of charging stations, computer networks, site selection for solar farms and process parameter selection in manufacturing etc., TOPSIS is one of the multi criteria decision making methods (MCDM) used to solve multi objective problems. It is based on the concept that the optimized solution should have the shortest distance from the ideal solution and the farthest distance from the negative ideal solution. The evaluation matrix for TOPSIS method is given in Table 7.

The following stages have been employed in this approach:

Step 1: The data has been normalized using following relation ship

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

Where, i = number of alternatives (trials)
j = number of criteria (Output responses)
X_{ij} = represents the actual value of the ith value of jth experimental run.

Table 7 Output parameter values used in the TOPSIS method

Sample number	Tool Rotational Speed (rpm)	Weld Speed (mm/min)	Ultimate Tensile Strength (N/mm^2)	Elongation %
1	1000	20	170.513	6.8
2	1000	28	146.772	3.6
3	1000	40	157.215	3.2
4	1400	20	180.029	5.2
5	1400	28	156.226	5.16
6	1400	40	146.76	5.1
7	2000	20	172.75	6.6
8	2000	28	173.773	4.94
9	2000	40	162.745	4

Table 8 Normalized values of output parameters

Sample Number	Ultimate Tensile Strength	Percentage of Elongation
1	0.347903	2.938144
2	0.299463	0.823494
3	0.320771	0.650662
4	0.367319	1.718153
5	0.318753	1.691822
6	0.299439	1.652706
7	0.352467	2.767854
8	0.354554	1.550633
9	0.332054	1.016659

Step 2: The weighted normalized matrix is built by multiplying each column of the normalized matrix with the respective weights. Here, equal weightage is given to all the responses. Therefore, $w_j = 0.50$ [8].

$$T = (t_{ij})_{mxn} = \left(w_j r_{ij}\right)_{mxn}, i = 1,2,\ldots,m \text{ ----- Eq. (2)}$$

Table 9 Weights of the output parameters for all samples

Sample Number	$(t_{ij})_{UTS}$	$(t_{ij})_{Elongation}$
1	0.173952	1.469072
2	0.149732	0.411747
3	0.160386	0.325331
4	0.18366	0.859077
5	0.159377	0.845911
6	0.14972	0.826353
7	0.176234	1.383927
8	0.177277	0.775317
9	0.166027	0.50833

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 16 shows the Best and worst values of output parameters.

Table 10 Best and worst values of output parameters

Output parameter	t_{bj}	t_{wj}
Ultimate Tensile Strength	0.18366	0.14972
Elongation %	1.46907	0.32531

Step 4:

In step 4, separation measures of each sample are calculated. Separation measure is the distance between the target value and the worst/best alternative. The seperation 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	0.009709	1.143998
2	1.057867	0.086416
3	1.143976	0.010666
4	0.609994	0.534823
5	0.623632	0.52067
6	0.643613	0.501022
7	0.085466	1.058928
8	0.693783	0.450829
9	0.960902	0.183724

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 values and corresponding values are given in Table 12.

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

From the final values of Table 12, it is observed that using conical tip tool at tool rotational speed of 1000 rpm and 40 mm/min weld speed has showed the highest value of 0.990763. More over the final values of sample 1 i.e., weld joint at 1000rpm TRS and 20 mm/min WS is the least so it can be concluded that low TRS and low WS results in poor joints. The optimal parameters set for joining AA 6061 plates with 12 mm thickness was found that conical tip tool at tool rotational speed of 1000 rpm and 40 mm/min weld speed.

Table 12 Final values obtained from TOPSIS method

Sample Number	$S_{iw}=d_{iw}/(d_{iw}+d_{ib})$	Rank
1	0.008415	9
2	0.92448	2
3	0.990763	1
4	0.532831	7
5	0.544989	6
6	0.562287	5
7	0.074682	8
8	0.606129	4
9	0.83949	3

V. CONCLUSIONS

In present study, the optimum ranges of process parameters for high quality double sided friction stir welding joints of AA6061 plates having 12mm thickness have been achieved. Multi objective technique TOPSIS method is employed to optimize the doublesided friction stir welding process parameters to obtain the optimum UTS and percentage elongation of AA6061 welded plates. From the investigation the following conclusions are drawn:

- 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 1000 rpm and 40 mm/min weld speed to achieve maximum ultimate tensile strength and maximum percentage of elongation of welded joint.
- For conical tool, joint efficiency values are maximum at tool rotational speed of 1400rpm at weld speed of 20 mm/min.
- From final values of TOPSIS method table, sample welded at 1000 rpm TRS and 20 mm/min WS is ranked 9th. This shows that weld both TRS and WS are at lowest values the heat generated because of FSW is not sufficient to form a sound weld.

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