INFLUENCE OF TOOL PIN PROFILE IN UNDERWATER FRICTION STIR WELDING OF ALUMINIUM 6061 ALLOY

Premkumar.P, Ruskin Bruce.A, Yogesh Krishnan P.R

Department of Mechanical Engineering, St.Joseph’s College of Engineering, Chennai 600119, Tamilnadu, India.

E-mail: prem1125@gmail.com

Abstract - Light metals like Aluminium and Magnesium are usually joined by welding processes like Friction Stir Welding (FSW). Aluminium being light weighted is used in various aeronautical applications. During welding using FSW, the Heat affected zone (HAZ) obtained is very much high due to direct exposure of air. In order to minimise the heat affected zone and also to improve the Weld strength, an attempt has been made to weld Aluminium Al 6061 alloy using Underwater Friction stir welding (UFSW). By carrying out the FSW process underwater, the hardness of the welded structures is also increased due to rapid cooling. In this present study, the effect of different pin profiles like cylindrical, square and conical profiles on the welded specimen is studied. Consequently, the mechanical properties of these welded specimens are also compared and analysed.

Keywords - Underwater Friction stir welding, Heat affected Zone, Hardness

1. INTRODUCTION

Friction Stir Welding is the obvious choice to weld Aluminium Alloys which are difficult to weld like the 5xxx series or the high strength alloys of 2xxx and 7xxx series (1). FSW involves rotation of non-consumable tool over the material specimens. The shoulder contact between tool and work piece provides frictional heat for the work pieces to be welded. The heat generated during the plunging, travelling and dwelling phases are sufficient to soften and join the work pieces (2). FSW reduces the porosity, surface cracking, material shrinkage of the welded joints (3). However, the thermal cycles experienced during FSW leads to reduction of mechanical properties due to coarsening and dissolution of strengthening precipitates which resulted in poor joint properties (4,5). In most of the Aluminium Welded specimens the Thermo-Mechanically Affected Zone (TMAZ) and the Heat Affected Zone (HAZ) are weak regions (6-8). The coarsening and dissolution of strengthening precipitates is prevented by rapid cooling (9). To avoid defects like Hydrogen Embrittlement, Oxidation, Porosity, Underwater Friction Stir Welding is used. The underwater conditions increase the weld properties because of lower heat input (10). However, there are only limited studies to prove the cooling effects of FSW on mechanical and micro structural properties. This urges researchers to implore more on the cooling effects of the specimen (11). The optimization results of UFSW indicated that the mechanical properties of the specimens showed a 6% increase than the FSW samples (12). High hardness and tensile strength of the welded specimen attributes to their use in the aerospace and submarine industry (13). The micro hardness distribution of UFSW is greater at the TMAZ and HAZ than the FSW Joint (14). Abbas et al. concluded that the optimum parameters to obtain a strong weld were 1300 rpm and a tool tilt angle of 40° (15). In this study, the influence of tool pin profile in Underwater Friction Stir welding of Aluminium 6061-T6 Alloys are studied. Different pin profiles like Cylindrical, Conical, Square profiles are taken into consideration. Hardness, tensile
and micro structural properties of the samples was studied. Optimisation of these results was done using RSM optimization software.

2. METHODOLOGY OF THE STUDY

![Methodology of study diagram]

3. EXPERIMENTATION

Selection of Materials
Aluminium 6061- T6 alloys are chosen for the study for their good machinability and workability. Aluminium 6061 alloys have excellent joining characteristics. The chemical composition of the aluminium alloy is listed in table 1.

Table 1. Chemical composition of Al 6061

| Component | Weight % |
|-----------|----------|
| Aluminium | 95.8-98.6|
| Chromium  | 0.04-0.35|
| Copper    | 0.15-0.4 |
| Iron      | 0.7 Max  |
| Magnesium | 0.8-1.2  |
| Silicon   | 0.4-0.8  |
| Tin       | 0.15 Max |
These alloys exhibit excellent corrosion resistance. Owing to their wide availability, these alloys are used for a variety of applications including couplings, brake pistons, bike frames, etc. Moreover, the industrial applications of Al 6061-T6 are highly desirable and economical. All these characteristics add to the selection of Aluminium Al 6061-T6 alloy.

The dimensions of the work piece were selected according to the standard dimensions followed in various experiments. The dimensions of Al 6061-T6 alloys include the length of 75mm, width of 100mm and thickness of 5mm.

**Fig 2.** Prepared samples of UWFSW

**Tool Design**

Among various tools available to carry out FSW process, the best suited HSS tool steel (HSS) is selected. The HSS tool steel is used in the Vertical Milling Centre (VMC). The three different tool pin profiles selected are displayed here.

**Fig 3** Different tool profiles
The dimensions of the HSS tool were determined based on the optimized parameters through literature survey. Moreover, an ideal fit for the collect is also needed for strong machining. The dimensions are listed below.

| PIN PROFILE | SHOULDER DIAMETER (mm) | PIN DIAMETER (mm) |
|-------------|-------------------------|-------------------|
| Cylindrical | 20                      | 5                 |
| Conical     | 20                      | 5                 |
| Square      | 20                      | 5                 |

The HSS tools prepared are heat treated to withstand high temperatures and to produce a sound weld.

Parameters selection and L12 orthogonal array

After a rigorous literature study, the parameters that have an impact on the properties of the welded specimen are selected. The process parameters selected for the study include Spindle speed, Welding speed and the tool pin profile. The range of these parameters was also identified beforehand. The L12 orthogonal array showing different combination of parameters is listed in table 3.

| WELDING SEQUENCE | SPINDLE SPEED (rpm) | WELDING SPEED (mm/min) | TOOL PROFILE |
|-------------------|---------------------|------------------------|--------------|
| 1                 | 1400                | 20                     | SQUARE       |
| 2                 | 1600                | 24                     | SQUARE       |
| 3                 | 1500                | 26                     | SQUARE       |
| 4                 | 1300                | 22                     | SQUARE       |
| 5                 | 1400                | 24                     | CONICAL      |
| 6                 | 1300                | 26                     | CONICAL      |
Underwater Friction Stir Welding

Underwater Friction Stir Welding is carried under Vertical Milling Centre (VMC). The Jig setup to withhold water during welding is shown in figure 4. The vertical Milling Centre used for experimentation is shown in figure 5. The aluminium plates were clamped to the bed of the VMC Machine. Different combinations of process parameters including spindle speed, welding speed, tool pin profiles are used to conduct the experiments. The experimentation was carried out using HSS tool steel by joining Al 6061-T6 plates of dimensions 75mm length, 100mm width, 5mm thickness.

| Experiment | Spindle Speed (rpm) | Welding Speed (mm/min) | Tool Pin Profile |
|------------|---------------------|------------------------|-----------------|
| 7          | 1500                | 22                     | CONICAL         |
| 8          | 1600                | 20                     | CONICAL         |
| 9          | 1400                | 26                     | CYLINDRICAL     |
| 10         | 1300                | 24                     | CYLINDRICAL     |
| 11         | 1500                | 20                     | CYLINDRICAL     |
| 12         | 1600                | 22                     | CYLINDRICAL     |

**Figure 4:** Jig to clamp Aluminium plates

**Figure 5:** Vertical Milling Centre used for UFSW
4. Tensile Test

Tensile test was conducted according to ASTM B557 standards to non-ferrous metals. The workpieces are machined according to the specified standards. An Universal testing machine is used to conduct the tensile test. Tensile test results provide us insights about the ultimate tensile strength, yield strength, % elongation, etc. A maximum load of 100 KN was applied on the specimen. The ultimate tensile testing machine is shown in figure 8. The samples obtained after tensile fracture is shown in figure 9.
The tensile test results obtained after testing is listed in table 4. The table shows results of Tensile Strength obtained from different welded samples.

| Welding sequence | Spindle speed (rpm) | Welding speed (mm/min) | Tool profile  | Pin profile | Tensile Strength (MPa) |
|------------------|---------------------|------------------------|--------------|-------------|------------------------|
| 1                | 1400                | 20                     | Square       | 79          |
| 2                | 1600                | 24                     | Square       | 77          |
| 3                | 1500                | 26                     | Square       | 72          |
| 4                | 1300                | 22                     | Square       | 72          |
| 5                | 1400                | 24                     | Conical      | 62          |
| 6                | 1300                | 26                     | Conical      | 65          |
| 7                | 1500                | 22                     | Conical      | 57          |
| 8                | 1600                | 20                     | Conical      | 63          |
| 9                | 1400                | 26                     | Cylindrical  | 44          |
| 10               | 1300                | 24                     | Cylindrical  | 49          |
| 11               | 1500                | 20                     | Cylindrical  | 42          |
| 12               | 1600                | 22                     | Cylindrical  | 45          |

5. Hardness Test

Hardness is defined as resistance to indentation or cracks. Hardness test was carried on welding specimens using the Rockwell Hardness Testing Machine. The Scale B in Rockwell Testing machine
is used for determining hardness in the welded samples. Load of 100 KN is applied on the welded samples to obtain indentation. The setup of Rockwell Hardness machine is shown in figure 10. Three values of hardness were obtained on each sample to obtain precision results. Hence a total of 36 tests were conducted on welded samples. Sample subjected to hardness testing is shown in figure 11. The results obtained as a result of the hardness test is tabulated in Table 5.

![Rockwell Hardness Testing Machine](image1)

![Sample subjected to Hardness test](image2)

### Table 5. Hardness Test Results

| Welding sequence | Spindle speed (rpm) | Welding speed (mm/min) | Tool Pin profile | Hardness (RHN) |
|------------------|---------------------|------------------------|-----------------|---------------|
| 1                | 1400                | 20                     | Square          | 80            |
| 2                | 1600                | 24                     | Square          | 78            |
| 3                | 1500                | 26                     | Square          | 75            |
| 4                | 1300                | 22                     | Square          | 75            |
| 5                | 1400                | 24                     | Conical         | 70            |
| 6                | 1300                | 26                     | Conical         | 62            |
| 7                | 1500                | 22                     | Conical         | 53            |
| 8                | 1600                | 20                     | Conical         | 58            |
| 9                | 1400                | 26                     | Cylindrical     | 48            |
| 10               | 1300                | 24                     | Cylindrical     | 52            |
| 11               | 1500                | 20                     | Cylindrical     | 49            |
| 12               | 1600                | 22                     | Cylindrical     | 54            |

6. Optimization
The optimization results were obtained using RSM methodology. The L12 orthogonal arrays as well as the results obtained from various tests were utilized to obtain optimized results. Various optimization results are discussed below.

**Response Surface Methodology**

The response surface methodology was carried out on L12 orthogonal array. The box- Behnken model and the coded coefficient values were tabulated in the tables.

| Table 6. Design of response surface model |
|------------------------------------------|
| Factor | Name         | Units | Type    | Low Actual | High Actual |
|--------|--------------|-------|---------|------------|-------------|
| A      | SPINDEL SPEED | rpm   | Numeric | 1300       | 1600        |
| B      | WELDING SPEED | mm/min| Numeric | 20         | 26          |
| C      | PIN PROFILE  |       | Numeric | 1          | 3           |

| Response | Name            | Units | Obs | Analysis | Min. | Max. | Mean   | Std. Dev. |
|----------|-----------------|-------|-----|----------|------|------|--------|-----------|
| Y1       | Hardness        | RHN   | 12  | Polynomial | 48   | 75   | 59.28  | 8.46349   |
| Y2       | Tensile strength | Mpa  | 12  | Polynomial | 42   | 79   | 60.554 | 12.6769   |
| Y3       | Yield Strength  | Mpa  | 12  | Polynomial | 37   | 72   | 53.683 | 11.9639   |

Regression equation for tensile strength, yield stress, hardness is obtained using the methodology. They are explained as follows,

Hardness = 59.15372 - 2.84845*A - 0.57905*B - 9.7448*C - 0.6819*A*B + 1.721067*B*C + 0.104433*C*A

Hardness = 69.8933 RHN
Tensile Strength = 59.79 - 0.68*A - 0.58*B -16.42*C -4.13*A*B - 2.87*A*C + 2.36*B*C
Tensile strength = 78.63706 MPa

Yield Stress = 52.83 -0.047*A -2*B-15.67 *C -4.62*A*B -3.07*A*C + 2.13*B*C
Yield stress = 72.00603 MPa

**Nomenclature**

A- Spindle Speed
B- Welding speed
C- Tool pin profile

**7. Results and Discussion**

Based on the regression equation, various plot of residuals for different parameters is obtained. They are shown in figures 12, 13, 14.

![Normal plot, Residuals vs Predicted plot for Hardness](image)

*Figure 12- Normal plot, Residuals vs Predicted plot for Hardness*
The contour plot and 3D surface plots of different parameters were obtained using the Design Expert software. The values of maximum tensile strength, yield stress and hardness are compared to obtain optimized results. They are illustrated in the below images.
Figure 15. Contour and 3D surface plot for Spindle speed vs Welding speed
Figure 16. Contour and 3D surface plot for Spindle speed vs Pin Profile
Figure 17. Contour and 3D surface plot for Welding Speed vs Pin Profile
From the plots, it is clear that the tensile strength, welding speed and spindle speed has greater impact than the tool pin profiles used to weld the samples. The surface plot clearly visualizes that maximum tensile strength is obtained at moderate range of parameters and not the maximum or minimum.

**Response Optimization- Tensile Strength**

Optimization of the obtained values provides us the best optimized results for carrying out the weld. The maximum strength was found to be 79Mpa for square profile at a tool traverse speed of 20 mm/min and a spindle speed of 1400 rpm. The results obtained after multi-response table is tabulated here.

| Spindle speed mm/min | Pin profile | Tensile Strength MPa | Yield Strength MPa | Desirability |
|----------------------|-------------|----------------------|--------------------|--------------|
| 1437.87              | Square      | 69.893               | 78.63706           | 72.00603     | 0.929442     |

**Conformity Test**

To confirm the correctness of obtained values, conformity test was conducted. The results obtained from the conformity test is tabulated below.

| Pin Profile | Spindle Speed (rpm) | Welding Speed (mm/min) | T1 MPa | T2 MPa | T3 MPa | Mean Tensile Strength (MPa) |
|------------|---------------------|------------------------|-------|-------|-------|-----------------------------|
| Square     | 1400                | 20                     | 78.4  | 80    | 77    | 78.46                       |

| Pin Profile | Spindle Speed (rpm) | Welding Speed (mm/min) | H1 RHN | H2 RHN | H3 RHN | Mean Hardness (RHN) |
|------------|---------------------|------------------------|--------|--------|--------|-------------------|
| Square     | 1400                | 20                     | 80     | 78     | 75     | 77.66             |

**Effect of Tool pin profile**

Tool pin profiles have a varying impact on the strength of the weldments. Of the three profiles used, square pin profile yielded the best results. This is because of the ratio between swept volume and static volume. The ratio between swept volume and static volume decides the path of flow of plasticized material from the leading edge of the tool to the trailing edge of the tool. The ratio is 1.56 for Square profiles which is the maximum among different profiles. Moreover, at 1200 rpm, square pin produces as much as 80 pulses/sec while a triangular pin generates 60 pulses/sec. As a result, square pin produces better results.

8. **Conclusion**

This study involving Underwater Friction Stir Welding of Al 6061- T6 alloys provides quality insights about the optimized parameters and the influence of tool pin profiles to obtain a sound weld.
The investigation provided great scope to study about the welding of Aluminium alloys, the strength of the welds, etc. We have inferred the following from the study,

- RSM methodology was used to obtain optimized parameters in this Underwater Friction Stir Welding of Aluminum Al6061-T6 alloys.
- A maximum strength of 79 MPa was obtained by the sample welded with square profile with a spindle speed of 1400 rpm and tool traverse speed of 20mm/min.
- The minimum Tensile strength of 48 MPa was obtained by the aluminum sample welded with a cylindrical profile with a spindle speed of 1400 rpm and tool traverse speed of 26mm/min.
- The optimum machining condition to obtain a sound weld was found to be with a spindle speed of 1437 rpm, tool traverse speed of 20mm/min with a square pin profile.
- Square pin profile yielded better results due to high ratio of swept volume to static volume.
- Besides, the square profile generates a greater stirring action, leading to the soundness of the weld.
- Hardness is uniformly distributed through the weldment and increase in hardness is attributed to the rapid cooling of the welded samples.

REFERENCES

[1] C. Y. Lee, W. B. Lee, J. W. Kim, D. H. Choi, Y. M. Yeon, and S. B. Jung, “Lap joint properties of FSW dissimilar formed 5052 Al and 6061 Al alloys with different thickness,” Journal of Materials Science, vol. 43, no. 9, pp. 3296–3304, 2008.

[2] M. B. Durdanovic, M. M. Mijajlovic, D. S. Milcic, D. S. Stamenkovic. 2009. Heat Generation during Friction Stir Welding Process. Journal of the Serbian Tribology Society.

[3] Esther T. Akinlabi, Stephen A. Akinlabi. 2012. Friction Stir Welding Process: A Green Technology. International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering. Vol:6, No:11.

[4] Threadgill PL, Leonard AJ, Shercliff HR, Withers PJ, Friction stir welding of aluminium alloys, Int Mater Rev 2009; 54:49-93

[5] Liang XP, Li HZ, Li Z, Hong t, Ma B, Liu SD, Study on the microstructure in a friction stir welded 2519-T87 Al Alloy, Mater Des 2012;35:603-8

[6] Simar A. Bechet Y, De Meester B, Denquin A, Pardoen T. Microstructure, local and global mechanical properties of FSW of Al6005A-T6. Master Sci Engg A 2008;486: 85-95

[7] Sivaraj P, Kanagarajan D, Balasubramanian V. Effect of post weld heat treatment on tensile properties and mechanical properties of FSW armour grade AA7075- T651 Aluminium alloy. Def Technol 2014; 10:1-8

[8] Dixit V, Mishra RS, Lederich RJ, Talwar R. Influence of process parameters on microstructural evolution and mechanical properties in friction stirred Al-2024(T3) Alloy. Sci Tech Weld Join 2009; 14:346-55

[9] TulikaGarg,Priyank Mathur, Varun Singhal, Underwater Friction Stir welding:An Overview (2014)

[10] Zhao Y, Lu Z, Yan K, et al. Microstructural characterizations and mechanical properties in underwater friction stir welding of aluminum and magnesium dissimilar alloys. Mater Des 2015; 65: 675–681.

[11] Guo JF, Chen HC, Sun CN, et al. Friction stir welding of dissimilar materials between AA6061 and AA7075 Al alloys effects of process parameters. Mater Des 2014;56: 185–192.

[12] Jie LH, Jie ZH, Lei Y. Homogeneity of mechanical properties of underwater friction stir welded 2219-T6 aluminium alloy. J Mater Engg perform 2011;20; 1419-22
[13] Huseyin Tarik Serindag, Binnur Goren Kiral, Dokuz. 2017. “Friction Stir Welding of AZ31 Magnesium Alloys – A Numerical and Experimental Study”. Latin American Journal of Solids and Structures. 14, pp. 113-130.

[14] L. Hui-Jie; Z. Hui-Jie; H. Yong-Xian. 2009. Mechanical properties of underwater friction stir welded 2291 Aluminium alloy. Trans. Nonferrous Met. Soc. China 20 (2010). 1387-1391.

[15] Mohd Abbas. Neha Mehani. Atishey Mittal. 2014. Feasibility of Underwater Friction Stir Welding and Its Optimization Using Taguchi Method. International Journal of Engineering Sciences & Research Technology.