International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056
Volume: 03 Issue: 02 | Feb-2016 www.irjet.net p-ISSN: 2395-0072

# OPTIMIZATION OF FSW PROCESS PARAMETER TO ACHIEVE MAXIMUM TENSILE STRENGTH OF ALUMINUM ALLOY AA6061

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**Abstracts -** This paper reports on an examination of the effect and optimization of welding parameters on the tensile shear strength in Friction Stir Welding process. The experimental readings were conducted under varying Tool Rotation Speed (rpm), Tool Traveling Speed (mm/min), and Tool Tilt Angle (degree). The settings of welding parameters were determined by using the Taguchi experimental design method. Experiments were conducted on AA6061 Aluminium alloy in a Vertical Machining Machine Centre. The output factors are measured in UTM. Results show strong relation and robust comparison between the weldment strength and process parameters. Hence FSW process variable data base is to be developed for wide variety of metals and alloys for selection of optimum process parameters for efficient weld. The level of importance of the welding parameters on the tensile shear strength is determined by using analysis of variance (ANOVA). The optimum welding parameter combination was found by using the analysis of signal-to-noise (S/N) ratio. The validation tests indicated that it is possible to increase tensile shear strength significantly by using the Taguchi method. The experimental results confirmed the validity of the used Taguchi method for enhancing the welding performance and improving the welding parameters in the Linear Friction Stir welding process.

**Key Words:** Tool rotation and travel speed and tool tilt angle. ANOVA, S/N ratio, OA.

## 1. INTRODUCTION

Friction stir welding (FSW) is an advanced welding process commonly known as a solid state welding process. This opens up whole new areas in welding technology. It is mainly appropriate for the welding of high strength alloys. The process uses a revolving, non-consumable tool, similar to a taper reamer, to produce frictional heat in the workpiece. By pressing this tool into contact with a seam to be welded, the base metal heats up and once it material is literally stirred together forming a weld without melting. These welds require low energy input and are without the use of filler materials and distortion. Initially developed for non-ferrous materials such as aluminium, by reaches about 80% of its melting point it becomes soft and deforms easily. By protection the tool rotating and moving it along the seam to be joined, the softened using suitable tool materials the use of the method has been extended to harder and higher melting point materials such as steels titanium alloys, copper and High Stainless steel (HSS) Material. This paper will concentrate on improvements for the friction stir welding of aluminium alloys.

## 2. SELECTION OF MATERIAL

The base material (BM) used in this investigation is aluminum alloy AA6061. Chemical composition of the material and mechanical properties is given in Table 1, 2 respectively.

**Table – 1:** Percentage of chemical composition of aluminum alloy -AA6061

| Si | Fe | Cu | Zn | Ti | Mn | Mg | Cr | Other | Al |
|---|---|---|---|---|---|---|---|---|---|
| 0.4-0.8 | 0.7 | 0.15-0.4 | 0.25 | 0.15 | 0.2-0.8 | 0.8-1.2 | 0.15-0.35 | 0.05 | 98.70 |

**Table – 2:** Mechanical properties of base metal –AA6061

| Material | Yield Strength (MPa) | Ultimate Tensile Strength (MPa) | Elongation ( %) | Hardness (0.5Kg) |
|---|---|---|---|---|
| Base Metal | 235 | 283 | 26.4 | 105 |

## 2.1 Cutting aluminium alloy plate

First of all eighteen pieces having size 200x125x6mm of AA6061 material are prepared for friction stir welding purpose. For this firstly AA6061 material blank is pressed in a press to make it straight and stress free. After that from this material blank, eighteen plates of size 200x125x6mm are cut by power hacksaw and milling machine. Square butt joint configuration, as shown in figure 1 has been prepared to fabricate FSW joints.

| Particular's | Values |
|---|---|
| Work Piece Material | Al 6061 |
| Work piece Dimensions | 200 (L) x 125 (W) x 6 (H) mm |

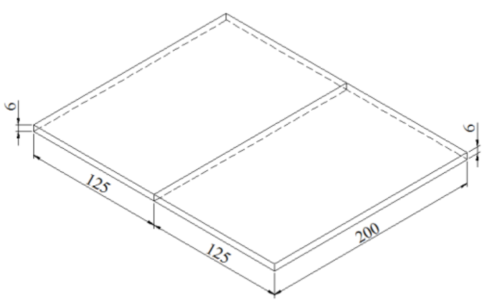


**Figure – 1:** Dimensions for the work piece

## 2.2 Design of Tool

Tool specification detail given in table and shown in drawing as given below:

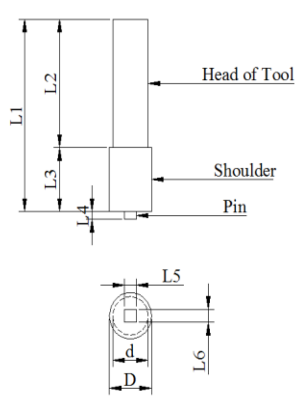


**Figure – 2:** Square tool pin profile

**Table – 3:** Tool specification

| Particular's | Index | Value |
|---|---|---|
| Total Tool Length | L1 | 75 mm |
| Head of Tool | L2 | 50 mm |
| Shoulder Length | L3 | 25 mm |
| Pin Height | L4 | 5.5 mm |
| Pin Length | L5 | 5 mm |
| Pin Width | L6 | 5 mm |
| Dia. of Tool Head | D | 15 mm |
| Shoulder Diameter | D | 18 mm |
| Tool Material | | High Speed Steel (HSS) |
| Hardness for Shank, Shoulder and Pin Profile | | 60-62 HRC |

## 2.3 Design of Fixture

Fixture is a job holding device which is mainly made up of MS steel plate. A fixture is something used to consistently test some item or device. We used a MS steel plate fixture for the process of friction stir welding. Joining a suitable sheet as required on the base of fixture, the sheet should have the required strength to withstand with operations. There may be many nuts on the fixture according to the requirement to hold the work piece. But in the experiment we used six nuts and bolt to hold the job in the fixture.

Table give detail dimensions specification required for design fixture.

**Table – 4:** Dimensions of Fixture

| Sr. No. | Fixture Part Name | Dimensions |
|---|---|---|
| 1 | Fixture Base Plate | 300(L) x 200(W) x 10 (H) mm |
| 2 | Clamping Plate | 270(L) x 40 (W) x 6 (H) mm |
| 3 | M18 (Nut Bolt) | 2 Nos. |
| 4 | M15 (Nut Bolt) | 4 Nos. |

**Photograph – 1:** Special design fixtures

### 3. TENSILE TESTING OF THE WELDED SPECIMEN

The welded joints are sliced using power hacksaw and then machined to the required dimensions to prepare tensile specimens as shown in figure 4. American Society for Testing of Materials (ASTM E8M-04) guidelines is followed for preparing the test specimens. Tensile test has been carried out in 100 ton, electro-mechanical controlled Universal Testing Machine at room temperature. The specimen is loaded at the rate of 1.5 KN/min as per ASTM specifications, so that tensile specimen undergoes deformation. The specimen finally fails after necking and the load versus displacement has been recorded. The ultimate tensile strength and percentage of elongation and joint efficiency have been evaluated.

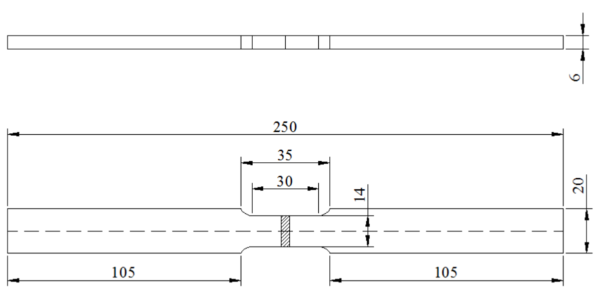


**Figure – 3:** Dimensions of tensile specimen according to ASME E8M-04

**Photograph – 3:** Specimens in UTM

(Material AA606 – after test)

**Photograph – 4:** Typical un-notch (Smooth) tensile tested specimens

**Table – 5:** Tensile strength testing result of welded specimen (Experimental Reading)

| Sr. No. | Type | Width In MM | Thickness In Mm | Area In MM² | Gauge Length In MM | Final Length In MM | Ultimate Load In N | U. T. S. In N/mm² | % Elongation | Joint Efficiency In % |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A | 13.08 | 6.04 | 78.91 | 25.00 | 27.23 | 9640.00 | 122.17 | 8.92 | 72.62 |
| 2 | B | 13.40 | 6.23 | 83.44 | 25.00 | 27.20 | 8800.00 | 105.46 | 8.80 | 63.10 |
| 3 | C | 13.05 | 6.10 | 79.61 | 25.00 | 26.25 | 5560.00 | 69.84 | 5.00 | 41.37 |
| 4 | D | 14.40 | 6.06 | 87.25 | 25.00 | 27.00 | 8800.00 | 100.86 | 8.00 | 60.12 |
| 5 | E | 13.80 | 6.04 | 83.36 | 25.00 | 27.50 | 10080.00 | 120.92 | 10.00 | 72.02 |
| 6 | F | 13.05 | 5.86 | 76.48 | 25.00 | 27.35 | 8400.00 | 109.84 | 9.40 | 65.48 |
| 7 | G | 13.80 | 5.78 | 79.68 | 25.00 | 27.05 | 10520.00 | 132.03 | 8.20 | 78.57 |
| 8 | H | 13.15 | 6.10 | 80.14 | 25.00 | 27.00 | 8320.00 | 103.82 | 8.00 | 61.61 |
| 9 | I | 12.85 | 5.89 | 75.70 | 25.00 | 27.15 | 8000.00 | 105.68 | 8.60 | 62.20 |

The welding experiments were carried out on the FSW machine by following the Taguchi designed matrix L9 in random order, as presented in Table 5 Mechanical properties like tensile strength, yield strength and percentage elongation were found out for the welded plates and the results are presented in Table 5. Each of the experimental results presented in Table 5 is an average of at least of two readings.

## 4. TAGUCHI ORTHOGONAL ARRAY

If there is an experiment having 3 factors which have three values, then total number of experiment is 27. Then results of all experiment will give 100 accurate results. In comparison to above method the Taguchi orthogonal array make list of nine experiments in a particular order which cover all factors. Those nine experiments will give 99.96% accurate result. By using this method number of experiments reduced to 9 instead of 27 with almost same accuracy.

The three factors used in this experiment are the rotating speed, tool tilt angle and travel speed. The factors and the levels of the process parameters are presented in Table 6 and these parameters are taken based on the trials to weld the FSW of steels. The experiment's notation is also included in the L9 orthogonal array which results in an additional column, in order to represent the parameters, as presented in Table 7.

**Table – 6:** FSW process parameter / Factor and levels to be taken

| Symbol | Welding Parameter / Factors | Unit | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|---|
| A | Tool Rotation Speed | rpm | 1000 | 1500 | 2000 |
| B | Tool Travel Speed | mm/min | 30 | 35 | 40 |
| C | Tilt Angle | degree (°) | 0° | 1° | 2° |

**Table – 8:** The Input parameter of L9 orthogonal array

| Sr. No. | Experiment's Notation | Friction Stir Welding Parameter Level | | |
|---|---|---|---|---|
| | | Tool Rotation Speed In rpm (A) | Tool Travel Speed In mm/min (B) | Tilt Angle In degree (C) |
| 1 | A | 1000 | 30 | 0 |
| 2 | B | 1000 | 35 | 1 |
| 3 | C | 1000 | 40 | 2 |
| 4 | D | 1500 | 30 | 1 |
| 5 | E | 1500 | 35 | 2 |
| 6 | F | 1500 | 40 | 0 |
| 7 | G | 2000 | 30 | 2 |
| 8 | H | 2000 | 35 | 0 |
| 9 | I | 2000 | 40 | 1 |

**Table – 9:** Response table for single to noise ratio (S/N ratio) and mean

| Ex. No. | Tool Rotational Speed (rpm) | Tool Traverse Speed (mm/min) | Tilt Angle (Degree) | UTS (N/mm2) | Joint Efficiency In % | S/N Ratio | Mean |
|---|---|---|---|---|---|---|---|
| A | 1000 | 30 | 0 | 122.17 | 72.62 | 38.91 | 97.31 |
| B | 1000 | 35 | 1 | 105.46 | 63.10 | 37.69 | 84.55 |
| C | 1000 | 40 | 2 | 69.84 | 41.37 | 34.03 | 55.44 |
| D | 1500 | 30 | 1 | 100.86 | 60.12 | 37.27 | 80.56 |
| E | 1500 | 35 | 2 | 120.92 | 72.02 | 38.84 | 96.51 |
| F | 1500 | 40 | 0 | 109.84 | 65.48 | 38.02 | 87.74 |
| G | 2000 | 30 | 2 | 132.03 | 78.57 | 39.60 | 105.29 |
| H | 2000 | 35 | 0 | 103.82 | 61.61 | 37.49 | 82.56 |
| I | 2000 | 40 | 1 | 105.68 | 62.20 | 37.57 | 83.35 |

In these tests, nine different welding parameter combinations were used. Therefore, the effect of each welding parameter on the weld strength cannot be clearly understood from the result of Table 9. Using MINITAB statistical software was used to explain the welding parameter effect [23]. From the results of Table 9, diagrams were drawn to display the welding parameters effects on the weld strength.

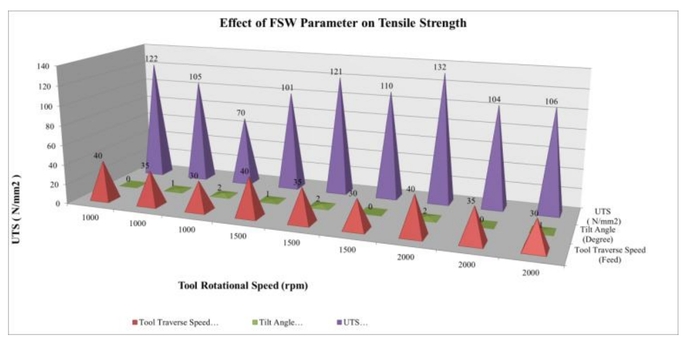


**Chart – 1:** Effect of FSW parameter on tensile strength

The effect of the friction stir welding parameters on the tensile test results for the design of the experiments are shown in Chart 1. As shown in Table 9, these tensile test results and the corresponding S/N ratio were calculated with Eq. (1).

$$S/N \text{ ratio } (\eta) = -10 \log_{10} ((1/n) \Sigma (1/ (y_{ij})^2)) \quad \text{.................... (1)}$$

## 5. ANALYSIS OF VARIANCE (ANOVA)

The relative importance among the welding parameters on weld strength is needed to be determined so that optimal combinations of the parameter levels can be assessed accurately. This can be achieved by using the analysis of variance. The purpose of the analysis of variance (ANOVA) is to investigate the importance of the welding parameters on the quality characteristic [13].

**Table – 10:** Analysis of variance (ANVAO) for tensile strength (SN Ratios)

| Source | DF | Seq. SS | Adj SS | Adj MS | F | P | Percentage of Contribution |
|---|---|---|---|---|---|---|---|
| Tool Rotational Speed (RPM) | 2 | 3.207 | 3.207 | 1.604 | 0.340 | 0.747 | **15.929** |
| Tool Travel Speed (MM/min) | 2 | 6.664 | 6.664 | 3.332 | 0.710 | 0.586 | **33.099** |
| Tilt Angle ( Degree ) | 2 | 0.812 | 0.812 | 0.406 | 0.090 | 0.921 | **4.031** |
| Error | 2 | 9.451 | 9.451 | 4.726 | - | - | 46.941 |
| Total | 8 | 20.134 | - | - | - | - | 100.000 |

**Table – 11:** Analysis of variance (ANOVA) for tensile strength (Means)

| Source | DF | Seq. SS | Adj SS | Adj MS | F | P | Percentage of Contribution |
|---|---|---|---|---|---|---|---|
| Tool Rotational Speed (RPM) | 2 | 222.630 | 222.630 | 111.310 | 0.290 | 0.775 | **14.029** |
| Tool Travel Speed (MM/min) | 2 | 537.490 | 537.490 | 263.750 | 0.700 | 0.588 | **33.870** |
| Tilt Angle ( Degree ) | 2 | 60.710 | 61.710 | 30.360 | 0.080 | 0.927 | **3.826** |
| Error | 2 | 766.090 | 766.090 | 383.040 | - | - | 48.275 |
| Total | 8 | 1586.920 | - | - | - | - | 100.000 |

**Note:** DF- Degree of Freedom, Seq. SS – Sequential Sum of Square, Adj SS –Adjusted Sum of Squares, Adj MS – Adjusted Mean Square, F test of hypothesis or Fisher ratio, P value of hypothesis

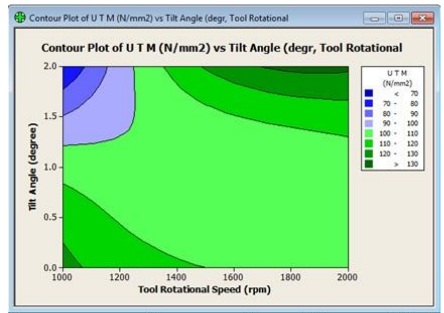


**Chart – 2:** ANOVA analysis for optimum tool rotational speed and tilt angle on ultimate tensile strength.

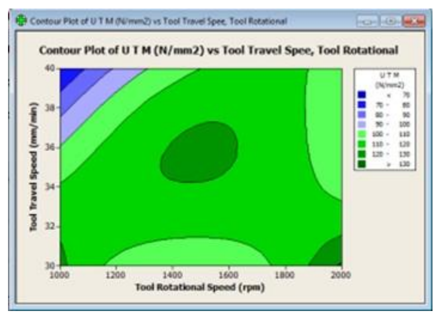


**Chart – 3:** ANOVA analysis for optimum tool rotational speed and tool travel speed travel on ultimate strength.

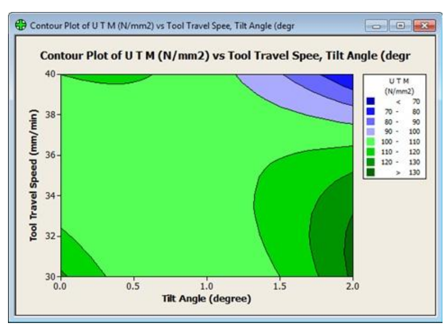


**Chart – 4:** ANOVA analysis for optimum tilt angle and tool travel speed on ultimate tensile strength.

The purpose of ANOVA is to determine which welding parameters highly affect the quality feature statistically [27, 30]. According to the results that are shown in Table 9, the Charts show the influence of the welding parameters on the tensile strength of Al 6061 sheet joined by FSW. The Charts are shown in Chart 2, 3. All of the dark green zones in the Charts show the maximum ultimate tensile strength. Chart shows ANOVA analyses for the optimum tool rotation speed and tilt angle on the ultimate tensile strength. For the relation between the tool rotation speed and tilt angle the maximum UTS was confirmed by welding parameters of 2000 rpm and 2˚ as shown in Chart 2. The relation between tool rotation speed, tool traverse speed and tilt angle in Chart 3 and 4 similar trends were observed as shown in Chart 2.

## 6. RESULTS OF TESTING

From the experimental results (tensile strength and MINITAB software), it is found the joint fabrication Friction Stir Welding 6061 aluminium alloy exhibited superior tensile properties by using parameter as tool rotational speed, tool travel speed and tool tilt angle. The possible cause for the effects of different welding parameters on tensile strength is interpreted and presented as follows.

### 6.1 Mean and signal to noise ratio

The Mean and signal to noise ratio are the two effects which influence the response of the factors. The influencing level of each selected welding parameter can be identified. The tensile strength of the FSW weld is taken as the output characteristic. The response table for the S/N ratio shows that the tool tilt angle ranks first in the contribution of good joint strength, while travel speed and rotation speed take the second and third ranks. The same trend has been observed in the response table of the mean which is presented in Tables 12 and 13 respectively. The responses for the plot of the S/N ratio and Mean are shown in Fig.4. The tensile strength is estimated to be the maximum at 2000 rpm rotation speed, 2° tool tilt angle and 8 mm/min travel feed; which is optimal from the plots obtained.

**Table – 12:** Response table for signal to noise ratio (S/N Ratio)

| Level | Tool rotational speed | Tool travel speed | Tool tilt angle |
|---|---|---|---|
| 1 | 36.88 | **38.60** | **38.14** |
| 2 | 38.04 | 38.01 | 37.51 |
| 3 | **38.23** | 36.55 | 37.49 |
| Delta | 1.35 | 2.05 | 0.65 |
| Rank | 2 | 1 | 3 |

The Optional setting parameters based on mean $A_3$ $B_1$ $C_1$

**Table – 13:** Response table for mean

| Level | Tool rotational speed | Tool travel speed | Tool tilt angle |
|---|---|---|---|
| 1 | 79.09 | **94.40** | **89.26** |
| 2 | 88.21 | 87.82 | 82.90 |
| 3 | **90.65** | 75.74 | 85.79 |
| Delta | 11.56 | 18.86 | 6.35 |
| Rank | 2 | 1 | 3 |

The Optional setting parameters based on mean $A_3$ $B_1$ $C_1$

### 6.2 Percentage of contribution

The percentage of contribution is the portion of the total variation observed in the experiment attributed to each significant factors and/or interaction which is reflected. The percentage of contribution is a function of the sum of squares for each significant item; it indicates the relative power of a factor to reduce the variation. The percentage of contribution of the rotational speed, welding speed and axial force for all responses are shown in Chart 5 (a) (b).

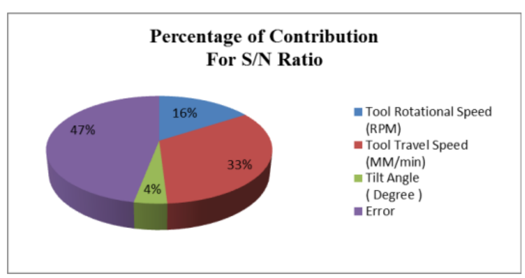


**Chart - 5(a):** Percentage contribution of factors S/N Ratio.

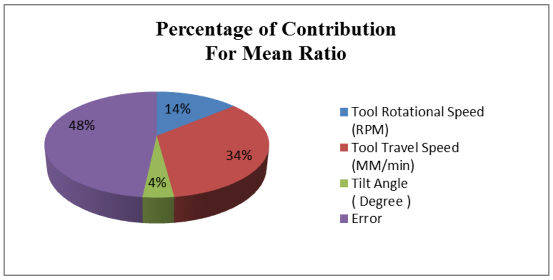


**Chart -5(b):** Percentage contribution of factors Mean Ratio.

### 6.3 Effects of process parameter on tensile strength (Base on Experimental Data Calculation) From Table 9 as explain below:

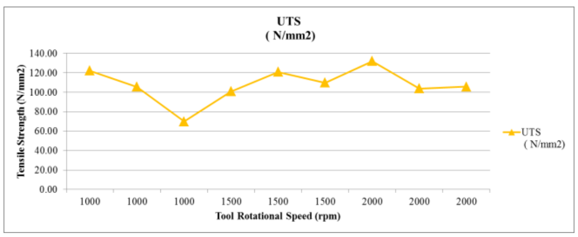


**Chart – 6:** Effect of rotational speed on tensile strength

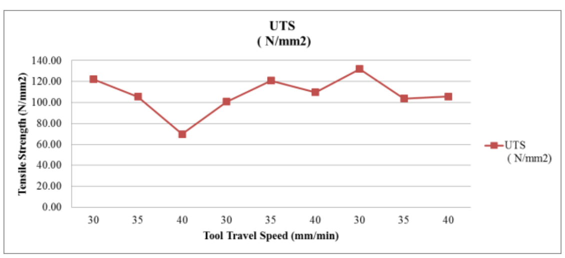


**Chart – 7:** Effect of tool travel speed on tensile strength

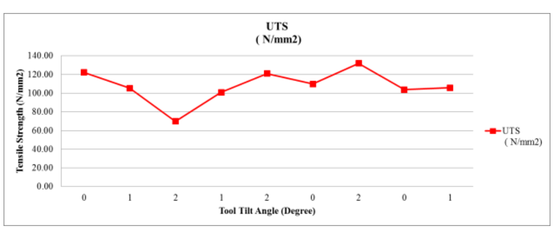


**Chart – 8:** Effect of tool tilt angle on tensile strength

In order to study the welding process parameters effects on tensile strength of the joints, tool which produced better welds was used.

Figure 6 shows the effect of tool rotational speed on tensile strength of the joints. The maximum UTS of about 132.03 was obtained at the tool rotational speed of 2000 rpm. With the rotational speed of 1000rpm, the wormhole phenomenon at the retreating side of the weld due to insufficient frictional heat generation and insufficient matrix transportation. The formation of this defect may be attributed to excessive turbulence of the weld caused by high tool rotational speed. Therefore, with the rotational speed of 2000 rpm, a just sufficient amount of frictional heat is generated which with proper turbulence of the weld results in the highest tensile strength.

The effect of work tool travel speed on tensile strength of the joints is not significant as shown in Chart 7. This is more obvious especially at speeds higher than 40 mm/min. When the travel speed is increased from 30 to 40 mm/min., the tensile strength decreases with a sharp slope compared to the speed between 35 and 40 mm/min. The excessive heat input per unit length of the weld at higher travel speeds and inadequate flow of the matrix which may cause tunnel defect factors contributing to lower strength of the higher tool travel speeds.

The influence of tool tilt angle on tensile strength of the welds is illustrated in Chart 8. Tilt angle affects the vertical and horizontal flow of the weld material tilt angle may cause tunnel and crack welds. At 0° tilt angle, the insufficient vertical and horizontal flow of the weld material may cause these defects that reduce the strength tilt angle, improves the flow characteristics of the material and hence, tool movement forges the weld material better to fill the defects and consequently increases the weld strength. Tensile strength of the welds increased when tilt angle was changed form 0˚ or 2˚.

## 7. CONFIRMATION TEST

The final step is verifying the improvement in responses by conducting experiments using optimal conditions. Three confirmation experiments were conducted at the optimum setting of process parameters. The rotational speed, welding speed and axial force were set at level 3 and the average tensile strength of friction stir welded 6061 aluminium alloy was found to be 131.36N/mm2, as shown in Table 14, which was within the confidence interval of the predicted optimal of tensile strength.

**Table – 14:** Confirmation experiment for Tensile strength

| Sr. No. | Tool Rotational Speed in (rpm) | Tool Travel Speed in (mm/min) | Tilt Angle in (°) | Ultimate Tensile Strength in (N/mm2) | Actual UTS in (N/mm2) | Predicted UTS in (N/mm2) |
|---|---|---|---|---|---|---|
| 1 | 2000 | 30 | 2° | 134.86 | 135.50 | 132.03 |
| 2 | 2000 | 30 | 2° | 135.57 | | |
| 3 | 2000 | 30 | 2° | 136.07 | | |

- The tool pin geometry (square pin shape) had a significant effect on weld appearance and tensile strength.
- The Taguchi method has been used to optimize the welding parameters of friction stir welding to weld a 6mm plate of IS: 3039.
- Using Minitab software and counter plot to maximum the Ultimate Tensile Strength of welding joints, for the given set of parameters, the optimum parameters were obtained as:
  - Optimum tool rotational speed: 2000rev/min.
  - Optimum tool travel speed (Transvers speed): 30 mm/min.
  - Optimum tilt angle: 2° Degree.
- The prediction of the Taguchi design approach was in good agreement with the experimental result.
- The L9 Taguchi orthogonal designed experiments of FSP on ASNCs were successfully conducted and the process parameters have a critical role in the quality of the obtained composites

## ACKNOWLEDGEMENT

I acknowledge my sincere thanks to M/s Govind INDUSTRIES and M/s OM INDUSTRIES Tiny Industries Co-Op., Industrial Estate Ltd., MIDC Area, Chikalthana, Aurangabad, also MATTEST Laboratory MIDC Waluj Area, Aurangabad who gave me an opportunity to carry experimental work in his industry and doing Test in his laboratory for preparing test report.Cordial thanks, to my mechanical engineering department's professor those who helped me.

## 8. CONCLUSIONS

From the present experimental investigation the following conclusions are derived:

- Base metal AA 6061 was found to exhibit the best characteristics for Friction Stir Welding.
- Tool material (HSS) found to withstand for 6082-T6 base metal without tool breakage.

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