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# Parametric Optimization of Hardness and Surface Roughness of a Friction Stir Welded joint by Making use of Data Envelopment Approach

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## ABSTRACT

*A suitable selection of machining parameters is necessary for any machining process in order to obtain the required output. In this paper we perform an experimental investigation to determine the optimal parametric setting during Friction Stir Welding (FSW) of Aluminium AA 6061 alloy. The FSW parameters process parameters considered are Rotational speed, Traverse speed and tilt angle whereas the quality characteristics considered are hardness (BHN) and surface roughness. The Taguchi method was applied in designing the experiments involved in this study to optimize the machining parameters. In accordance with the Taguchi quality design, a L9 (33) orthogonal array was chosen to design the experiment. The process parameters that were taken and their levels incorporated in the array were chosen after conducting initial experiments and literature survey. An attempt was also made to obtain significance of the machining parameters that affect the machining performance by making use of Analysis of Variance (ANOVA). By considering the significant machining parameters so obtained, the verification of the improvement in the quality characteristics for the FSW of Aluminium AA 6061 was done and the results so obtained were found out to be an improvement over the results obtained while using the original parameters (original setup).Mathematical models relating to the machining performance were established by making use of linear regression for the* *effective machining of Aluminium AA 6061. Apart from the optimization of each process parameter taken individually, multi response optimization has also been performed on both the process parameters that have been mentioned above by making use of Data Envelopment approach. Confirmation tests back up the results and it was observed that the practical values obtained for the optimal setup is inline with the theoretical results.*

***Keywords:—*** *Friction Stir Welding (FSW), AA 6061, Orthogonal Array, ANOVA, Data Envelopment.*

## I. Introduction

Friction stir welding is one of the solid state welding processes where two components are rubbed together at a controlled rotational speed to induce friction. That friction is used to generate enough heat to allow both components to reach a plastic state where the materials are forced together to form a bond. The force is laterally applied and is termed as 'up-set' which is used to fuse the components. The bond is created when layers of plastic material from both components inter wine and create new layers of combined material [1]. Friction welding can replace conventional welding and one piece construction as one of the most economical welding processes available. In addition it also gives benefits in design, strength and cost reduction. The process can provide increased design flexibility, superior strength and significant cost savings over other conventional welding processes. Heat treatable wrought Aluminium- Magnesium-Silicon alloy AA 6061 has excellent welding characteristics among high strength Aluminium alloys. These types of alloys are used extensively in marine frames, pipelines, storage tanks and aircraft applications. The welding defects such as large distortion, solidification cracking, porosity and oxidation are not observed in FSW compared to many of the fusion welding processes that are generally used for joining structural alloys [2].

In order to produce an excellent quality welded joint, it is necessary to optimize the process parameters. In the present research an experimental investigation is done on the FSW of Aluminium AA 6061 alloy taking into account Hardness and Surface Roughness as the quality characteristics. The experimentation process is designed using the Taguchi method where the process parameters considered are Welding speed, axial force and tool rotational speed.

Multi optimization is done by making use of the Data Envelopment approach while ANOVA is made use of to determine the significance of the process parameters with respect to the quality characteristics.

## II. Methodology

In this study 4mm thick plates of 100mm x 70 mm of 6061 Aluminium alloy was used as the base metal. The chemical composition of the alloy and its properties are shown in Table 1 and Table 2 respectively. The configuration used is of the butt type and the welding was carried out by using a vertical milling machine. The tool used was made of H13 Tool Steel of cylindrical geometry, It had a length of 50mm, Head diameter of 17mm, Pin diameter of 5mm and Pin length of 5.5mm. The process parameters under investigation were selected based on literature survey and the respective levels were selected based on preliminary experiments. Each experiment was run thrice and the average values for the quality characteristics were taken in order to account for variance

**Table 1: Chemical Composition of Base Metal (%wt)**

| Material | Mg | Fe | Cu | Cr | Si | Al |
|---|---|---|---|---|---|---|
| 6061-T6 | 0.8 to 1.2 | 0.33 | 0.25 | 0.18 | 0.4 to 0.8 | Re-maining |

The experimental investigation is conducted with the aim of optimizing the FSW process [5] in order to improve the above discussed quality characteristics namely Hardness and Surface Roughness, Several researches have been carried out by researchers showcasing the techniques involved in the selection of the optimal parametric values for Hardness [3] and Surface Roughness [4]. Taguchi method has been widely used in the selection of the process parameters. Taguchi method makes use of Orthogonal Arrays (OAs) [6] for designing the experiments. The predominant advantage of this technique lies in its simplicity and adaptability. They provide the required information making use of only the least possible number of trials. However they still yield results which have good precision and are reproducible.

**Table 2: Properties of Base Metal**

| Property | Metric |
|---|---|
| Density | 2.7 g/cc |
| Brinell Hardness | 95 |
| UTS | 310 MPa |
| Modulus of elasticity | 68.9 GPa |
| Poisson's ratio | 0.33 |
| Thermal conductivity | 167 W/mK |

In order to determine the performance characteristics under the optimal machining parameters, a specially designed experimental procedure is required. A full factorial experimental design will cover all the possible arrangements possible for a particular experimental setup. However as the number of factors and levels increases, the total number of experiments also increases. Making it unviable both financially and in terms of time taken. Hence Taguchi's orthogonal arrays are made use of to reduce the number of experiments required [9].

**Table 3: Process Parameters and their Levels**

| Nota-tion | Factor | Unit | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|---|
| A | Tool rotational speed | rpm | 1000 | 1100 | 1200 |
| B | Traverse speed | mm/min | 45 | 55 | 65 |
| C | Tilt Angle | Degrees | 0 | 1 | 2 |

The experiment includes three process parameters each of three levels. Therefore each process parameter will contribute 2 degrees of freedom each. Therefore there are 6 degrees of freedom in total. The interaction between the parameters is neglected [6] [8].

While selecting an Orthogonal Array it should be noted that the degrees of freedom of the Orthogonal Array must be greater than or equal to those of the process parameters. [10]. An L9 array will have 8 degrees of freedom (i.e.: 9-1=8). It has already been specified that the process parameters used here have 6 degrees of freedom. The degree of freedom for the Orthogonal Array is less than the degrees of freedom of the process parameters. Hence it is possible to use an L9 for the experiments in this study. The experimental layout for the process parameters in terms of an L9 Array is given in table 4.

**Table 4: Experimental layout considered**

| Experiment | A | B | C |
|---|---|---|---|
| 1 (Initial setup) | 1000 | 45 | 0 |
| 2 | 1000 | 55 | 1 |
| 3 | 1000 | 65 | 2 |
| 4 | 1100 | 45 | 1 |
| 5 | 1100 | 55 | 2 |
| 6 | 1100 | 65 | 0 |
| 7 | 1200 | 45 | 2 |
| 8 | 1200 | 55 | 0 |
| 9 | 1200 | 65 | 1 |

## III. Experimental Setup and Results

The experiments were conducted by making use of a CNC vertical milling machine; such a machine was chosen that possessed a rotatable head so as to vary the Tilt angle. The butt joint configuration was achieved by securing the AA 6061 plates in position by making use of mechanical clamps. Tool rotational speed was selected as a process parameter as it is the most important parameter that affects the FSW as it greatly influences the grain refinement and heat input during the process [21]. Along with Tool rotational speed, the traverse speed plays a major role in determining the quality of the weld [22]. The tilt angle plays a crucial role in the process as a variation in the tilt angle directly affects the Z torque, Z load and X load [23].

The tool used was made of H13 Tool Steel of cylindrical geometry, it had a length of 50mm, Head diameter of 17mm, Pin diameter of 5mm and Pin length of 5.5mm. H13 is known for its excellent hot hardness. It gains its elevated temperature strength from precipitation of chromium, vanadium and molybdenum carbides upon hardening and tempering. The dissolution temperature of chromium, vanadium and molybdenum carbides is above 550°C which makes the material suitable for FSW tool material.

Three experiments were conducted for each trial to account for variance and the average of these experimental results have been tabulated for analysis. The levels selected for the experimentation have also been taken in such a manner that these levels are free of weld defects.

The experiments are conducted as per the arrangement of the orthogonal array in Table 4. Three sets of experiments are conducted for each run and the average values of the quality characteristics are calculated and tabulated as shown in Table 5.

**Table 5: Experimental results**

| Expt | Hard-ness (BHN) | S/N ratio for Hard-ness (dB) | Surface Rough-ness (µm) | S/N ratio for Surface Roughness (dB) |
|---|---|---|---|---|
| 1 | 15.07 | 23.5623 | 1.400 | -2.92256 |
| 2 | 14.85 | 23.4345 | 1.374 | -2.75973 |
| 3 | 14.63 | 23.3049 | 1.231 | -1.80516 |
| 4 | 12.99 | 22.2722 | 0.997 | 0.02610 |
| 5 | 11.77 | 21.4155 | 0.754 | 2.45257 |
| 6 | 17.79 | 25.0035 | 1.418 | -3.03352 |
| 7 | 10.91 | 20.7565 | 0.723 | 2.81723 |
| 8 | 14.93 | 23.4812 | 1.041 | -0.34901 |
| 9 | 15.71 | 23.9235 | 0.898 | 0.93447 |

## *IV. Selection of Optimal Parameters*

The experimental results are obtained by conducting the experiments are shown in table 5. The results showcase the effect of the three control parameters on the 2 quality characteristics. The S/N ratios are also displayed in the same table. Once the calculations are made, the graphs for the particular control parameters at their three levels of application are plotted. Figure 1 and figure 2 show the graphs

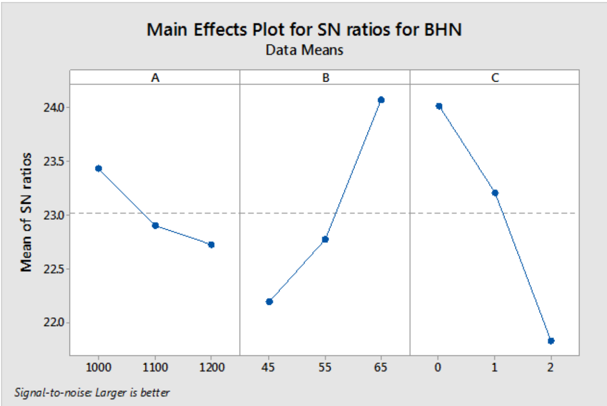


*Figure 1: Main effects plot for S/N ratios for BHN (Hardness)*

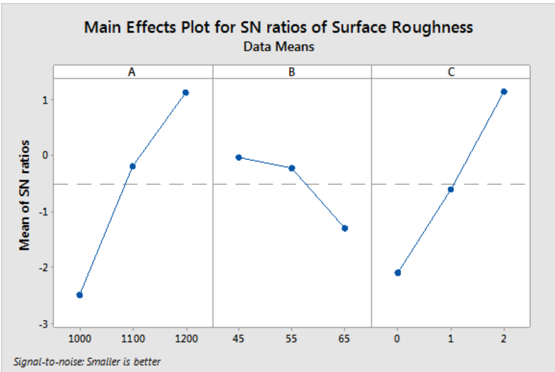


*Figure 2: Main effects plot for S/N ratios for Surface Roughness*

From the figures, we can surmise that the optimal parametric setup for best Hardness is A1B3C1 where A1 = 1000, B3 = 65 and C1 = 0. Similarly the optimal parametric setup for Surface Roughness is A3B1C3 where A3 = 1200, B1 = 45 and C3 = 2

## V. Theoretical and Experimental Comparison

The predicted optimum value of S/N ratios can be calculated from the following relationship

$(\eta_j-\eta_m)$ ; j=1....4 (Eq.3)

Here

$\eta_m$ = Grand mean of S/N ratio

$\eta_j$ = Mean S/N ratio at optimum level

k= number of main design parameters that affect the quality characteristics.

Using the relationship given in Eq.3, we calculate the theoretical values for the S/N ratios for the quality characteristics at their optimum level of arrangement. The results are correlated with the values obtained by performing the confirmation experiments at the optimized level (A1B3C1 for Hardness and A3B1C3 for Surface roughness) and are tabulated in table 6.

A hardness of 17.98 BHN and a surface roughness of 0.6548µm were obtained as an average for three repetitions of experiments conducted at the optimal level.

**Table 6: Comparison of the S/N ratios between experimental and Theoretical optimized results (in dB)**

| Quality character- | Experimental | Theoretical |
|---|---|---|
| Hardness | 25.0958 | 25.4297 |
| Surface Roughness | 3.6778 | 3.2937 |

We can observe from the confirmation experiments that they are closely in line with the theoretical values that are expected.

## VI. ANOVA for Single Level Optimization

ANOVA is a statistic based objective decision making tool, to detect differences in average performance of groups of items tested. ANOVA helps in formally testing the significance of all main factors and their interactions by comparing the mean square against the estimate of experimental errors at certain specific confidence levels.

**Table 7: ANOVA for Hardness**

| Source | DOF | Adj SS | Adj MS | F-value | P- value |
|---|---|---|---|---|---|
| A | 2 | 1.5556 | 0.7778 | 7.000 | 0.125 |
| B | 2 | 14.8732 | 7.4366 | 66.93 | 0.015 |
| C | 2 | 18.5273 | 9.2636 | 83.37 | 0.012 |
| Error | 2 | 0.2222 | 0.1111 | | |
| Total | 8 | 35.1782 | | | |

**Table 8: ANOVA for Surface Roughness**

| Source | DOF | Adj SS | Adj MS | F-value | P- value |
|---|---|---|---|---|---|
| A | 2 | 0.30662 | 0.15331 | 8.57 | 0.104 |
| B | 2 | 0.03640 | 0.01820 | 1.02 | 0.496 |
| C | 2 | 0.22085 | 0.11042 | 6.17 | 0.139 |
| Error | 2 | 0.03577 | 0.01789 | | |
| Total | 8 | 0.59964 | | | |

It is observed that with respect to Hardness, the significance of the input parameters are the Tool Rotation Speed, Traverse Speed and Tilt Angle with the Tool Rotation Speed being the most significant and the Tilt Angle being the least significant of the lot. Whereas for Surface roughness it is observed that the Traverse Speed is the most significant parameter whereas the Tool Rotation Speed is the least significant parameter of the lot.

## *7. Multi Optimization Using Data Envelopment*

Data Envelopment Analysis based Ranking (DEAR) method for multi optimization of Taguchi experiments was proposed in the year 2002 by Hung-Chang and Yan Kwang. Here a set of original responses are mapped into a ratio so that the optimal levels can be found. This ratio so obtained is equivalent to the Multi Response Performance Index (MRPI). The steps involved are:-

Step 1: Determine the weights associated with each response for all experiments using an appropriate weighting technique.

Step 2: Transform the observed data of each response into weighted data by multiplying the observed data with it's own weight.

Step 3: Divide the weighted data of larger - the better type with weighted data of smaller-the better type or nominal- the best type

Step 4: Treat the value obtained in step 3 as MRPI and obtain the solution.

The data obtained after application of DEAR is displayed in Table 9

**Table 9 : Calculation of weighted responses and MRPI using Data Envelopment**

| Trial | Response Weights | | Weighted Response | | MRPI |
|---|---|---|---|---|---|
| | w(BHN) | w(Surface Rough-ness) | W(BHN) | W(Surface Rough-ness) | |
| 1 | 0.117140 | 0.081668 | 1.76529 | 0.114335 | 15.4396 |
| 2 | 0.115429 | 0.083213 | 1.71413 | 0.114335 | 14.9922 |
| 3 | 0.113719 | 0.092878 | 1.66371 | 0.114333 | 14.5515 |
| 4 | 0.100972 | 0.114679 | 1.31162 | 0.114335 | 11.4717 |
| 5 | 0.091489 | 0.151638 | 1.07682 | 0.114335 | 9.4181 |
| 6 | 0.138282 | 0.080630 | 2.46004 | 0.114333 | 21.5164 |
| 7 | 0.084804 | 0.158140 | 0.92521 | 0.114335 | 8.0921 |
| 8 | 0.116051 | 0.109830 | 1.73265 | 0.114333 | 15.1544 |
| 9 | 0.122114 | 0.127320 | 1.91842 | 0.114333 | 16.7791 |

The higher the value of the MRPI, closer is the corresponding factor combination to the optimal value. The MRPI is treated as a single response problem and the data is analysed to determine the optimal level for the factors.

**Table 10 : Optimal levels of MRPI**

| Factor | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| A | 14.9944 | 14.1354 | 13.3419 |
| B | 11.6678 | 13.1882 | 17.6157 |
| C | 17.3701 | 14.4173 | 10.6872 |

By taking into consideration the average MRPI for the three input parameters at the three levels as shown in Table we can say that the multi optimization of the two quality characteristics occur at the level A1B3C1.

Confirmation experiments conducted at the levels A1B3C1 show that the values obtained for hardness and surface roughness are initial setup of the machine as shown in table 4 (corresponding to trial 1).

## VIII. Mathematical Models

Regression is performed on the data using MINITAB 17. The following equations is hence obtained for the 2 quality characteristics for single level optimization. They are:

Hardness = 13.14 – (0.00500*A) + (0.1527*B) –(1.747*C)

Surface Roughness = 3.355 – (0.002238*A) + (0.00712*B) – (0.1918*C) Where A, B, C are the process parameters.

## IX. Conclusions

An attempt was made to optimize the FSW process with respect to the selected quality characteristics. The necessary levels at which the process parameters have to be set to obtain an optimized result for the quality characteristics have been obtained.

1. For optimum Hardness, the recommended parametric combination is A1B3C1 where A1 is 1000 mm/min, B3 is 65mm/min and C1 is 0 degrees by using this optimal setup the Hardness was improved by 19.31%. For optimum surface roughness the recommended parametric combination is A3B1C3 where A3 is 1200 mm/min, B1 is 45mm/min and C3 is 2 degrees. By using this optimal setup the surface roughness was improved by 53.23%.

2. It is observed that the Tool rotation speed is the most significant parameter that affects the Hardness of Aluminium 6061 followed by Traverse speed and Tilt angle. With an increase in tool rotation speeds the rate of increase in heat input increases which leads to the formation of a coarse microstructure hence reducing the hardness. A higher traverse speed results in a finer grain structure and increases the hardness. The levels so obtained for optimal hardness are in line with these statements.

3. Traverse speed is the most significant parameter that affects the Surface roughness of Aluminium 6061 followed by Tilt angle and Tool rotation speed. Increase in traverse speed decreases the peak temperature and causes lower heat input. More surface blemishes appeared when small inclination angles were used As a result, the recommendatory inclination angle values for inclination angle are proposed based on these observations. Increase in the tool rotational speed leads to the production of more heat and fewer materials precipitate in the formation of the weld. The flow ability increases and there is a decrease in the forward friction

4. Multi optimization has been performed for both quality characteristics and the optimal level

of the parametric arrangement is found to be A1B3C1.

5. The mathematical models for the calculation of the quality characteristic (taken one at time) in terms of the process parameters have been obtained by regression.

6. By conducting the conformational experiments we can see that the results so obtained are in close line with the theoretical models that were obtained.

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