

# Modeling and Analysis of Friction Stir Welding of Aa6061 Aluminium Alloy Using Response Surface Methodology

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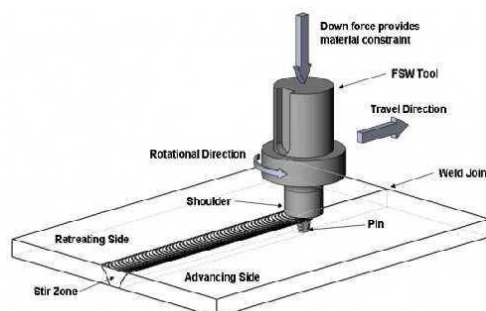
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**ABSTRACT:** Friction stir welding (FSW) is an emerging solid state joining process in which the material that is being welded does not melt and recast. This process uses a tool to generate frictional heat in the abutting surfaces. FSW has been used in all types of production industries because of better welded surface and moderate strength. FSW is normally used to join aluminium alloys. Automotive industries commonly uses friction stir welding. This project work deals with the welding of 6061 Aluminium alloy by varying welding parameters such as welding speed, spindle speed and shoulder penetration. Three factor three level box benken design was used for conducting the experiments.

**KEYWORDS:** Friction stir welding, box benken design, AA6061 Aluminium alloy

## I. INTRODUCTION

The friction stir welding (FSW) [1] is a solid state joining process developed by The Welding Institute (TWI), emerged as a Welding technique to be used in high strength aluminium alloys that were difficult to join with conventional techniques. The process was developed initially for aluminium alloys, but since then FSW was found suitable for joining a large number of materials. In FSW the material to be joined is plasticized by heat generated by friction between the surface of the plates and the contact surface of a special tool, which composed of two main parts: shoulder and pin [2]. Shoulder is responsible for the generation of heat and for containing the plasticized material in the weld zone, While the pin mixes the material of the components to be welded, thus creating the joint.



FSW joints usually consist of four zones, as opposed to primarily three zones in “normal” welds, different regions as shown in figure 1. a) unaffected base metal; b) heat affected zone (HAZ); c) thermo mechanically affected zone (TMAZ) and d) friction stir processed (FSP) zone (nugget). The formation of these regions is affected by the material flow

behavior under the action of the rotating non-consumable tool. The material flow behavior is predominantly influenced by the FSW tool profile, tool dimensions and welding process parameters. Frictional heat and plastic flow during FSW create fine and equiaxed dynamic-recrystallized grains in the stir zone (SZ) and elongated and recovered grains in the thermo mechanically affected zone (TMAZ). The heat affected zone (HAZ) is often identified by means of only material hardness changes as there is no difference in grain structure compared to the base metal. This softened HAZ region can be characterized by the dissolution and coarsening of the strengthening precipitates during friction stir welding [3]

### **Types of FSW**

The different types of friction stir welding processes are mentioned below

#### **i) Linear friction welding**

Linear friction welding, (so named because the relative motion is linear across the interface, rather than rotary), is already used to join blades onto discs in the aero engine industry.

Lower cost linear friction welding machines are now being developed for automotive applications, such as the fabrication of brake discs, wheel rims and engine parts.

#### **ii) Rotary friction welding**

Rotary friction welding, in which one component is rotated against the other, is the most commonly used of the processes, and many carbon steel vehicle axles and sub-axles are assembled in this way.

The process is also used to fabricate suspension rods, steering columns, gear box forks and drive shafts, as well as engine valves, in which the ability to join dissimilar materials means that the valve stem and head can be made of materials suited to their different duty cycles in service.

### **Applications of FSW**

The different areas of engineering applications where friction stir welding used are

- Automotive,
- Marine applications,
- Aerospace,
- Railway Rolling Stock,
- Fabrication,
- Shipbuilding and Offshore etc.

### **Aluminum Alloy**

Aluminum alloy 6061 is a medium strength alloy with excellent corrosion resistance property. It has the highest strength of the 6000 series alloys. Alloy 6082 is known as a structural alloy. In plate form, 6061 is the alloy most commonly used for machining. As a relatively new alloy, the higher strength of 6061 has seen it replace 6082 in many applications. The addition of a large amount of manganese controls the grain structure which in turn results in a stronger alloy.

It is difficult to produce thin walled, complicated extrusion shapes in alloy 6061. The extruded surface finish is not as smooth as other similar strength alloys in the 6000 series.

### **Applications of aluminum alloy 6061**

AA6061 is typically used in the following areas namely

1. Shipbuilding and Marine Construction
2. Aerospace Industry
3. Railway Industry
4. Land Transportation

## **II. LITERATURE REVIEW**

**K.Elangovan, et.al [8]**, studied that, Influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone, Five different tool pin profiles (straight cylinder, tapered cylinder, threaded cylinder, triangle and square) with three different shoulder diameter have been used to fabricate the joints. The FSP zone has been analyzed macroscopically. Tensile properties of the joints have been evaluated and correlated with the FSP zone formation.

**S.Rajakumar, et.al [9]**, studied that, the influence of process and tool parameters on tensile strength properties of AA7075-T6 joints produced by friction stir welding was analyzed. Square butt joints were fabricated by various process parameter

and tool parameters. Strength of the joints were evaluated and correlated with microstructure, micro hardness of the weld nugget.

**C.MChen, et.al [10]**, studied that Finite element modeling of friction stir welding thermal and thermo mechanical analysis. A three dimensional model based on finite element analysis is used to study the thermal history and thermo mechanical process and the shoulder. The thermal history and the evolution of longitudinal, lateral, and through-thickness stress in the friction stirred weld are simulated numerically. The x-ray diffraction technique is used to measure the residual stress of the welded plate and the measured result are used to validate the efficiency of the proposed model.

**H.Badarinarayan, et.al [11]**, studied that, the tool geometry is found to significantly affect the hook formation. First, welds are made to compare the effect of three shoulder profiles concave, convex and flat on the hook geometry and static strength. Next with the concave shoulder profile selected. The effect of two different pin profile cylinder and triangular are evaluated in 5754-o sheets.

**Mohamed merzoug, et.al [12]**, found that, Parametric studies of friction stir welding of aluminium 6060-T5 alloys. This experiment approach let us notice that the shape of the tool and in particular the pawn has a great influence on mechanical resistance of the joint of welding. The importance of these phenomena depends on the same time on the nature of material and the choice on parameters (geometry, positioning, tool rotating, penetration depth and the force applied of the pin and the shoulder)

**K.Elangovan, et.al [13]**, have found that the welding parameters and tool pin profile play major roles in deciding the weld quality. In this investigation an attempt has been made to understand the effect of welding speed and tool pin profile on FSP zone in AA2219 aluminium alloy. Five different tool pin profile (straight cylinder, tapered cylinder, threaded cylinder, triangle and square) have been fabricate the joints at three different weld speed. Tensile properties of the have been evaluated.

**K.Elangovan, et.al [14]**, predicting tensile strength of friction stir welded AA6061 aluminium alloy by mathematical model. The welding parameters such as tool rotational speed, welding speed, axial force and tool pin profile play a major role in deciding the joint strength An attempt has been made to develop a mathematical model to predict tensile strength of the friction stir welding by in corporating process parameter. Four factors and five level central composite design has been used to minimize number of experimental condition.

### III. METHODOLOGY

#### Response Surface Methodology

RSM is a combination of experimental designs and statistical techniques for empirical model building and optimization. RSM was originally developed for the model-fitting of physical experiments by Box and Draper and later extended to other fields.

RSM is very useful for modeling and analysis where a response of interest is influenced by several variables and the objective is to optimize this response. By conducting experiments and the posterior application of regression analysis a model of the response variable of interest is obtained. The real relationship between the response and the independent variables is unknown. For that reason, the first step in RSM is to find an approximation of the true functional relationship between the response and the independent variables. The observed response  $y$ , can be written as a function of the independent variables  $x_1, x_2, x_3, \dots, x_k$ , as follows

$$y = f(x_1, x_2, x_3, \dots, x_k) + \varepsilon$$

Where,  $\varepsilon$  is a random error.

Plotting the expected response  $y$ , a surface known as the response surface is obtained. As remarked previously, the form of  $f$  is unknown and can be complicated. This is why an approximation is needed. Frequently, a low-order polynomial function

is employed in some region. If the response is well-modeled with a linear function, the approximation function is a first-order model. If the system has curvature, a higher-order polynomial model must be used, such as a quadratic model.

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i < j} \beta_{ij} x_i x_j + \epsilon$$

Almost all RSM problems use one of these models. However, it is unlikely that a polynomial model will be a good approximation of a true functional relationship over the entire space of the independent variables; but for small regions polynomial models work reasonably well.

When RSM is used, the objective is not only to investigate the response over the space, but also to locate the region where the response reaches its optimum or near-optimum value. By studying the response surface model, the combination of factors (*i.e.*, the values of the independent variables) which gives the optimal response can be obtained.

- The steps by which the response surface method should be undertaken can be summarized as follows:
- Conduct the experiment with the independent variables varying around the present operating point.
- Obtain a fitted equation with data obtained in the experiment. Normally, regression methods are used in this step. Frequently, a linear model represents the model sufficiently well.
- Move the experimental point in the direction of steepest ascent (or descent if a minimum is sought) and repeat the previous steps.
- When little improvement is obtained, the optimum is near.
- Conduct a 3-level factorial experiment around this point.
- Obtain a fitted quadratic equation by regression methods.
- Based on this quadratic equation, determine the optimum.
- Conduct further experiments to verify the obtained results.

Previously, if there are a lot of possible input factors, a screening experiment should to be conducted in order to eliminate the less important factors.

Obtaining the optimal values of the independent variables can be very complicated if, instead of a simple response, more than one response is sought (multi-response).

Reaching the optimum is even more difficult when the response involves several independent process variables that often are constrained to a certain range in certain parameters.

For the case in which more than one response is taken into account, a response surface model is built for each response. Then, a set of operating parameters that optimizes all the responses within their range is selected.

Finally, the contour plots of all the responses are overlaid and the best operating point or range is selected. With the increase of both the number of responses and the number of independent process variables, the search space becomes more complex.

In addition, the optimal values of the process variables can differ or contradict one another. A consequence of this is that the search space is even more complex with multiple constraints and many local optimal points.

All these facts make it more and more difficult to apply traditional mathematical methods (such as the steepest ascent) that search for the global (or near global) optimum.

To overcome these problems Genetic Algorithms have been applied to the optimization of response surfaces with good results.

### **Box-Behnken Design**

Box-Behnken designs are response surface designs, specially made to require only 3 levels, coded as -1, 0, and +1. Box-Behnken designs are available for 3 to 21 factors. They are formed by combining two-level factorial designs with incomplete block designs. This procedure creates designs with desirable statistical properties but, most importantly, with only a fraction of the experiments required for a three-level factorial. Because there are only three levels, the quadratic model is appropriate.

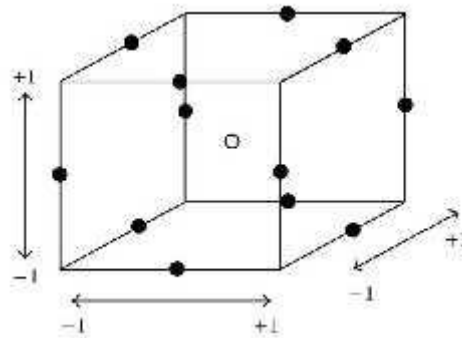
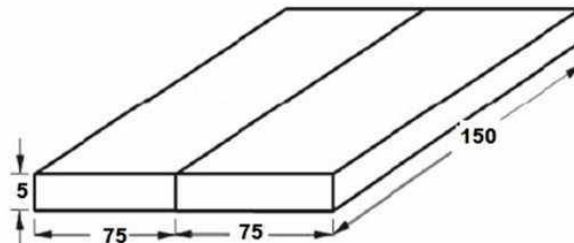


Fig 2. Box-Behnken design for three factors represented in cube

#### IV. EXPERIMENTAL CALCULATION

Test plates of size 150 mm x 75 mm x 5 mm were prepared from Al 6061 by using cutting machine.



#### Plan of Investigation

The project work carried out in the following steps:

1. Identifying the important process parameter.
2. Finding the upper and lower limits of the process parameter Viz. Spindle speed (N), Welding speed (W), Plunge Depth(Pd)
3. Development of design matrix.
4. Conducting the experiments as per the design matrix.
5. Recording the responses. Viz. Yield strength
6. Development of the mathematical model
7. Presenting the effects of the process parameters on the mechanical properties in graphical form and analyzing the results.

#### Process Parameters

Based on preliminary trials, the independent process parameters affecting the Yield strength of the weld specimens were identified as,

1. Spindle speed (N)
2. Welding speed (W)

### 3. Plunge Depth(Pd)

#### Spindle speed

Spindle speeds of 700, 800, 900, 950, 1100 and 1500 rpm were investigated. Therefore, the lowest and the highest spindle speed values were chosen as 700 and 1100 rpm, respectively. The rotational speed between the low and high setting was chosen as rpm. Consequently, the three rotational speeds representing the low, medium and high settings in the final weld matrix were 700, 900 and 1100 rpm respectively.

#### Transverse speed

The investigated traverse speeds were 1.6,2.4,3.2,4.0,4.8mm/sec. The minimum traverse speed that caused minimal machine vibration was 1.6mm/sec, while the maximum speed where no weld defect was observed was 300 mm/min. The three speeds chosen to represent low, medium and high speeds were 1.6,2.4,3.2mm/sec respectively.

#### Plunge depth

The investigated plunge depths varied from 0, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30 and 0.35 mm. It was reported that when the tool is tilted, it gives rise to a shoulder plunge.

#### Finding the limits of Process Parameters

Trial runs are conducted to find the upper and lower limit of process parameters, by varying one of the parameter and keeping the rest of them at constant values. Feasible limits of the parameters were chosen in such a way that the joint should be free from visible defects. The upper limit of a factor was coded as +1 and lower limit as -1. The intermediate coded values being calculated from the following relationship.

$$x_i = 2[2x - (x_{max} + x_{min})] / (x_{max} - x_{min})$$

Where  $x_i$  is the required coded value of a variable  $x_i$  and  $x$  is any value of the variable from  $x_{max}$  to  $x_{min}$  is the lower limit of the variable and  $x_{max}$  is the upper limit of the variable. The selected process parameters with their limits, units and notations are given in Table 3

S.NO	PARAMETERS	-1	0	1
01	Spindle speed(rpm)	700	900	1100
02	Welding speed(mm/s)	1.6	2.4	3.2
03	Plunge depth(mm)	0.05	0.10	0.15

Table.3 Parameters and its Levels

#### Development of Design Matrix

The selected design matrix is shown in Table 4. It is a three factor three level box behnken designs consisting of 15 sets of coded conditions *i.e.*, 15 experimental runs allowed the estimation of the linear, quadratic and two way interactive effects of the process parameter on the tensile strength.

Exp No.	Spindle speed (rpm)	Welding speed (mm/s)	Plunge depth (mm)
1	0	0	0
2	0	0	0
3	-1	0	1
4	0	1	1
5	0	1	-1
6	-1	-1	0
7	0	-1	-1
8	1	0	-1
9	0	0	0
10	0	-1	1

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11	1	1	0
12	-1	1	0
13	1	0	1
14	1	-1	0
15	-1	0	-1

Table 4.Box Behnken Design Matrix

**Experimental design matrix**

Experimental runs for conducting experiments are shown in Table 4.3. As per design matrix obtained before. By using the tabulation experiments were conducted.

No of Experiments	Spindles speed (rpm)	Welding speed (mm/s)	Plunge depth (mm)
1	900	2.4	0.1
2	900	2.4	0.1
3	700	2.4	0.15
4	900	3.2	0.15
5	900	3.2	0.05
6	700	1.6	0.1
7	900	1.6	0.05
8	1100	2.4	0.05
9	900	2.4	0.1
10	900	1.6	0.15
11	1100	3.2	0.1
12	700	3.2	0.1
13	1100	2.4	0.15
14	1100	1.6	0.1
15	700	2.4	0.05

Table 5. Experimental Design Matrix

**Tool specification**

Non-consumable tools made of high carbon high chromium steel were used to fabricate the joint because of its high strength, high hot hardness, easy to process, easily available and low cost. This study uses Hexagonal these 3 x 3 combinations of friction stir tools were used for conducting experiments. Friction stir tool has two parts namely shoulder and pin. In this study shoulder diameter of 18 mm and pin diameter of 5 mm was used.



Fig 4 Tool profiles used for the experiment

**Welded Specimen**



**Fig 5 Specimen before Tensile testing(ASTM E04)**



**Fig 6 Specimens after testing**

**V. RESULTS AND DISCUSSION**

**Tensile Strength Results**

Tensile strength results for welded specimens were measured and corresponding results are shown in table 6.

No of Exp.	Spindle speed (rpm)	Welding speed (mm/s)	Plunge depth (mm)	Tensile Strength (MPa)
1	900	2.4	0.10	83.14
2	900	2.4	0.10	81.46
3	700	2.4	0.15	66.58
4	900	3.2	0.15	77.06
5	900	3.2	0.05	73.79
6	700	1.6	0.10	72.86
7	900	1.6	0.05	77.83
8	1100	2.4	0.05	64.20
9	900	2.4	0.10	84.78
10	900	1.6	0.15	78.07
11	1100	3.2	0.10	66.37



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12	700	3.2	0.10	66.47
13	1100	2.4	0.15	67.41
14	1100	1.6	0.10	83.90
15	700	2.4	0.05	70.87

**Development of Mathematical model**

Tensile strength of the joints is functions of spindle speed, welding speed,Plunge depth, and it can be expressed as

$$T = f(N, W, P)$$

Where,

T-The response

N- Spindle speed, rpm

W - Welding Speed, mm/s

P – Plunge depth, mm

For the three factors, the full quadratic equation was developed using Response Surface Methodology in Minitab 17 as follows.

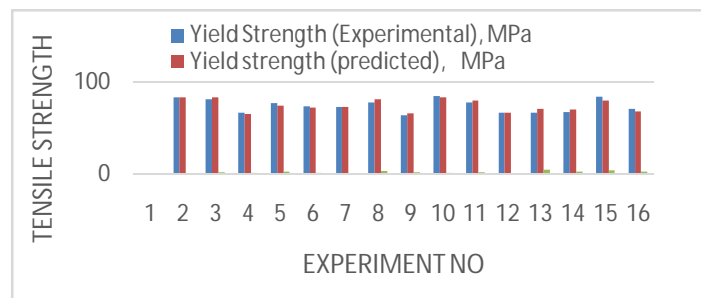
$$T = -158.7 + 0.480 N + 14.1 W + 255 P - 0.000252 N^2 - 1.02 W^2 - 2315 P^2 - 0.0174 N*W + 0.188 N*P + 18.9 W*P$$

By using above full quadratic equation predicted Tensile strength is calculated and compared with the experimental values. Percentage error was calculated using the equation Percentage error = predicted value-experimental value and tabulated in Table 5.2.

By using the Experimental values and Predicted values from the Table 5.2 a comparison graph was drawn and shown in Fig 5.1

Expt No	Tensile Strength (Experimental), MPa	Tensile strength (predicted), MPa	Percentage error
1	83.14	83.3668	0.2268
2	81.46	83.3668	1.9068
3	66.58	65.2500	1.33
4	77.06	74.3545	2.7055
5	73.79	72.1865	1.6035
6	72.86	72.8148	0.0452
7	77.83	81.0073	3.1773
8	64.20	65.9793	1.7793
9	84.78	83.3668	1.4132
10	78.07	80.1513	2.0813
11	66.37	66.8820	0.512
12	66.47	71.0740	4.604
13	67.41	70.3953	2.9853
14	83.90	79.7588	4.1412
15	70.87	68.3233	2.5467

**COMPARISON OF EXPERIMENTAL TENSILE STRENGTH, PREDICTED TENSILE STRENGTH AND PERCENTAGE OF ERROR**



**VI. CONCLUSION**

Friction stir welding of aluminium alloy (AA 6061) was studied in this project. Experiments were conducted for various combinations of Spindle speed, Welding speed, and plunge depth at 3 levels using box benhken method. Tensile strength of the weld examined using universal testing machine and the Microstructure of the joint was analyzed using optical microscope. Mathematical model was developed based on the results to predict tensile strength.

The following observations are made from the studies:

1. The increase in spindle speed, welding speed, plunge depth results in increase in the Tensile strength and it reaches maximum and then decreases.
2. In parent material large grain are seen without affected by thermo mechanical treatment.
3. In heat affected zone higher grain size in contact with welded zone. Also extended grains due to thermo mechanical effect can be seen at both advancing and retreating sides of the weld area.
4. In the weld zone fine grains are seen.

Using the results, optimal result carried out using Minitab 17. The optimal setting for obtaining maximum tensile strength be spindle speed as 900 rpm, welding speed as 2.4 mm/s, plunge depth as 0.10mm. The response (tensile strength) for this optimal solution is “84.78Mpa”

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