

Design and Analysis of Friction Stir Welding Using Dissimilar Alloys (AA 6061 and AA 6082) Aluminum Alloys

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Abstract: Friction stir welding (FSW) is a new solid-state joining process and this joining technique is energy efficient, versatile and environment friendly. Frequently it can be used to join high-strength aerospace aluminum alloys and other metallic alloys that are hard to weld by conventional fusion welding. FSW is considered to be the most significant development in metal joining in a decade. The scope of this investigation is to evaluate and experiment the effect of joining parameters on the mechanical properties of dissimilar aluminum alloys (AA 6082 and AA 6061 Aluminum Alloy) joints produced using friction stir welding. Friction stir weld was performed on the dissimilar aluminum alloys using different rotational speeds and traverse speeds and the influence of these parameters on the mechanical performance of the weld has been investigated in terms of hardness, tensile testing and statistical analysis.

Key Words: Friction stir welding, RSM, Al Alloy 6061, Al Alloy 6082.

1. Introduction

Friction stir welding (FSW) is a relatively new and promising solid state joining process developed and patented by The Welding Institute (TWI), Cambridge, U.K., Figure 1.1 shows the schematic drawing of FSW process. The work piece is placed on a backup plate and clamped rigidly by a fixture to prevent lateral movement during FSW. A specially designed frustum shaped tool with a pin extending from the shoulder is rotated with a speed of several hundred rpm and slowly pushed into the joining line. The pin usually has a diameter one-third of the shoulder and typically has a length slight less than the thickness of the work piece. The pin is forced into the work piece at the joint until the shoulder contact the surface of the work piece (figure 1.2 a). As the tool descends further, its surface friction with work piece creates more heat and later plasticizes a cylindrical metal column near the inserted pin and the immediate material under the shoulder. The weld usually thins the parent metal by about 3-6 % of original thickness. The work piece to be joined and the tool are moved are similar to each other such that the tool tracks along the weld interface and the rotating tool provides the ‘stir’ action. The plasticizing metal within a narrow zone moves while transporting metal from the leading face of the pin to the trailing edges. As the tool passes, the weld cools, thereby joining the two plates together (figure 1.2 b). On tool extraction a hole is left as the tool is withdrawn from the work piece (figure 1.2 c).

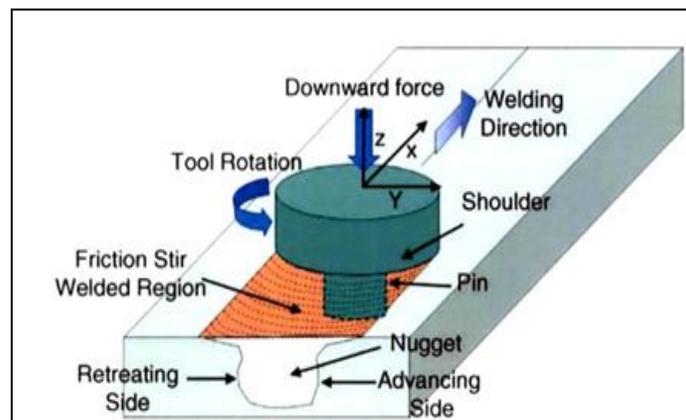


Figure 1.1 Schematic drawing of friction stir welding

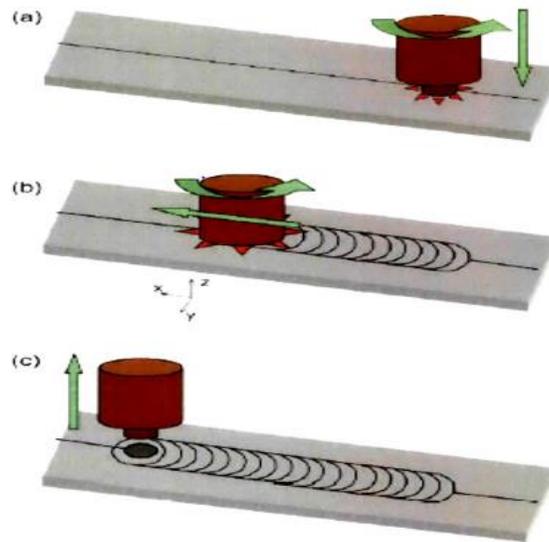


Figure 1.2 Description of the three main stages of FSW (a) plunge phase (b) translational and rotational motion of the tool through the plates (c) tool extraction

2. Principle of friction stir welding

The basic principal of Friction stir welding is heating the metal to a temperature below re-crystallization temperature using Friction generated by the cylindrical shouldered tool on metal. This tool having characteristic profile pin, which is rotated and pushed into the joint area between two pieces of sheet or the plate material. The parts have to be done secure clamping using the fixtures to prevent the joint faces from being forced apart. The Frictional heat is produced between the wear-resistant welding tool and the experimental work pieces, which causes the metals or alloys to soften without reaching the melting point. The tool moves along the joint line of the work materials. The plasticized material gets transferred to the moving edge of the tool pin and forced through similar contact with the tool shoulder and pin profile. The cooling of the material leads to the creation of a solid phase bond between the clamped work pieces.

3. Properties of material Aluminum Alloys AA 6082 and AA 6061 and process parameters

The test plates of size 160 mm X 80 mm X 8 mm are prepared from aluminum alloy AA6082 plates using CNC cutting machine. The chemical composition and mechanical properties of the base material are presented in Table 1 and Table 2, respectively.

3.1 Chemical Composition

Table 1. Chemical composition of aluminum alloy 6082 and 6061

Elements	Mg	Mn	Fe	Si	Cu	Cr	Al
6061	1.1	0.12	0.35	0.58	0.22	0.04	Bal
6082	0.60-1.20	0.40-1.00	0.50	0.70-1.30	0.10	0.25	95.2-98.3

3.2 Physical Properties

Table 2. Physical properties of aluminum alloy 6082 and 6061

Base metal	Density(kg/m ³)	Melting temp °C	Modulus of elasticity GPa	Poisson's Ratio
6061	2700	580	69	0.33
6082	2710	555	69	0.33

3.3 Mechanical Properties

Table 3. Mechanical properties of aluminum alloy 6082 and 6061

Base Metal	Yield stress, Mpa	Ultimate tensile strength, Mpa	Hardness number, BHN	Elongation %
6061	235	283	95	10-13 %
6082	250	140 to 330	95	10%

4. Welding Tool

The welding tool of FSW plays a prominent role welding process which has an impact in the mechanical properties and quality of microstructure of the material. Therefore the tool is designed carefully which may alter the weld quality. The tool should have idealistic and higher mechanical properties than weld materials. The difficulties associated are mainly with finding proper tool material. The experiment is conducted using FSW machine shown in Fig. 1 to fabricate the joints. The welding was done by single pass.



Fig 1. FSW machine



Fig 2. Tool pin profile

From the different tool materials like tool steel, carbon boron nitride, carbide, high carbon, high speed steel and high chromium steel (HCHCr). H13 is chosen as tool material because of its high strength, high hot hardness, easy to process, easily available and low cost. The FSW tools are manufactured using CNC Turning center and wire cut EDM machine. Fig 3 shows the tool designing and experimentation of the tool with the help of solid works auto desk.

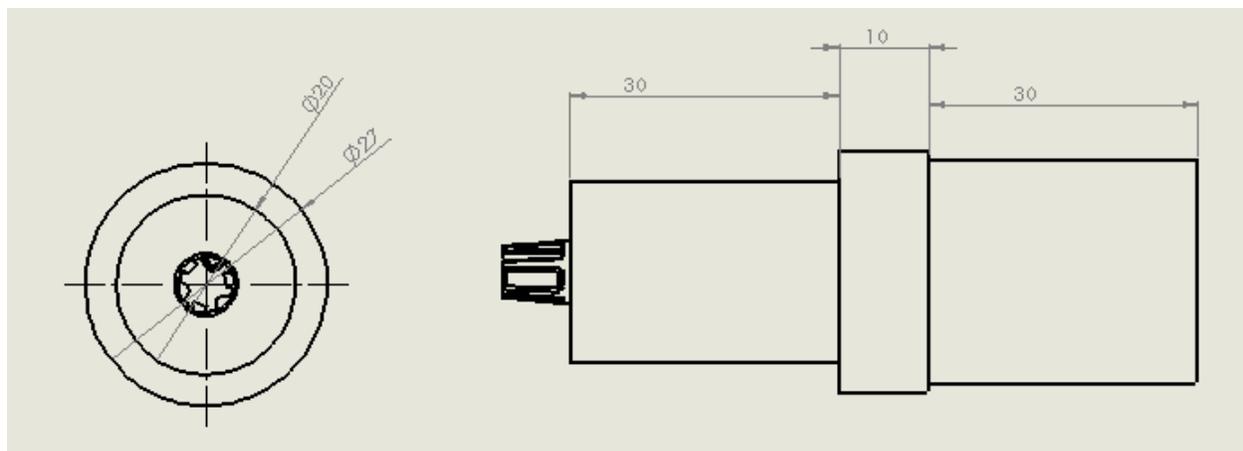


Fig 3. Tool designed using solid works software

The friction stirring tool consists of a pin, or probe, and a shoulder. Contact of the pin with the work piece creates frictional and deformational heating and softens the work piece material; contacting the shoulder to the work piece increases the work piece heating, expands the zone of softened material, and constrains the deformed material. Fig 4. shows the most important tool parts.

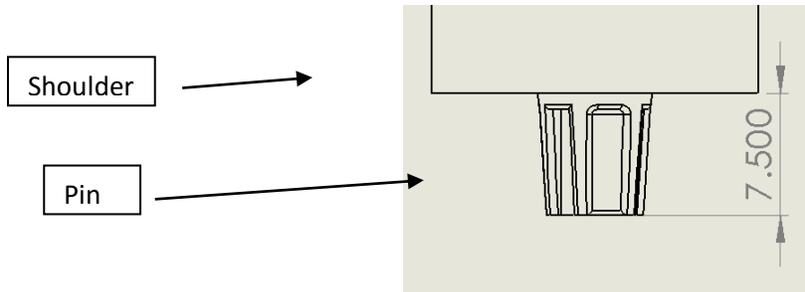


Fig 4. Tool pin and important parts

Naturally, the important effects to the tool during welding are high temperature, abrasive wear and dynamic effects. Therefore, the good tool materials will be having the properties of good wear resistance, high temperature strength, temperature resistance, good toughness.

5. Plan of Investigation

The follow a line of investigation work was to be carried out in the following steps:

1. Identifying the imperative process parameter.
2. Finding the upper and lower limits of the process parameter Viz. tool rotational speed (N), welding speed (S), and axial force (F)
3. Development of design matrix
4. Conducting the experiments as per the design matrix
5. Recording the responses, viz. Ultimate Tensile Strength (UTS), Yield Strength (YS), Percentage of Elongation (POE)
6. Development of the mathematical model
7. Checking the satisfactoriness of the models developed
8. Conducting the consistency test runs and comparing the results.
9. Presenting the special effects of the process parameters on the mechanical properties in graphical form and analyzing the results.

5.1 Important process parameter

Based on initial trials, the independent process parameters affecting the mechanical properties were identified as: tool rotational speed (N), welding speed (S) and Tilt angle (T)

5.2 Finding the limits of control variable

Test 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. The upper limit of a factor was coded as +2 and lower limit as -2. The intermediate coded values being calculated from the following relationship

$$X_i = 2 \frac{2X - (X_{max} + X_{min})}{(X_{max} - X_{min})}$$

Where X_i is the required coded value of a variable X; and X is any value of the variable from X_{min} to X_{max} , 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 4.

Table 4 : Process parameter and its levels

Std	1	2	3	4	5	6	7	8	9
Tool Speed	900	1120	1120	1120	1120	1120	1400	1400	1400
Feed rate	100	60	80	100	125	165	80	100	125
Degree	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

5.3 Development of Design Matrix

The selected design matrix is shown in Table 5. It is a three factor five level central composite rotatable designs consisting of 20 sets of coded conditions composed of a full factorial $2^3 = 8$, plus 6 centre points and 6 star points thus 20 experimental runs allowed the estimation of the linear, quadratic and two way interactive effects of the process parameter on the mechanical properties.

5.4. Conducting the experiment as per the design matrix

The experiments were conducted as per the design matrix at random, to avoid the possibility of systematic errors infiltrating in to the system.

5.5 Recording of the responses

Tensile test specimens are prepared as per ASTM E8 standard shown in Fig. 6 and transverse tensile properties such as ultimate tensile strength, yield strength, and percentage of elongation of the FS welded joints are evaluated using computerized UTM. For each welded plate, three specimens are prepared and tested. Fig. 5 shows tensile specimen after fracture of weld. The average values of the results obtained from those specimens are tabulated and presented in Table 5

Fig 5. Typical tensile specimen



Fig 6. Tensile specimen after fracture



Table 5: Estimated mechanical properties

Std	UTS N/mm2	Elongation %	Yield Stress N/mm2
1	196.941	9.520	181.262
2	181.888	8.720	151.767
3	190.237	7.960	155.051
4	199.403	9.560	161.194
5	182.157	7.000	177.446
6	169.984	5.560	143.312
7	108.138	1.920	98.476
8	195.351	7.520	159.015
9	201.178	8.980	184.574

5.6 Development of mathematical model

Ultimate tensile strength, yield strength, and percentage of elongation of the joints are functions of rotational speed, welding speed, and tilt angle and it can be expressed as

$$Y = f(N, S, T)$$

Where

Y-The response

N- Rotational speed, rpm

S- Welding Speed, mm/s

T-Tilt angle, degrees

For the three factors, the selected polynomial (regression) could be expressed as

$$UTS = 713.416 + -0.683336 * \text{Tool Rotation} + -1.69573 * \text{Weld Feed} + -0.00125722 * \text{Tool Rotation} * \text{Weld Feed} + 0.000305072 * \text{Tool Rotation}^2 + 0.0168008 * \text{Weld Feed}^2$$

$$YS = -69.434 + 0.134205 * \text{Tool Rotation} + 3.0318 * \text{Weld Feed} + -0.00423627 * \text{Tool Rotation} * \text{Weld Feed} + 0.000100582 * \text{Tool Rotation}^2 + 0.0130571 * \text{Weld Feed}^2$$

$$EL = 62.7155 + -0.0531229 * \text{Tool Rotation} + -0.414824 * \text{Weld Feed} + -4.7619e-05 * \text{Tool Rotation} * \text{Weld Feed} + 2.21365e-05 * \text{Tool Rotation}^2 + 0.00234346 * \text{Weld Feed}^2$$

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

DESIGN EXPERT 9 software packages are used to calculate the values of those coefficients for different responses and are presented in Table 5. After determining the coefficients, the mathematical models are developed.

5.7 Developed final mathematical model

The developed final mathematical model equations in the coded form are given below table 6

Regression Coefficient	Ultimate tensile strength	Yield stress	Elongation
A	295.61	339.73	0.7727
B	109.38	556.86	0.1263
AB	62.73	712.28	0.0900
A²	248.72	27.04	1.31
B²	503.25	303.96	9.79

$$UTS = 177.077 + -6.07871 * A + 3.69766 * B + -3.96025 * AB + 5.97941 * A^2 + 8.50541 * B^2$$

$$YS = 160.174 + -6.51657 * A + 8.34312 * B + -13.3442 * AB + 1.9714 * A^2 + 6.61015 * B^2$$

$$EL = 7.87308 + -0.31079 * A + 0.125659 * B + -0.15 * AB$$

5.8 Checking the adequacy of the developed model

The adequacy of the models so developed is then tested by using the analysis of variance technique (ANOVA). Using this technique, it is found that calculated F ratios are larger than the tabulated values at a 95% confidence level; hence, the models are considered to be adequate. Another criterion that is commonly used to illustrate the adequacy of a fitted regression model is the coefficient of determination (R²). For the models developed, the calculated R² values and adjusted R² values are above 70%. These values indicate that the regression models are quite adequate. The results of the ANOVA are given in Table 6. The validity of regression models developed is further tested by drawing scatter diagrams. Typical scatter diagrams for all the models are presented in Fig. 7-9. The observed values and predicted values of the responses are scattered close to the 45° line, indicating an almost perfect fit of the developed empirical models.

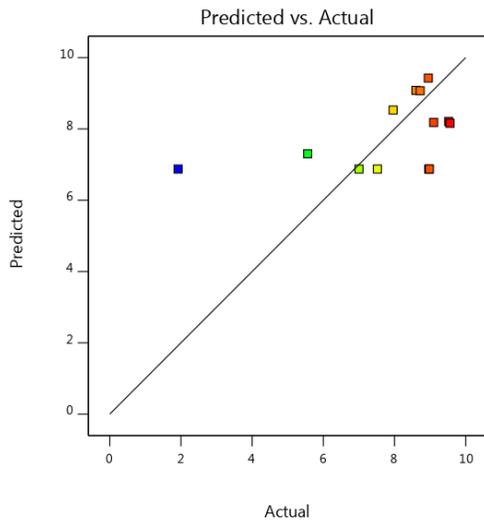


Fig. 7: Scatter diagram of the ultimate Tensile strength, Mpa

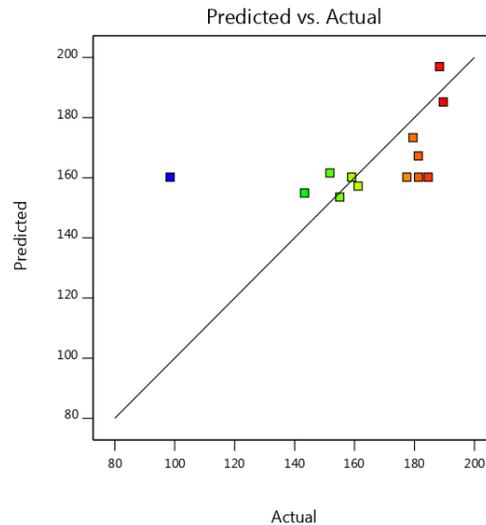


Fig. 7: Scatter diagram of the yield stress

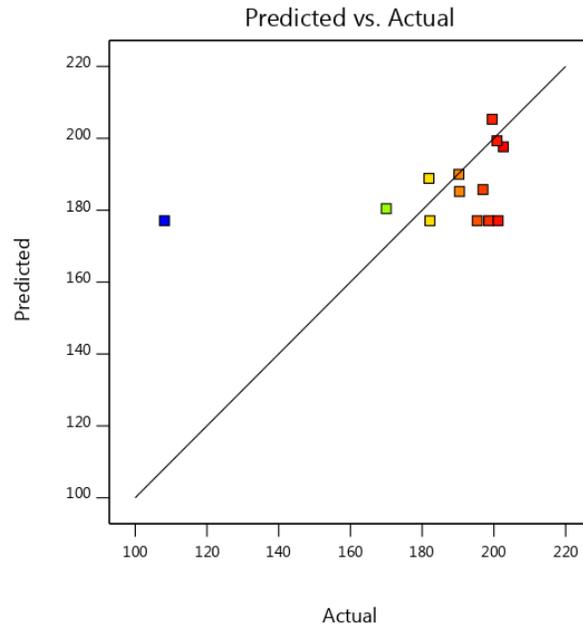


Fig. 9: Scatter diagram of the percentage of elongation.

Table 7: ANOVA test results

Response	Sum of squares		Degree of freedom		Mean square		F - value	P - value
	Model	Residual	Model	Residual	Model	Residual		
UTS	1921.53	5727.24	5	7	384.31	818.18	0.4697	0.7887
YS	1921.53	5727.24	5	7	384.31	818.18	0.4697	0.7887
EL	11.33	42.23	5	7	2.27	6.03	0.3757	0.8507

6. Analysis of the Results

The effects of the different process parameter on the mechanical properties of FS welded aluminum alloy AA6082 and AA6061 are predicted from the mathematical models using the experimental interpretation are available in Figures 10 showing the general trends between cause and effect. Effect of rotational speed (N) Fig. 10 shows the direct outcome of rotational speed on mechanical properties. It is seen that as the rotational speed increases the tensile strength, yield strength and percentage of elongation of FS welded aluminum alloy AA6082 and AA6061 increases and then it decreases. The highest rotational speed results in the metallurgical transformation such as solubilisation, re-precipitation, and coarsening of strengthening precipitates at the weld zone and lowering of dislocation density which decrease the tensile strength of the FS welded joints. It is clear that in FSW as the rotational speed increases the heat input also increases. More heat input destroys the regular flow behavior.

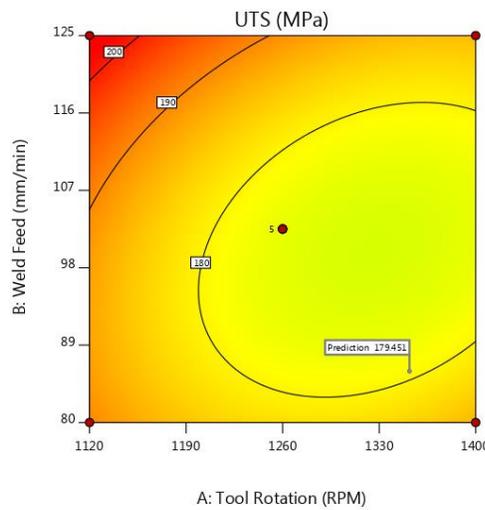


Fig 10. Effect of tool rotation on properties

Confirmation experiments

Experiments are conducted to verify the regression equations of UTS, YS and EL. Nine weld runs are made using different values of rotational speed, welding speed and tilt angle other than what were used in the design matrix. The results obtained are quite satisfactory and the details are presented in Table 8

Table 8: Confirmation results

Response	Predicted mean	Predicted Median	Standard Deviation	SE Prediction	95% PI Low	95% PI High
UTS	177.077	177.077	30.5323	33.4465	97.9885	256.165
YS	160.174	160.174	28.6038	31.3339	86.0813	234.267
EL	6.876	6.876	2.45612	2.69055	0.513861	13.2381

7. Conclusions

The following conclusions are arrived at from the above investigations.

1. The relations between process parameters for FS welding of AA6082 and AA6061 aluminum alloy have been established. The response surface methodology was adopted to develop the regression models, which were checked for their adequacy using ANOVA test, scatter diagrams and found to be satisfactory.
2. Confirmation tests have shown the development model is reasonably correct.
3. The increase in the tool rotational speed, welding speed and tilt angle to the increase in the ultimate tensile strength and it reaches a maximum value and then it decreases. This inclination is common for yield strength and percentage of elongation.

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