Effects of Friction Stir Welding Parameters of Dissimilar Aluminum Alloys on Residual Stress and Microhardness

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\textbf{Abstract.} The aim of this research is to use a full factorial design to determine the significant factors of friction stir welding (FSW) process of dissimilar AA6061-T6 and AA7075-T651 aluminum alloys, on the surface residual stress and microhardness. There are a total of three factors studied: rotation speed, welding speed and workpiece layout. The results showed that the factors that have a statistically significant effect on residual stress occurring are welding speed, workpiece layout and interaction between rotation speed and welding speed. The appropriate parameters for FSW process of dissimilar aluminum alloys are rotation speed of 1400 rpm, welding speed of 50 mm/min and the layout of the workpiece by advancing side (AS) uses AA6061-T6 sheet, while retreating side (RS) uses AA7075-T651 sheet, which will result in the surface residual stress of -34.33 MPa. This compressive residual stress will be beneficial to the welded joint for retard the occurrence of cracks caused by fatigue. The hardness of all workpieces have similar tendency, thermo-mechanically affected zone (TMAZ) area in both AS and RS gave the least hardness, which found that the AA6061-T6 and AA7075-T651 sheets had a hardness of approximately 55HV and 110HV respectively.

1. Introduction

Friction stir welding (FSW) has been invented and developed by The Welding Institute (TWI), United Kingdom, 1991. FSW is widely used in automotive, shipbuilding, trains and aerospace applications, which mainly used in the welding of aluminum alloys and can be welded to dissimilar materials. On the other hand, it is well known that welding different types of aluminum alloys is difficult to weld using the traditional fusion welding [1, 2]. Therefore, the welding of different types of aluminum alloys is preferable to use FSW, which consists of many factors such as rotation speed, welding speed, characteristics of welding tool, tilt angle, etc. These factors all affect the properties and quality of the welded joint. Now a day, these factors are still being studied continuously [3–5]. One of the most interesting response of welded joint is the surface residual stress as well as microhardness, as they play an important role in cyclic applications where most of the welds are damaged due to fatigue [6, 7]. The compressive residual stress will be beneficial, which increases fatigue life and retard cracks initiation. Thus, residual stress determination is performed using X-ray diffraction (XRD) method, which is widely used method and does not need to destroy the workpiece. The experimental design method is a powerful method that can be used to study the factors that affect surface residual stress and microhardness [8–10]. In this research, the $2^3$ full factorial design experiment will be used for determining significant factors of three FSW process parameters: rotation speed, welding speed and workpiece layout, to the residual stresses occurred and microhardness after the FSW process.
2. Experimental Procedure

2.1. Materials
This research uses dissimilar materials which are AA7075-T651 and AA6061-T6 aluminum alloy, with each piece having a width of 100 mm, length of 200 mm and thickness of 6.5 mm. The chemical composition measured by the energy dispersive X-ray fluorescence (EDXRF) method, as shown in Table 1. The prepared workpiece will be welded in a single pass and using a square butt joint. For FSW tools made from tool steel AISI H13 or equivalent to DIN1.2344 or JIS SKD61, which have 6x6 mm square pins, the length of pin 6 mm and the tool shoulder 18 mm, this tool has a hardness of approximately 55 HRC after the heat treatment process.

Table 1. Chemical composition of AA7075-T651 and AA6061-T6 aluminum alloys.

| Alloys          | Elements ( % w/w) |
|-----------------|-------------------|
|                 | Cu    | Mn    | Mg    | Zn    | Cr    | Fe    | Si    | Al     |
| AA7075-T651     | 1.83   | 0.09  | 4.95  | 7.39  | 0.32  | 0.37  | -     | Balance |
| AA6061-T6       | 0.34   | 0.16  | -     | 7.39  | 0.32  | 0.37  | 0.64  | 0.84   | Balance |

2.2. Design of Experiment of Friction Stir Welding
In this research, the FSW process was done with the CNC machining center Bridgeport VMC500 and the schematic diagram of FSW process, as shown in Figure 1. For the design of this experiment used a full factorial design of 2^3 by 2 replication total of 16 experiments with three factors: rotation speed, welding speed and workpiece layout each factor consists of a low and high levels where the desired response is the surface residual stress at the middle of the weld beat, as shown in Table 2.

![Schematic diagram of FSW process](image)

Figure 1. Schematic diagram of FSW process.

Table 2. Full factorial design of FSW process.

| Factors            | Unit  | Level | Low (-1) | High (+1) |
|--------------------|-------|-------|----------|-----------|
| Rotation speed     | rpm   | 1.000 | 1.400    |           |
| Welding speed      | mm/min| 30    | 50       |           |
| Workpiece layout   | -     | Layout A a | Layout B b |

a AS uses a piece AA6061-T6 and RS uses a piece AA7075-T651
b AS uses a piece AA7075-T651 and RS uses a piece AA6061-T6
2.3. Residual Stress Measurement

For surface residual stress from FSW workpieces will be obtained from XRD with \(\sin^2\psi\) method, which is a non-destructive method, by Stress-tech XSTRESS 3000 equipped with a Chromium tube source radiation. Eleven tilt angles were used both positive and negative values \((0, 18.4^\circ, 26.6^\circ, 33.2^\circ, 39.2^\circ, 45^\circ)\) and temperature during measurement about 25 °C. The location for measurement surface residual stresses by using XRD is at the welding center line of longitudinal direction.

2.4. Microhardness Measurement

Vickers microhardness value of workpieces will be obtained from Startec SMV-1000 machine with apply force about 1.961N or HV0.2, holding time 10 sec and using a magnification of 100X for measuring the width of the pressing mark. Then, preparing and polishing the cross section area of workpiece for measure the hardness from the center of the friction stir welding to the left and right, as shown in Figure 2. Each side measured 6 positions, totalling 13 positions, each position 2 mm apart and measured two times to find the average.

![Figure 2. Position for measuring microhardness.](image)

3. Results and Discussion

3.1. Residual Stress and Experimental Design Results

From a visual inspection through the microscope, it was found that the welded area of all FSW workpiece according to the experimental design had no defects occur, both aluminum alloys are well bonded, no cracks or bubbles are found, as shown in Figure 3. For the result of surface residual stress obtained from the XRD measurements according to the full factorial design measuring were found to have both tensile residual stress (positive value) and compressive residual stress (negative value), as shown in Table 3, which is different from the traditional fusion welding (MIG or TIG welding) that the middle of the weld beat gives tensile residual stress. This FSW workpieces shows that the welded joint is likely to be a longer fatigue life than the welded joint by traditional fusion welding methods due to surface residual stress. The analysis of experimental design was performed by the statistical software MINITAB, according to the results, as shown in Figure 4, indicating that welding speed, workpiece layout and interaction between rotation speed and welding speed were statistically significant factors (p-value < 0.05), the adjusted coefficient of determination \((R^2)\) was 68.47%, indicating that the model was sufficient to fit the data. The validation of the data, as shown in Figure 5. The Normal Probability Plot graph found that the residual data of the residual stress tends to be linear because the points of the residues are arranged in a straight line. The Histogram graph found that the residual data of the residual stress values had a normal distribution, which the characteristics of the graph were similar to the bell-shaped. The Versus Fits graph found that the residual data were scattered evenly and do not have a clear trend pattern, therefore the residual data have independent of predicted values. The Versus Order graph found that the residual data were distributed consistently and did not have a clear trend, therefore the residual data have independent of the experiment sequence. The results of the analysis of variance (ANOVA), as shown in Table 4, found that the lack of fit was insignificant because the p-value of lack of fit is greater than the significance level 0.05, meaning that the equation is suitable for the experimental results and for the p-value (at the significant level 0.05) of
the main effects: welding speed, workpiece layout and 2-way interactions between rotation speed and welding speed were less than 0.05, therefore those effects were significant factors which then be used to construct the regression equation for predicting the surface residual stress. The equation for predicting the surface residual stress at the middle of weld beat obtained from the regression analysis of factors that have a significant, as shown in Equation (1).

\[
\text{Residual stress} = -2.74 - 8.55(\text{Welding speed}) + 11.68(\text{Workpiece layout}) \\
- 11.36(\text{Rotation speed} \times \text{Welding speed})
\] (1)

Using Equation (1), the surface residual stress was calculated by substitute the value +1, +1 and -1 to rotation speed, welding speed and workpiece layout respectively, which mean rotation speed = 1,400 rpm, welding speed = 50 mm/min and workpiece layout = layout A, then the most compressive surface residual stress value approximately -34.33 MPa

![FSW workpieces](image.png)

**Figure 3.** FSW workpieces.

**Table 3.** Result of surface residual stress.

| Standard Order | Run Order | Rotation speed | Welding speed | Workpiece layout | Residual stress (MPa) |
|----------------|-----------|----------------|---------------|------------------|----------------------|
| 7              | 1         | 1,000          | 50            | Layout B         | 5.3                  |
| 14             | 2         | 1,400          | 30            | Layout B         | 10.6                 |
| 8              | 3         | 1,400          | 50            | Layout B         | -3.0                 |
| 6              | 4         | 1,400          | 30            | Layout A         | 32.4                 |
| 2              | 5         | 1,400          | 30            | Layout A         | 9.5                  |
| 3              | 6         | 1,000          | 50            | Layout A         | -11.7                |
| 11             | 7         | 1,000          | 50            | Layout A         | -27.5                |
| 15             | 8         | 1,000          | 50            | Layout B         | 19.5                 |
| 9              | 9         | 1,000          | 30            | Layout A         | -14.8                |
| 4              | 10        | 1,400          | 50            | Layout A         | -21.0                |
| 5              | 11        | 1,000          | 30            | Layout B         | 1.6                  |
| 12             | 12        | 1,400          | 50            | Layout A         | -48.0                |
| 16             | 13        | 1,400          | 50            | Layout B         | -3.9                 |
| 1              | 14        | 1,000          | 30            | Layout A         | -32.7                |
| 13             | 15        | 1,000          | 30            | Layout B         | 9.0                  |
| 10             | 16        | 1,400          | 30            | Layout A         | 30.9                 |
The base material (BM) of the workpiece, located at a distance of 15 mm, found that the workpiece AA7075 T651 has an average hardness of about 100HV that closed to a standard value, while the workpiece AA7075-T651 has an average value of about 150HV, which is slightly lower than the standard. The weld nugget area near the pin produces relatively consistent hardness with AS of the workpiece AA6061-T6 and AA7075-T651, the average hardness at this area is around 60HV and 130HV, respectively. On the RS of the workpiece AA6061-T6 and AA7075-T651 have hardness for this area about 60HV and 110HV respectively. The position with the least hardness, the range from 8

### Table 4. Analysis of variance for residual stress (coded units).

| Source                          | DF | Seq SS  | Adj SS  | Adj MS  | F      | P     |
|---------------------------------|----|---------|---------|---------|--------|-------|
| Main Effects                    | 3  | 3566.6  | 3566.6  | 1188.9  | 7.51   | 0.008 |
| Rotation speed                  | 1  | 216.1   | 216.1   | 216.1   | 1.37   | 0.273 |
| Welding speed                   | 1  | 1169.6  | 1169.6  | 1169.6  | 7.39   | 0.024 |
| Workpiece layout                | 1  | 2180.9  | 2180.9  | 2180.9  | 13.78  | 0.005 |
| 2-Way Interactions              | 3  | 2538.9  | 2538.9  | 846.3   | 5.35   | 0.022 |
| Rotation speed+Welding speed    | 1  | 2065.7  | 2065.7  | 2065.7  | 13.05  | 0.006 |
| Rotation speed+Workpiece layout | 1  | 205.9   | 205.9   | 205.9   | 1.3    | 0.283 |
| Welding speed+Workpiece layout  | 1  | 267.3   | 267.3   | 267.3   | 1.69   | 0.226 |
| Residual Error                  | 9  | 1424.3  | 1424.3  | 158.3   |        |       |
| Lack of Fit                     | 1  | 179.6   | 179.6   | 179.6   | 1.15   | 0.314 |
| Pure Error                      | 8  | 1244.7  | 1244.7  | 155.6   |        |       |
| Total                           | 15 | 7529.9  |         |         |        |       |

#### 3.2. Microhardness Results

The base material (BM) of the workpiece, located at a distance of 15 mm, found that the workpiece AA6061-T6 has an average hardness of about 100HV that closed to a standard value, while the workpiece AA7075-T651 has an average value of about 150HV, which is slightly lower than the standard. The weld nugget area near the pin produces relatively consistent hardness with AS of the workpiece AA6061-T6 and AA7075-T651, the average hardness at this area is around 60HV and 130HV, respectively. On the RS of the workpiece AA6061-T6 and AA7075-T651 have hardness for this area about 60HV and 110HV respectively. The position with the least hardness, the range from 8
to 10 mm, which is the area of TMAZ on both the AS and RS of all workpieces is affected by the heat from the size of the welding tool shoulder, thus AA6061-T6 and AA7075-T651 will have an average hardness value around 55HV and 110HV respectively, as shown in Figure 6.

![Vickers Microhardness](image)

**Figure 6.** Results of Vickers microhardness.

4. Conclusions
The full factorial design was used for determining significant of FSW process parameters of dissimilar aluminum alloys to the occurrence of residual stresses and microhardness.

- Statistically significant factors of FSW process were welding speed, workpiece layout and interaction between rotation speed and welding speed.
- The appropriate FSW process parameters that will cause the minimum surface residual stress at the center of the weld beat approximately -34.33 MPa were rotation speed 1,400 rpm, welding speed 50 mm/min and workpiece layout that AS uses a piece of AA6061-T6 and RS uses a piece of AA7075-T651.
- The hardness of all workpieces have similar tendency, therefore, choosing the appropriate parameters must consider other properties together.

In the future, additional fatigue testing will be performed to find the S-N graph in order to compare stress values with the number of cycles of each workpiece.

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