Influence of D/d ratio on stir zone formation and properties of friction stir welded dissimilar joints of AA5086 and AA6061 aluminum alloys

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Abstract. A well-known method known as Friction stir welding (FSW) is used for combining materials that are distinct from each other. In FSW, a profiled spinning shoulder shifts between sheets of the sections that are to be connected. Heat is produced due to the friction between the base and the tool shoulder when the tool is turning along the weld line. In contrast to fusion welding processes, the heat produced is lower. In these works, the effect of macro/microstructures characterization and the tensile characteristics of the dissimilar AA5086 and AA6061 aluminum alloys on the ratio of tool shoulder diameter and tool pin diameter (D / d) used in the FSW were explored. This study shows the superior tensile characteristics on welding components in contrast to the counterparts made of the sealing units made using a tool profile of threaded cylinders, a 1 ° tool tilting angle, tool rotation speed of 1100 rpm, the welding speed of 22 mm / min and the shoulder diameter is 21 mm. Further, the joints fabricated using threaded cylinder tool profile exhibited superior macrostructure compared to its counterparts.

1. Introduction

Initially, friction stir was developed and designed for improved welding alloys joints at the welding institute, Cambridge, UK (TWI) in 1991[1]. FSW is a robust joining method which has been systematically developed and applied to various forms of melting material for material that is difficult for welding. Because of its many benefits, FSW’s ability to weld otherwise un-weldable alloys has become a technology with a large interest. FSW produces a solid state process in which the steel is not felt and reconditioned compared with a variety of fusion welding methods routinely used to bind structural alloys [2]. In a number of aluminum alloys, including those historically known to be un-weldable, defect less welds with strong mechanical properties were made. Frictions stir welding would not experience problems like the porosity, segregation of alloys and hot cracking; and soldering has a strong finished surface because it does not need the cleaning of post welds [3]; there has been a lot of effort to understand the impact of process parameters on material; flow behavior. The influence on research topics of significant importance are several critical components, including spinning speed, welding speed, axial power, diameter of the tool pin, diameter of the tool shoulder, the profile of the tool pin, angle of tilt on soldering properties. Most of them adopt conventional experiments to analyze the influence of the FSW method parameters where, at each time a single parameter is considered retaining the other parameters.
Aluminum AA6061 and AZ31 Magnesium Alloys were experimentally investigated by Malarvizhi et al. [7]. The findings of shoulder diameter show a superior tensile strength of 21 mm (3.50 times the plate thickness) has superior tensile characteristics relative to the others due to the joint’s strength. [8,9] dissimilar stir welding friction in AA5083-AA6082 has been studied. They have taken into account the effect on process parameters of shifts in rotation and cross speed. In both aluminum alloys AA5182-H111 and AA6016-T4, the mechanical efficiency of a related and differential friction stir weld has been evaluated [10]. The friction stir welding of dissimilar AA6061–AA5083 was studied by Shigematsu et al. [11].

They suggest that welding property is greatly affected by the material combination, such as the hardness distribution and strength of the tensile. Jamshidi Aval et al. [12] proposed that the difference in strengthening mechanism have resulted in complex comportments in AA5086 or AA6061, which in turn affect the hardness of the welded cross component. The hardness variations primarily depend upon the recovery and generation of fine grains of the weld nugget in the related joint of AA5086-O, however, the hardness variations of AA6061 / AA6061 and AA6061 / AA5086 in the weld zone joints are affected by resulting ageing phenomenon.

2. Experimental Details

AA5086 and AA6061 alloys have been mounted on the retrieval and forward side of the spinning tool as seen in the figure, with plates of 100 mm x 50 mm x 6 mm. Tables 1 and 2 respectively demonstrate the chemical composition and mechanical properties of the base metals. All joints were welded by ass and were made with high-speed steel instruments. The width of the tool shoulder was between 15 and 21 mm. The sample was 6 mm in diameter and 5.7 mm in height. The instrument was fed into the joints of the two softening plates at a steady cross rate. Tables 3 and 4 demonstrate the welding specifications and tool details. Heat input was determined by Heurtier et al. [13] using the following equation.

\[ q = \frac{2\pi}{3S} \mu * P * \omega * R_s * \eta \]

where \( q \) – specific heat input in kJ/mm; \( S \) - Welding speed; \( \mu \) – friction coefficient; \( P \)– axial force in kN; \( \omega \)– angular velocity in rps; \( R_S \)– shoulder radius and \( \eta \) – process efficiency.

Metallographic research samples were cut by a wire cut electric discharge machine perpendicular to the welding path. Both samples of welds were polished in the grit series of the following guidelines: 220, 320, 500, 800, 1200, 1500, 2000, 2500 and 3000 [14]. These samples were coated with polishing cloth 0f 75 % ethanol and 25% glycerol and polishing solutions made of alumina of 1, 0.3 and 0.05Å. In 100 ml distilled water, 2 g NaOH was pre-etched for the AA5086–AA6061 tests, and in 95 ml distilled water, rinsed in a 5 ml HNO3 solution. Even before application of the dedicated etchants, the lamellar like shear belts and other fine microstructures were carried out. Cotton swabs have been employed on the AA5086–AA6061 alloy to add this etchant. The alloy AA5086–AA6061 has used a variant of the Keller reagent that includes the same sections of methanol, HF and HNO3. The AA5086–AA6061 was spun several times before visible etching was. Optical light microscopy is used to view the etched samples for better vision. The entire welding zone containing the transition areas, base material and stir zone was examined to see the entire length at low magnification. In order to view the intercalated microstructures, the weld region was further studied at a higher length. The transversal tensile properties of joints such as production power, tensile strength, and elongation were measured by un-scoring smooth tensile specimens and notching tensile specimens. Tensile trials were conducted with 100 kN, universal test electromechanical controlled.
Figure 1. Schematic of FSW

Table 1. Shows the base metal chemical composition

| Alloys       | Mg   | Mn   | Cu   | Cr   | Si   | Fe   | Al   |
|--------------|------|------|------|------|------|------|------|
| AA6061-T6    | 1.201| 0.152| 0.201| 0.040| 0.601| 0.751| Balance |
| AA5086       | 4.123| 0.451| 0.030| 0.100| 0.240| 0.341| Balance |

Table 2. Gives the base metals mechanical properties

| Alloy        | Yield strength (MPa) | Ultimate strength (MPa) | Hardness HV 0.05 @15 Sec |
|--------------|----------------------|-------------------------|--------------------------|
| AA6061       | 260                  | 310                     | 110                      |
| AA5086       | 112                  | 250                     | 65                       |

Table 3. Parameters used in FSW process parameters for joint fabrication

| Parameter                           | Value |
|-------------------------------------|-------|
| Tool rotational speed (rpm)         | 1100  |
| Welding speed (mm/min)              | 22    |
| Axial force (kN)                    | 13    |
### Table 4. Frictions stir welding tool details

| Tool material | HSS |
|---------------|-----|
| Shoulder diameter | 15, 18, 21 mm |
| Tool pin profile | Threaded cylindrical |
| Pin diameter (major) | 6.00 mm |
| Pin diameter (minor) | 5.00 mm |
| Pin length | 5.070 mm |
| Tool inclination angle | 1° |

### 3. Experimental Discussion

#### 3.1. Macrostructure

The top surface of the welded joints (beads) is visible without defects. However, the weld cross section is considered a defect in the tunnel at low magnification. Table 5 demonstrates the macrostructure tool shoulder effect of weld cross section in terms of diameter of the instrument. A defect free joint from the three produced joints was developed with the 18 mm and 21 mm shoulder diameter. The main reason for increase in tensile strength is due to the combination of tools having a diameter of 21 mm.

### Table 5. Macrostructure tool shoulder effect on diameter

| Diameter of Tool shoulder (mm) | D / d | Weld Joint- Top structure | cross section of Macro structure joints | Remarks |
|-------------------------------|-------|--------------------------|----------------------------------------|---------|
| 15                            | 2.5   | ![Image](image1.png)     | ![Image](image2.png)                   | Defect in the Pinhole is noticed on the Retreating side because of insufficient heat input |
| 18                            | 3.0   | ![Image](image3.png)     | ![Image](image4.png)                   | Defect Free |
| 21                            | 3.5   | ![Image](image5.png)     | ![Image](image6.png)                   | Defect Free |

#### 3.2. Microstructure

Alone with optical microscopy, the cross-section of the fault free welding joint was analyzed. AA 5086 and AA 6061 are based on the base material microstructure of unlike in size and distribution as seen in the figure 2. When it passes from the base material, the grain sizes can easily be seen to decrease. A sharp demarcation then occurs where it joins the remoting field.
As the frictional heat is generated in an FSW operation, the tool shoulder is rubbed and the materials are mechanically transferred using the tool sensor. Thus, DRX of both the material is formed by the weld field. Because of this extreme plastic deformation in the sold area, solid state material is flowing and the two products are both seen in mixed flow patterns.

**Figure 2.** Macrostructure of friction stir welded surface

**Figure 3.** Aluminum alloy joint Microstructure of AA5086 – AA6061 of various dissimilar regions.
3.3 Tensile properties

The tensile test specimens and transverse tensile characteristics, such as performance power, stress strength and percentage of joints elongation were evaluated. The tensile specimen dimension is seen in the figure 4. The specimens are seen in the figure 5 before and after tensile testing. And table 6 shows values. Two specimens were checked in each condition. The joint made using a 21 mm shoulder diameter tool (3.5 times the thickness of the sheet) produced greater tensile characteristics from the three joints. The strength of the tensile joint is 183MPa, which is nearly 59% of aluminum alloy AA6061 and 73% of AA5086 aluminum alloy’s tensile strength.

![Figure 4. Dimensions of the smooth tensile specimen](image)

![Figure 5. Specimen before and after tensile testing](image)

| S.NO | D/d ratio | Tool shoulder diameter in mm | Specimen | Yield strength (Mpa) | Tensile strength (Mpa) | Elongation in gauge length (30mm) | Area Reduction (%) |
|------|-----------|------------------------------|----------|---------------------|-----------------------|----------------------------------|-------------------|
| 1    | 3         | 18                           | Smooth   | 151                 | 189                   | 10                               | 6.32              |
|      |           |                              | Smooth   | 141                 | 177                   | 6.66                             | 1.68              |
|      |           |                              | Notch    | 126                 | 158                   | 6.66                             | 7.64              |
|      |           |                              | Smooth   | 146                 | 183                   | 13.3                             | 3.97              |
| 2    | 3.5       | 21                           | Smooth   | 148                 | 185                   | 13.3                             | 2.5               |
|      |           |                              | Notch    | 160                 | 200                   | 6.66                             | 5.03              |
3.4 Micro Hardness

Hardness distribution maps were built using the FSW cross-section of the FSW joint fabricated using a method with a diameter of 21 mm (Load of 0.05 kg, load time of 15 seconds and horizontal direction interval of 1.0 mm).

| Vertical distance, mm | -10 | -9  | -8  | -7  | -6  | -5  | -4  | -3  | -2  | -1  |
|----------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1.5                  | 64.4| 76.3| 53.3| 73.1| 69.8| 62  | 78.2| 74.9| 89.7| 88.2|
| 3.0                  | 57.9| 62.3| 69.1| 58.7| 63  | 75.9| 71.3| 86.9| 86.3| 80.6|
| 4.5                  | 69.2| 68.4| 65.8| 63.2| 53.4| 45.4| 56.4| 65.6| 77.2| 71.2|

| WCL                  | AA 6061 Advancing side | AA 5086 Retreating side |
|----------------------|------------------------|-------------------------|
| 109                  | 104                    | 87.4                    |
| 80.5                 | 85.8                   | 69.1                    |
| 76.2                 | 80                     | 53.2                    |

![Graph showing hardness distribution maps for AA 6061 Advancing side and AA 5086 Retreating side at different WCL and vertical distances.]
4. Discussion

S. Malarvizhi et al. [7] studied AA6061 Aluminum and AZ31 Magnesium and recorded superior tensile characteristics compared to their counterparts for joint made with a 21 mm diameter in the shoulder with a plate thickness of 3.5 times. In FSW analysis, Colligan [16] considered that material flow in the mixing zone was due to 2 effects. The aluminum alloy material flow rate was calculated. The first one is the extraction process, which is carried out after plastic deformation by applying forces and by propelling the pin movement. The second is because of the pin rotation as the flow generator. Because of high viscosity levels the stirring effect is very different from the extrusion-induced flow. Ouyang et al. [17] examined the material flow behavior of FSW from related and diverse aluminum alloys and inferred that not all of the materials that had been affected by the stir welding pin had been 'stirred' during the soldering process. Most material movement is accomplished by simple extrusion. A modest vertical flow and material extrusions possible on either side of the pin from front to back. The rotating pin is supplied with frictional heat so that extractions are allowed. The FSW visualization on AA2024 and AA6013 aluminum alloys by Ying et al. [18] have analyzed the solid-state flow visualization and found a distinct flux of the plate content on the forward side and the backside. The material on the retreats side never reaches the revolving region by the pin, but the material on the forward sides shapes and rotates around the fluidized bed near the pin. The material on the side of the advance begins to slow down behind the pin after several revolutions. The grain structure in the stir region is representative of the idealized definition of fluid particles, which accommodates shear flows in liquid and liquid regimes [19].

5. Conclusions

From this investigation, the analysis of the three joints resulted in stronger tensile properties for the joint manufactured using a 21.00 mm shoulder-diameter method (plate's thickness is 3.5 times). The tensile strength of the 183MPa joint is about 59% of the aluminum alloy AA6061 tensile strength, as well as 73% of the aluminum alloy tensile strength of AA5086, and the elongation rate compared with the tensile strength of the alloy is 13.3% higher. The diameter of the tool's shoulder plays a critical role as the primary source of heat output. The radius of the shoulder tool has a direct proportional relationship in relation to the frictional heat generation can be obtained from the Heurtier equation, $q = \frac{2\mu}{3S} \times R_\beta$.

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