Influence of Friction Stir Welding Parameters on Mechanical Properties of dissimilar AA 7475 to AISI 304

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Abstract. Joining of dissimilar materials is difficult and challenging. Trend towards replacement of high density material (HDM) by low density material (LDM) is gaining importance in automotive industries. In the present work, friction stir welding (FSW) of high strength dissimilar materials i.e. aluminium alloy AA7475-T761 and stainless steel AISI 304 was conducted. The mechanical properties and microstructure of butt joint were investigated on using Taguchi L⁸ orthogonal array (OA). Different combinations of FSW parameters were used to obtain the maximum value of UTS. It was observed that most dominating parameter affecting UTS is tool rotational speed, contributing 42.19%, followed by traverse speed with 38.96% and shoulder diameter with 12.60%. The maximum UTS was observed 75.22% of base material AA 7475 (452MPa) under the optimum combination of parameters; tool rotational speed at 450 rpm, traverse speed 63 mm/min and shoulder diameter 14 mm. The microstructure of the resulted efficient joint shows appreciable variation in grain sizes in different zones and the micro hardness was found maximum in SZ on the retreating side.

Keywords: Aluminum, Friction Stir Welding (FSW), Mechanical Properties, Microstructure, Microhardness, Steel

1. Introduction

Recent days various transportation industries are focusing and adopting the low density material (LDM) by replacing high density material (HDM) without compromising or degrading the safety and service issues [1-2]. The LDMs are suitable as they offer low inertia and lead to fuel economy. Among LDMs, aluminium alloy (AA) finds extensive application in aerospace and transportation industries. In addition, AA offers numerous features such as good forming ability, anti-corrosive and low absorbing energy, etc. Apart LDMs, stainless steel (SS) one of HDMs, finds substantial applications in exhaust parts and fuel tanks of automotive industries [3]. In order to decline inertia and enhancing of mechanical properties, AA and SS were joined by using a green technology FSW. In 1991, FSW was established as well as patented by "The Welding Institute" (TWI), UK [4]. It is a solid-state welding process due to which it avoids number of quality issues such as distortion, porosity, alteration of...
microstructure and solidification cracks, etc., inevitable in fusion welding process [5]. FSW process is conducted using a competent fixture where both base material (BM) plates are rigidly clamped with suitable joint configuration such as butt, lap and T joint, etc. A rotating tool (non consumable) with suitable pin profile is plunged into the butt joint of the clamped plates. Rubbing action between tool shoulder and BMs generates heat; followed by plastic deformation due to stirring action of tool pin induces sufficient heat to soften the BMs. Further faying surfaces are joined continuously when tool is traversed along the joint-line. Nevertheless, limited literature was observed for the feasibility of FSW between AA and SS. Uzun et al. [6] conducted FSW of AA6013-T4 to X5CrNi18-10 stainless steel. They reported fatigue strength 30% lower than of BM AA6013-T6 without showing tensile testing results. Goel et al. [7] investigated materials mixing in friction stir welded (FSWed) joint of AA 7475 and AISI 304. They found that FSW parameters tool diameter 14 mm, tool rotation 560 rpm and traverse speed 50 mm/min renders 71% joint efficiency as compared to AA with 7.31% elongation. Jiang et al. [8] joined AA 6061 and AISI 1018 steel using FSW and obtained sound welded joint. Watanabe et al. [9] investigated joining of AA5083 and SS400 mild steel and observed maximum UTS of FSWed joint approximately to 14% lower than of BM AA5083. Habibina et al. [10] analyzed the effects of FSW parameters on AA 5050 to SS 304 and obtained joints of superior qualities by decreasing tool rotational speed 710 to 500 rpm simultaneously raising the traverse speed 40 to 80 mm/min. In addition, tool offset (up to 1.5mm) results higher UTS by avoiding voids and other defects in the SZ. Chen [11] performed optimization on FSW parameters to joining of AA 6061 and SS 400 low-carbon steel. He found good quality of UTS as well as impact values at transverse speed of 0.9 mm/s and rotational speed of 550 rpm. It is concluded from the available literature that sound quality of joint exclusively depends on FSW process parameters (PP).

Despite numerous advantages of FSW of HDMs, very few researches pertaining to high strength alloys are reported in literature. Most of the researches that have been performed are motivated to joining of LDMs i.e. AA5xxx, 6xxx series with AISI 304. 2xxx and 7xxx AAs and negligible research are reported on marine-grade AAs. The vast applications and scarcity of literature motivated us to analyze the mechanism of joining between dissimilar materials. Thus, FSW is performed on AA 7475 with AISI 304 SS with butt joint configuration. The metallurgical characteristics and tensile strength of joints were analyzed and presented. Taguchi’s L$_8$ OA is used to explore the effect of three FSW parameters viz tool rotational speed, traverse speed and shoulder diameter.

2. Experimental Procedure

In this study, AA 7475 and AISI 304 were selected as BMs. Both plates of dimension 180 × 45 × 2.5 mm were used with butt joint configuration to conduct FSW. SS and AA were placed on advancing side (AS) and retreating side (RS) respectively. The UTS of the steel and AA was 505 N/mm$^2$ and 468 N/mm$^2$ respectively. A non consumable tool of material tungsten carbide consisting cylindrical pin of diameter 4.5 mm and length 1.7 mm was used to conduct all experiments. Apart those, other parameters such as tool to plate tilt angle of 1.5°, plunge depth of 2.2 mm and tool offset were kept fixed in all experiments. The tool offset was maintained at 1.5 mm towards AA being weaker material in order to avoid
defects of tunneling and kissing bond [12]. Subsequently, acetone cleaned plates (dried condition) were placed over backing plate and clamped in the sturdy fixture. Thereafter, a retrofitted robust Vertical Milling Machine (Make: Bharat Fritz Werner, India) was used to conduct all experiments. Using wire electrical discharge machine, coupons of all experiments were cut according to ASTM E8m standard. A tensometer was used to compute UTS of all specimens. Metallographic investigation was performed on specimens using metallurgical microscope. Microhardness was evaluated using hardness testing machine at the joint mid-section by indenting a load of 2 N at 0.5mm indentation distance and delay time of 20 s. The range of FSW PP used for experimentation is shown in Table 1. Taguchi’s $L_8$ OA is considered for performing the eight experiments (shown in Table 2). Three FSW parameters viz tool rotational speed, traverse speed and shoulder diameters were considered at two levels. Subsequently, the UTS of eight joints were measured and their corresponding signal-to-noise (S/N) ratio were evaluated statistically. Using analysis of mean (ANOM) and analysis of variance (ANOVA) the optimal FSW process parameter arrangement was determined to obtain the maximum UTS.

### Table 1. FSW process parameters and their levels.

| FSW Process parameters | Symbol | Units | Levels |
|------------------------|--------|-------|--------|
| Tool rotational speed  | A      | rpm   | 450 560|
| Traverse speed         | B      | mm/min| 40 63  |
| Shoulder diameter      | C      | mm    | 12 14  |

### Table 2. UTS and S/N ratio values.

| Expt. No. | Tool rotational speed (A) | Traverse speed (B) | Shoulder diameter (C) | UTS (MPa) | S/N ratio |
|-----------|---------------------------|---------------------|------------------------|-----------|-----------|
| 1         | 1                         | 1                   | 1                      | 260.0     | 48.30     |
| 2         | 1                         | 1                   | 2                      | 259.4     | 48.28     |
| 3         | 1                         | 2                   | 1                      | 301.0     | 49.57     |
| 4         | 1                         | 2                   | 2                      | 340.0     | 50.63     |
| 5         | 2                         | 1                   | 1                      | 180.0     | 45.11     |
| 6         | 2                         | 1                   | 2                      | 230.0     | 47.23     |
| 7         | 2                         | 2                   | 1                      | 240.0     | 47.60     |
| 8         | 2                         | 2                   | 2                      | 276.0     | 48.82     |

### 3. Results and discussion

FSW experimentation under different combination of parameters was successfully conducted. Minitab software was used to analyze the collected UTS data. The FSW parameters optimization to attain high UTS is described in the following sections. Microstructure and microhardness of the sound joint (sample 4) resulted under optimal combinations of FSW PPs are detailed further.

3.1. Analysis of UTS

Effects of three PP were scrutinized on UTS through S/N ratio and ANOM techniques. In order to maximize UTS, “higher-the-better” characteristic is opted to assess the S/N ratio. All
the values of UTS with S/N ratio for different levels of FSW PP are available in Table 2. The ANOM values for UTS are given in Table 3.

Table 3. Response Table for S/N ratio (UTS)

| Process parameters | Symbol | Units | Levels | Max-Min | Rank |
|--------------------|--------|-------|--------|---------|------|
| Tool rotational speed | A | rpm | 49.19 | 47.19 | 2 | 1 |
| Traverse speed | B | mm/min | 47.23 | 49.16 | 1.93 | 2 |
| Shoulder diameter | C | mm | 47.65 | 48.74 | 1.09 | 3 |

Table 4. The ANOVA table for UTS

| Source | Sum of Squares | DF | Mean Square | F Value | P value | % Contribution |
|--------|---------------|----|-------------|---------|---------|----------------|
| A      | 8.03          | 1  | 8.03        | 26.99   | 0.036   | 42.19          |
| B      | 7.42          | 1  | 7.42        | 24.33   | 0.039   | 38.96          |
| C      | 2.40          | 1  | 2.40        | 8.06    | 0.112   | 12.60          |
| Residual | 1.19     | 4  | 0.2977     |         |         | 6.25           |
| Total  | 19.045        | 7  | 18.15       |         |         |                |

Figure 1. Main effect plots for S/N ratio (UTS).

Figure 2. Fractured tensile test coupon.

On the basis of ANOM (Table 3) it can be validated that the UTS is highly susceptible to changes in rotational speed (A). From the main effect plot (Figure 1), the optimum
combination of parameters yielding maximum UTS is \( A_1B_2C_2 \), i.e. tool rotational speed (A) at 450 rpm, traverse speed (B) 63 mm/min and shoulder diameter (C) 14 mm. The maximum UTS was observed 75.22% of base material AA 7475.

ANOVA was used to extricate the relevant conclusion from UTS values as shown in Table 4. Values of prob > P < 0.05, between 0.05 and 0.1 and above 0.1 indicate that parameters are most significant, significant and insignificant, respectively. The tool rotational speed and traverse speed were found as most significant PP (P < .05). Moreover, the percentage contribution of each parameter is evaluated to determine its importance on UTS. Table 4 shows that tool rotational speed (A) contributes maximum towards UTS by 42.19%. Another parameter, traverse speed (B) is also found as good contributor i.e. 38.96% to UTS. However, third parameter tool shoulder diameter (C) contributes marginally towards UTS (only 12.60%).

In order to establish the relation between FSW parameters and UTS, a regression analysis was also performed. This analysis delivers the relationship between process parameters and their response in terms of equation which delivers the response value (UTS). The prediction equation of the UTS in terms of existing FSW parameters was obtained as given in equation (1):

\[
UTS_{avg} = 310.8 - 141.1A + 107.9B - 43.3C - 7.8AB - 62.8AC + 26.2BC
\] (1)

The significance of the relationship between UTS and existing parameters is characterized by the value of coefficient of determination i.e. R- squared. Using equation (1), a high value of R- squared is obtained 99.54% which shows that variation in the value of UTS up to 99.54% is explained by the variation of FSW parameters values and rest very small variation (0.46%) in the value of UTS is not clarified by variation of FSW parameters values. Hence this states that a strong relationship exist between UTS and FSW parameters.

Apart this it is evident from Fig.1, UTS decreases when tool rotational speed is increased from level 1 to level 2. Higher tool rotational speed (level 2) might have generated large amount of heat which might have caused formation of IMC and grain growth [13]. However, lower tool rotational speed (level 1) might have produced sufficient heat for the consolidation of soften materials and dynamic recrystallization producing joints with fine grains [14]. The UTS increases as the value of traverse speed raises from level 1 to level 2. At very high traverse speed, tool spends lesser time of stirring due to which low amount of heat is generated. This may result in improper mixing and consolidation of the materials which may decrease strength. However at low traverse speed, material is exposed to considerable stirring action and results in high amount of heat generation along the weld line due to severe plastic deformation. Moreover, the weld zone is exposed to longer duration of high temperature heat causes formation of IMCs, grain growth which ultimately reduces the joint strength. Thus traverse speed at level 2, within the selected range of traverse speed, perhaps induced optimum generation of heat for adequate mixing of BMs in the weld zone and offered better UTS. Shoulder diameter at level 1 might not have generated sufficient heat input and caused inadequate material movement and mixing of dissimilar materials which resulted to decrease of UTS. Increase in shoulder diameter increases the area of contact with BMs. This raises the frictional heat which might be proper to soften SS and consolidates the mixing of BMs and render increment in UTS of FSWed joint [15].
3.2. Microstructure
The microstructure of AS and RS is characterized in three different zones i.e. first SZ, second thermo-mechanically affected zone (TMAZ) and third one heat-affected zone (HAZ). Micrographs of sample 4 (yielding maximum strength at optimized parameters) are shown in Figure 3. Appreciable variation in grain size is visible from the given below Figure 3. From the micrographs it is observed that fine equiaxed grain formation takes place which advocates that grain refinement has been taken substantially in the SZ due to continuous dynamic recrystallization (CDRX). In the TMAZ, the heat and strain remains less than the SZ leading to distorted /partially recrystallized along the welding direction. The highly distorted grains are observed at RS of TMAZ. Since HAZ experiences only thermal cycles, grains are found with large size as well as coarser type. The grains are generally smaller in AS side due to decrease in strain deformation rate. Coarser grain structure leading to lower strength might have been the reason for fracturing of the sample (Fig. 2) from the RS.

3.3. Microhardness
The average micro-hardness of BM was observed as 164 HV for AA 7475 and 243 HV for AISI 304. The nature of micro-hardness across the FSWed joint is characterized by the joint integrity and microstructure at different zones. Microhardness profile reveals that the maximum hardness occurs at the interface zone, which was assumed to be the presence of brittle IMCs. Microhardness distribution also implies that the considerable grain refinement takes place in the SZ due to CDRX in FSW (Figure 4). Thus, highest micro-hardness is found in SZ of RS, compared to TMAZ/HAZ. Being free from thermo-mechanical action, HAZ is exposed to heat only due to which coarse grains are formed. The resulted coarse grains attribute to low microhardness values.
4. Conclusion

FSW experimentation and optimization of welding parameters were successfully conducted on dissimilar materials AA7475-T761 and AISI 304 using Taguchi $L_8$ OA.

The results are summarized as follows:

- FSW is a competent process for joining of dissimilar materials AA to SS.
- Increment of traverse speed and decrement of tool rotational speed leads to deliver high UTS.
- UTS is largely influenced by tool rotational speed (contributes 41.29%) successively effected by shoulder diameter (contributes 38.96%).
- The optimum combination of the FSW PP is obtained as $A_1B_2C_2$, i.e., tool rotational speed 450 rpm, traverse speed 63 mm/min and shoulder diameter 14 mm which delivers maximum UTS.
- Optimized parameter combination yields to the maximum value of UTS 340MPa (75% of softer BM AA 7475).
- Significant grain refinement occurs in SZ on both AS and RS. However TMAZ of AS also confirms the considerable grain refinement. This feature attributes to the maximum strength of the joint.
- HAZ was found with non-deformed coarse grains.
- The microhardness of SZ on RS was found greater than the TMAZ, HAZ and BM.

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