Wear behaviour study of Friction Stir Welded Dissimilar Metals: AA6101-T6 and AA6351-T6 Aluminium Alloys

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Abstract. Aluminium alloys are difficult to weld together under the standard welding techniques. Among the all welding processes, friction stir welding has proved its importance in joining of different aluminium grades. In the present work, joining of two dissimilar aluminium alloys AA6101 & AA6351 has been carried out by friction stir welding process with different rotational speeds and a constant welding speed. Radiography study of the weld joint explains the defects present in the welded zone. A good quality weld zone is due to the proper selection of tool rotational speed as it helps in uniform mixing. The micro hardness test and wear behaviour were studied for the weld zone. The higher tool rotational speed of FSW reduces the wear volume due the increase in hardness of the weld zone. The SEM analysis shows the different worn out behaviour of the weld surfaces. Better burr free surfaces are obtained with the weld zones welded at high rotational speed.

Key words: Friction stir welding, micro hardness, ball on disc wear test, wear surface morphology

1. Introduction

Friction stir welding (FSW) is a solid-state joining method patented in 1991 at The Welding Institute (TWI) UK [1]. It produces high quality welds in materials like aluminum, nickel, magnesium, titanium and steel which are widely used in industries like automobiles, aerospace and shipbuilding [2]. FSW has been found suitable for joining the materials which are considered as un-weld able or difficult to weld [3]. Friction stir welding follows the simple principle of heat generation through friction and the applied force generates the required plastic flow for solid state joining. The schematic diagram of friction stir welding is shown in figure no 1. Two separate plates which are to be joined are clamped together on baking plates with a zero root gap. FSW tool which is a combination of shoulder and pin is inserted between these plates and the tool rotates between these plates and also traverses along weld direction. Friction produced during rubbing of tool with plate’s surfaces converts into heat. This frictional heat helps the work-piece material for softening and flow towards the tool rotating Direction and welding occurs [4]. The welding parameters such as tool pin profile, axial force, rotational speed and welding speed etc., plays a major role in deciding the weld quality and strength of the weld joint [5]. Won-Bae Lee et al. [6] studied the microstructures and wear property of friction stir welded AZ91 Mg alloy/SiC particles reinforced composite (AZ91/SiC/10p) and observed that the
specific wear loss was less compared to the base metal. R. Palanivel et al. [7] observed that the wear resistance increases as tool rotational speed, welding speed and axial force increases up to certain level then decreases in friction stir welded joint of two dissimilar aluminum alloy AA5083H111-AA6351T6. They also observed that the pin profile plays an important role on the strength of the weld joint. Vivek Gopi et al. [8] studied the relationship between wear rate with hardness and applied load. Prakash et al. [9] studied the tribological behavior using a computer aided pin on disc wear testing machine of friction stir processed Al 6061 sheet with metal reinforced. They observed that wear rate decreases as the weight percentage of Al2O3 increases. The SEM of wear surfaces shows tracks covered with the compact debris and delamination. Karam et al. [10] studied the possibility of joining two dissimilar alloy i.e.A319 and A413 using friction stir welding. The flash formation on upper surface, tunnel defect with the welded part. Ramulu P. Janaki et al. [11] studied the effect of process parameter on the formation of internal defects of friction stir welded joint of AA 6061 T6 of thickness 6.1 mm. They found that the defect is due to less tool plunge, insufficient heat generation and plastic deformation. They also observed that higher welding speed, higher rotation speed and higher plunge depth are preferred for producing a defect free weld. The literature review reveals that many research works are confined to the welding of similar materials and the weld characteristics. In the present study, the dissimilar aluminum alloys AA 6101-T6 and AA 6351-T6 of 6 mm thick plates are joined by FSW considering different welding parameters. The study on wear characterization and weld defects has been carried out.

2. Experimental study:
Two aluminum alloys of AA6101-T6 and AA6351-T6 series are used in this experimental work. The dimensions of aluminum plates of 150×50×6 mm (length, width, and thickness, respectively) have been used for the friction stir welding butt joint configuration. The chemical compositions and mechanical properties of these two aluminum alloys are listed in Table 1 and 2 respectively. AA6101 and AA6351 are the precipitation hardening aluminum alloys, containing magnesium and silicon as its major alloying elements, Al-Mg-Si grade alloy of the 6xxx series with a temper condition of solution heat treated and artificially aged [12]. In this work, four different joints are made by computerized friction stir welding machine shown in Figure 2. At the advancing side AA 6101-T6 was kept and in the retreating side AA6351-T6. The plates were rigidly clamped with zero root gaps to prevent separation during welding from the joint line. The FSW tool was fabricated from EN32 tool steel having a surface hardness of 65 HRC and oil hardened. The cylindrical threaded pin profile having tool tilt angle 2° has been use for this study. The flat faced shoulder diameter and pin diameter were fixed at 18 mm and 6 mm respectively. Tool geometry, welding speed and rotational speed are selected based on the previous trials and reported studies. Four welded samples are prepared with rotational speed 900 rpm, 1100 rpm, 1300 rpm, 1500 rpm and with welding speed of 60 mm/min. The welding process parameters used for study are presented in Table 3.

Table 1. The work piece alloys (chemical composition).

| Aluminum Alloys | Cu | Mg | Si | Fe | Mn | Al |
|-----------------|----|----|----|----|----|----|
| 6101 T6         | 0.05 | 0.65 | 0.5 | 0.5 | 0.03 | rest |
| 6351 T6         | 0.10 | 0.80 | 0.95 | 0.60 | 0.70 | rest |

Table 2. Mechanical properties of working alloys.

| Al Alloy | UTS (MPa) | Y.S. (MPa) | Elongation (%) | Hardness (VHN) |
|----------|-----------|------------|----------------|----------------|
| 6101T6   | 220       | 195        | 15             | 71             |
| 6351T6   | 310       | 285        | 14             | 95             |
X-Ray radiographic inspection was carried out on the welded plates using radiographic unit operated at 100 kV, 5 mA and duration of 5 seconds to determine the quality of the weldments for pores and discontinuities at weld nugget. Hardness tests are performed with a micro-hardness tester. The ball-on-disc geometry has been chosen to study wear behavior of the specimens at weld zones and base metal zones at room temperature. The dimensions of the wear specimens are 30 mm × 15 mm × 6 mm (shown in figure 3). The parameters used in the wear test are constant load of 30 N, rotational speed 200 rpm, ball radius 3 mm and test duration of 1 minute. After the test the scratch radius and depth are measured with the help of microscope for volumetric loss. The volumetric loss is computed by equation according to ASTM G 99 – 95a standard [13].

$$\text{Volume of Wear (V_w)} = \frac{1}{6} \times \pi \times h_1 \times (3 r_1^2 + h_1^2)$$

where \(V_w\) = Volume of Wear in mm³, \(h_1\) = Scratch depth in mm, \(r_1\) = Scratch radius in mm

All the tests are repeated twice and the average values have been considered. Scanning Electron Microscopy was used for studying the morphology of the worn out surfaces of the wear specimens.

### 3. Results and Discussion:

#### 3.1 Quality of weld inspection

In order to determine the quality of the weldments for pores and discontinuities at weld nugget, visual inspection and X-Ray radiographic inspection have been carried out using the digital radiography system. The X-ray was generated from the source of 100 KV of voltage, 0.5 mA of and the exposure time of 5 s.
Visual inspection was carried out to find the defects at the outer surface where as radiography test find the defects at inner surface of the welded zone. A little concavity was found on the weld surfaces have which is due to the FSW tool plunging in the surface. A small amount of flashes in the weld portion of the work pieces is also observed. A comparison of the quality of weld is given in table 4.

### 3.2. Wear behaviour studies

The ball-on-disc wear testing is carried out on the samples prepared from the weld nugget zone to find out the average wear volume and micro hardness. The average wear volume and the micro hardness are given in table 5. The wear volume of base metal is less than the wear volume of FSW weld samples. The highest and lowest SZ hardness are obtained with the welds fabricated with 1300 rpm, 60 m/min, 4kN and with 900 rpm, 60 mm/min and 8kN respectively.

**Table 4. Photographs of FSW joints and radiograph images.**

| FSW joint designations | Rotational speed (rpm) | Weld photo | Visual inspection | Radiography images | Observations                                       |
|-----------------------|------------------------|------------|-------------------|--------------------|---------------------------------------------------|
| DS1                   | 900                    |            |                   |                    | Moderate mixing, slight sign of incomplete fusion |
| DS2                   | 1100                   |            |                   |                    | Good mixing                                       |
| DS3                   | 1300                   |            |                   |                    | No evidence of voids and cracks                    |
| DS4                   | 1500                   |            |                   |                    | Sufficient mixing with complete penetration.       |

Low hardness may be due to lack of mixing of two alloys at weld nugget during welding. As the tool rotational speed increases, the hardness of the dissimilar friction stir welded joints increases first and then decreases because of better stirring of metal, coarsening and dissolution of strengthening...
precipitates during the thermal cycle of the FSW. It is observed that the specimen welded at 1300 rpm, exhibits the least wear loss due to intense plastic flow and mixing of dissimilar alloys. The wear volume of FSW samples is inversely proportional to the micro-hardness.

**Table 5.** Average wear volume (mm$^3$) and average micro hardness of wear specimens.

| FSW joint designations | Rotational speed(rpm) | Welding speed (mm/min) | Average wear volume (mm$^3$) | Average micro hardness (HV) |
|------------------------|-----------------------|------------------------|-----------------------------|-----------------------------|
| AA6101                 |                       |                        | 2.305                       | 44.5                        |
| AA6351                 |                       |                        | 1.9303                      | 58.3                        |
| DS1                   | 900                   | 60                     | 3.273                       | 47.81                       |
| DS2                   | 1100                  | 60                     | 3.1407                      | 65.3                        |
| DS3                   | 1300                  | 60                     | 2.369                       | 90.65                       |
| DS4                   | 1500                  | 60                     | 2.5525                      | 67.6                        |

Figure 4. SEM photographs of worn out surfaces.
3.3. Surface Morphology of wear specimens

SEM photographs of the worn out surfaces of the both base metals and dissimilar FSW specimens are shown in figure 4 (a-f). The worn surface is characterized by fairly long and extensive ploughing grooves. Wear debris produced are predominantly metallic and dark in colour. The SEM image of the base metal AA6101 shows the deep grooves and numerous pits, where in the AA6351 the grooves are shallow in nature and contained fewer pits. The worn surfaces of the joints welded at 1300 rpm and 1500 rpm are relatively smoother than the other two. The grooves are fine and slight plastic deformation is observed at the edge of the grooves. Granular and plate like debris particles are observed to be present in the grooves. The welded joint shows uniform wear character as compared to the parent metals.

4. Conclusions

The Friction stir welding used successfully to join dissimilar aluminum alloys (AA6101 and AA6351). The Dissimilar weld fabricated with 1300 rpm tool rotational speed, 60 mm/min weld speed and 4kNaxial force process parameters has exhibited good weld and better property against wear. The hardness increases at high tool rotational speed during welding and due to which the wear reduces. This indicates that a proper selection of the tool rotational speed is an important process parameter for getting a better wear resistant weld zone. The SEM analysis also indicates the uniform wear surface of the weld zones, welded at high tool rotational speed.

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