Effect of parametric study on microstructure during FSW process

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Abstract. The work focuses on the improvement of strength-weldability combination in Friction Stir Welding (FSW) joint of 7075 and 6061 Aluminium Alloys. Although Al-6061 and Al-7075 both are heat treatable but they are having somewhat different mechanical properties. The 7075-T6 has more tensile strength and hardness than that of 6061-T6. The lower hardness of 6061-T6 allows it to weld easily whereas 7075 prone to cracking during welding. Owing with the result that FSW could play significant role in order to improve the weldability, microstructure of cross section as well as the mechanical properties of joint was characterized. The welds were considered by using three rotational speed and three feed. It was revealed that the tensile strength of the joint (153.13 MPa) became very less in comparison to the base metal and it has been decreased again when the speed decreases from 700rpm and 15mm/sec to 2000rpm and 25mm/min. The findings such as tensile strength as well as the fracture revealed that mechanical properties and the microstructure of welding are not desirable for any structural application.

Keywords: Friction Stir Welding; Microstructure; Crack; Material Properties; rotational speed; feed

1. Introduction

Reducing weight, minimizing stress concentration at joint and finding a structure with mixed material properties is a promising demand which can be fulfilled by the combination of light weighted materials, with excellent performance especially dissimilar grades of aluminum alloy [1,2,3,4,5,6]. However, so far, no conventional fusion welding methods are there capable of joining material with high weld efficiency. FSW is a solid-state welding with parent material remaining in solid state to find a joint of such heat treatable alloys with low residual stresses and high tensile properties [10, 11, 16]. Although a number of studies on friction-stir-welded Al alloys carried out, a relatively limited work focused particularly on micro structural behavior and on how the microstructure influence in order to predict mechanical properties. Microstructure analysis in FSW has become important especially when material properties of a welded structure of two different materials are to be studied. Due to the high demand of joined dissimilar materials with mixed material properties, especially in the aerospace, railways, shipbuilding, automotive, storage tanks, marine Alloys such as AA6xxx and AA7xxx ((Al-Mg-Si alloys) and Al-Mg-Zn alloys) are most widely used [6,15]. AA7075 possesses excellent performance, corrosion resistance, low density and hence
found application in defense, aerospace, etc. Although the material carries numerous properties, fusion welding of AA7075 can have problems such as formation of dendritic structures, residual stresses, porosity, etc. [9,12,16]. Joints like riveting in dissimilar parts of 6061-T6 and 7075-T6 provides more stress and increase the weight [2]. A number of researches are also available focusing the micro structural evolution and correlation between the associated parameter-mechanical property for similar alloys [7, 11, 13, 14], the evidence with regard to dissimilar material welding is rare [9,10]. Studies also focused on different tool pin profiles with threaded pin on material flow and weld quality [3,5, 8] and finds the threaded profile tool pin provides smooth material flow and better intermixing in order to get defect free weld. Literatures support weld under square tool pin that results in defect free uniformly distributed weld with intermediate rotational speed during FSW of AA6061 alloy [4]. Several literatures investigate the influence of tool offset and placement of material for FSW of AA alloys in order to study the material flow and tensile strength. It has been investigated that tool pin profiles affects on micro structure and mechanical behavior of FSW welded joints and concluded tool pin with square shape frustum probe as superior profile in order to provide uniform mixing of material.

This work focuses on the micro structural changes when two dissimilar alloys AA6061 and AA7075 joined by the FSW process by considering best material placement position, suitable process parameters, suitable pin profile as in previous literature and finds suitability in improving the material properties such as tensile strength, hardness.

2. Experimental procedure

In the present study, aluminum 6061 (AA6061) and 7075 (AA7075) were considered as work material. Plates (AA7075-AA6061) are of 6 mm thickness with width 80mm and length of 150mm. Fig. 1 shows the experimental setup.

![Figure 1. Photographic view of the experimental setup](image)

Before experimentation, EDS (Electron Dispersive Spectroscopy) was done for the base metal (6061 and 7075) in order to determine the parent composition. The work piece was polished, and the edges were cleaned to remove oxides. The joint configuration (butt joint) was obtained by the positioning the plates by using clamp and fixture. In each experiment, at the advancing side the 6061 plate was placed and 7075 placed at retreating side. HcHCr (High carbon High chromium) D2 steel (non-consumable) with threaded cylindrical pin involved to weld the joints. The shoulder diameter considered as 18 mm keeping pin diameter and length as 6mm and 5.6mm respectively. The controlling parameters as shown in table 1 were considered for present experiment to find the effect of FSW. The procedure considered a single pass to join AA6061- AA7075.
Table 1. Controlling Parameters

| Controlling Parameters | 700  | 1400 | 2000 |
|------------------------|------|------|------|
| Rotational Speed (rpm) | 700  | 1400 | 2000 |
| Feed Rate (mm/min)     | 15   | 20   | 25   |

As shown in fig. 2, the tool has a rotating round shoulder with a cylindrical threaded pin that helps in softening the material at the joint during joining. It includes high carbon high chromium steel carrying 1.5 to 2.35% of carbon and 12% of chromium. As the threaded profile of the tool facilitates better mixing of material from the retreating to the advancing side (as given in previous literature), a cylindrical threaded tool was considered for the experiment in the present analysis. The tool’s tilt angle of welding was 1.8°. The torque and force were recorded under a frequency of 16 Hz. Before undergoing analysis through optical microscope and SEM, the samples are subjected to a solution of Etching reagents (mixture of 25 ml of Ethanol, 25 ml of Hydrochloric Acid, 25 ml of Nitric Acid, 1-3 drops of Hydrofluoric Acid). A velvet cloth with alumina powder and lavigated diamond paste was used in order to achieve mirror-like surface finish of the sample in order to make known the microstructure of Al. For tensile test three specimens cut from welded sample. All the tests were performed in Universal Testing Machine. The sample size as shown in fig. 3 was according to ASME guideline. Vickers Pyramid Number (HV) was used to measure the hardness of welding zone at various tool rotation speeds and different traverse speeds. The micro hardness test was conducted under the load of 300 g.f for 15 s at neighboring distance of about 1 mm to 1 mm.

Figure 2. 2FSW tool

3. Result and Discussion

A variation in the deformation has been seen from top side of the weld towards bottom along the thickness. It has been observed that the deformation is more at top surface. This is due to the fact that steering zone at top is under the contact with the shoulder as well as pin. At plate thickness along top to bottom direction of the weld, the rise in temperature decreases since the lower surface of the weld was continuous contact with the pin only, area of which is less than the shoulder of the tool. Also the plastic deformation is more at the nugget zone due to more heat input. At low
rotational speed intermixing of material give rise to a smooth flow of material as a result of less heat; thereby the grain size becomes finer due to better interlocking. Grain size becomes larger and irregular when speed increases to 1400rpm and then to 2000rpm as the heat input increases. The tensile strength (ultimate) and the maximum elongation of the specimens under tensile test were given in Table 2.

Table 2. Tensile strength and Elongation

| Sample No | Tensile Strength (MPa) | Elongation length (Gauge length 50 mm) | % Elongation |
|-----------|------------------------|----------------------------------------|--------------|
| 1         | 153.13                 | 56.4mm                                 | 10.4         |
| 2         | 92.43                  | 56.9mm                                 | 13.8         |
| 3         | 47.67                  | 55.2mm                                 | 12.8         |

It has been observed that all the joints have less tensile strength in comparison to parent (7075-6061) aluminum alloys. The welding joint produced low tensile strength at 700 rpm which is about 76% of that of AA7075 alloy and 60% of that of AA6061 alloy. The strength produced at 700rpm is 153.13MPa whereas with varies in speed from 700 to 1400rpm it decreases to 92.43MPa. On further increasing the speed tensile strength again decreases.

From table 2 it has been clear that the tensile strength is appreciably subjective to tool speed and feed rate and hence influences the quality and the strength of joint. Therefore as the speed varies heat input that improves the turbulent flow of the material. As insufficient material flows towards the advancing side and it results poor joint strength. Although the tensile strength of welding joint structure at nugget zone is directly influenced by the welding speed, also the aging behavior of the structure, amount of alloying element along with the grain size of second phase behaves as deciding factors for tensile strength. But such a low tensile strength is always associated with various defects like tunnel, voids, cracks etc which is revealed through micro structural analysis.

Figure 4. Microstructure specimens of base metal

AA6061

AA7075
Figure 5. Grain boundaries of dissimilar AA7075-AA6061 joint with retreating and advancing side (a) 700 rpm (b) 1400 rpm (c) 2000 rpm

Fig. 4. Shows microstructure of the parent material and fig. 5. shows the variation in the microstructure of retreating and advancing regions of friction stir zone of 7075-6061 at 700, 1400 rpm and 2000 rpm under low magnification. The SEM image of welded region shows grain density as well as the irregularity of grain shape. Large grains with loose grain arrangement has been obtained at high rotational speed in comparison to 700 rpm. Therefore, heat input and hence material flow rate is considered as an significant parameter that affect the grain growth. Simultaneously at low
rotational speed (700 rpm) and even at moderate welding speed of 20 mm/min as there is tunnel defects found as shown in fig. 6.

Figure 6. Sample with Tunnel Defect at 700 rpm

This may be due to insufficient heat input towards advancing side and improper intermixing of the material. There were no such defects seen in the specimens welded at high rotation speeds (1400 rpm & 2000 rpm). Simultaneously the fracture location supports the result of tensile strength. Fig. 7 shows SEM image of welded specimen showing three zone including the stir zone (SZ), thermo mechanically affected zone (TMAZ), and heat affected zone (HAZ). Figure shows the crack location initiates near advancing side of TMAZ which is definitely affected by the grain density and hence strain becomes localized.

Figure 7. SEM fractographs of different regions of FSW at constant feed 25 mm/min with increase of rotational speed (for a, c, e, rpm=700 rpm and for b, d, f, rpm= 1400 rpm)

Fig. 7(c) and (d), shows macrograph of TMAZ for the welded joints showing fracture location and that crack increases when rotational speed as well as feed increases. Although the grains in steering zone becomes finer than TMAZ and HAZ zone, crack starts from lower side of steering zone and then propagate through TMAZ towards HAZ zone. In HAZ heat input is there but
there is no plastic deformation. The effect of welding speed or feed on fractural evolution in the nugget, heat and thermo-mechanically affected zone are shown in fig.8.

It is cleared that the crack occurred with higher welding speed. For 700 rpm, and 15mm/min a regular surface corresponding to the different zone is present, but when the revolution as well as welding speed increases, marks of striation as well as crack reaches HAZ. Also little more dislocation crack starts at TMAZ and propagate towards SZ. Higher rotational speed as well as higher welding speed (25 mm/min) gives rise to more strain due to more heat input. At the same time upon continuous heating material becomes softens and slippery which restrict material flow towards AS from RS that causes voids in advancing side (AA6061). Therefore very high rotational speed and welding speed are not preferable. If we consider the tensile strength and the fracture behavior that concluded the effect of heat flow. The alloys were investigated to find out the solubility of the second phases and the result can be obtained from the strengthening of weld region. The micro hardness of base material 7075 and 6061 are 59.6 HV and 50.8 HV respectively. It has been seen that micro hardness of stirred zone is more than that of base metal as well as the HAZ and TMAZ zone. This is because the HAZ zone doesn’t undergo any plastic deformation but only experiences thermal cycle. The influence of tool transverse and rotational speed on micro hardness of...
the different welded sample at different zone was observed.

**Table 3.** Microhardness with rotational speed and feed

| Experiment No | Tool Rotational Speed (rpm) | Welding Speed (mm/min) | Load (gm) | Hardness (HV) |
|---------------|----------------------------|------------------------|-----------|---------------|
| 1-1           | 700                        | 15                     | 300       | 156           |
| 1-2           | 20                         | 15                     |           | 187           |
| 1-3           | 25                         | 15                     |           | 212           |
| 2-1           | 1400                       | 15                     |           | 90            |
| 2-2           | 20                         | 15                     |           | 109           |
| 2-3           | 25                         | 15                     |           | 163           |
| 3-1           | 2000                       | 15                     |           | 72.3          |
| 3-2           |                            | 20                     |           | 73.3          |
| 3-3           |                            | 25                     |           | 108           |

Table 3 depicts that how hardness value decreases when the rotational speed increases. At low rotational speed, heat is generated for short duration and cooling rate is also slow hence there is enough time for grain growth. At higher rotational speed recrystallization occur as a result of which there is variation in grain size from upper to lower surface (larger grain size at middle zone in comparison to upper and lower zone). Therefore hardness is less in comparison to lower rotational speed. At the same time with increase in traverse speed micro hardness increases. As at higher traverse speed the tool moved faster causing faster cooling which restrict the grain growth and the size of the grains are less. Hence the hardness is more. The result depicts that lower speed and tool feed have no such significant effect on joint strength and bonding.

![Figure 9. EDS analysis at low and high rotational speed](image)

As shown Fig. 9, EDS mapping indicates high amount of oxides at joints with high speed and feed rate and hence formation of oxides liable for crack creation site and prone to failure resulted in poor joint strength.
4. Conclusion

Current study follows the conclusions.

1. Investigation shows that the tensile strength decreases as a result of FSW. At low rotational speed (700rpm) and feed rate (15mm/sec) the tensile strength becomes more in comparison to higher rotational speed and welding speed. A maximum ultimate tensile strength of 153 MPa was obtained from the joint welded Joint having tool Speed as 700 rpm, welding speed of15 mm/min.

2. Very high rotational speed and feed results in inferior joining due to excessive heat generation and lead to irregular grain arrangement. Simultaneously at very low rotational speed and feed gives rise to tunnel defect for insufficient material flow towards advancing side. Therefore, an intermediate rotational speed below 1400rpm is favourable.

3. Although little fine grains are there in TMAZ, still crack initiate in TMAZ due to high tensile strength. Nugget zone shows no fracture surface where as minimum voids and crack are found at TMAZ zone.

4. Micro hardness can be improved by lowering rotational speed (700 rpm) and intermediate feed(20mm/min).

5. EDS mapping of fracture surface shows that there is presence of oxides with increase in rotational speed which is not desirable.

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