Influence of SiC Powders on Aluminium Alloy 7075-T6 Joints by Friction Stir Welding Process

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Abstract. Friction Stir Welding (FSW) is a process of joining two similar or dissimilar materials by the application of heat generated between two contact surfaces. The main advantage of FSW is that during the welding process, the materials are joined with lesser heat and increased bond strength. However, there is a lot of scope for increasing the mechanical and metallurgical properties of the weldments. Silicon Carbide (SiC) in powder form has an impact on the enhancement of mechanical and metallurgical properties. Hence, in the present work the influence of SiC powders on mechanical and metallurgical properties of AA 7075-T6 joints fabricated by single pass FSW was analysed. Totally 18 samples of friction stir welded aluminium alloy were taken, of which nine samples without SiC powders and the remaining with SiC powders. The samples were subjected to various tool speeds and traverse speeds keeping the axial force / load constant. The tool used for making the samples is high carbon steel D3 (heat treated to 58-60 HRC). During FSW process parent material gets mixed with the SiC powders due to severe stirring process in the nugget zone and powders will get distributed along the weld length. Microstructural study was conducted across various zones of welded samples (nugget zone, thermo mechanically affected zone, heat affected zone and unaffected base material) to understand the grain boundary behaviour. Scanning electron microscopic analysis (SEM) analysis was carried out in the nugget zone to determine the material flow due to stirring process and also to observe the deposition of SiC powders. Tensile strength for all the fabricated joints were evaluated and correlated with the microstructures, microhardness values of the weldments. Finally, the results of mechanical and metallurgical properties were compared with the weldments made without SiC powder and with SiC powder. It was observed that weldments made with SiC powders showed superior improvement of material behaviour in both mechanical and metallurgical properties.

1. Introduction

Friction Stir Welding (FSW) being a successful solid state joining process for both similar and dissimilar materials of varying melting points. It utilizes the heat generated by the friction produced when the tool rotates against the base material. The tool pin plunges into the material to plasticize the parent material and facilitates the material movement from the retreating side to advancing side, thus producing a strong metallurgical bond. The schematic representation of (FSW) process and tool design used in the present work is shown in Fig. 1(a) & Fig. 2. Major constraints such as high heat input, higher temperature (>Tm) restricts the application of fusion welding process in dissimilar joints. In spite of its high strength to weight ratio leads for major applications in aircraft industries [8], better corrosion resistance, etc., light alloys such as aluminium and its alloys are difficult to join using fusion methods. FSW would be a better option to solve this issue of joining and significant research works have been reported in various aluminium alloys.

Even though enough work has been reported on the effect of FSW process parameters [3, 10, 11, 14, 15], tool selection (cylindrical, triangular and square), tool pin design (straight, tapered & threaded) [12], multi-stage heat treatment and its effect on mechanical properties [4, 9, 16], continuous research is done for further improvement.
in material properties joined by FSW process. Addition of hard SiC particles with soft aluminium alloy (AA6XXX series) [18] and homogenous distribution of the same have been reported to have improved mechanical properties [6] and increase in wear resistance proportional to SiC particles in the alloy [2]. The aim of present work is an attempt to fabricate the joints without and with SiC powders by single pass friction stir welding process and the results to be correlated with both mechanical and metallurgical properties.

2. Experimental procedure

The aluminium alloy plates of T6 temper condition (AA 7075-T6) were cut to the required dimension (100 mm x 160 mm x 6.35 mm) and a single pass friction stir welding was carried out in all the trials. A cylindrical, non-consumable tool of high carbon steel D3 (heat treated to 58-60 HRC) was used for welding; the chemical compositions of both material and tool are listed in table 1 & 2. While a constant axial force / load of 8 KN was used in all experiments, three different tool rotation speed and traverse speeds were used in the present work and are listed in table 3. In order to add the SiC powders a groove has been made with 4 mm depth in the plate as shown in Fig. 1(b).

The tensile samples were wire cut electro-discharge machined to dimensions as per ASTM E8 M-04 standards as shown in Fig. 3. Standard sample preparation techniques were followed to polish the samples for microstructural analysis and were etched using Keller’s reagent (5 ml HNO3, 2 ml HF, 3 ml HCL and 190 ml distilled water).

Fig. 1. (a) schematic of FSW process; (b) schematic of plate with groove sectional view (All dimensions are in mm)
Table 1 Chemical composition (wt. %) of base metal

| Elements | Mg | Mn | Zn | Fe | Cu | Si | Cu | Al   |
|----------|----|----|----|----|----|----|----|------|
| Composition | 2.1 | 0.12 | 5.1 | 0.35 | 1.2 | 0.58 | 1.2 | Bal  |

Table 2 Chemical composition (wt. %) of high carbon steel D3

| Elements | C  | Si | Mn | Cr   | V  |
|----------|----|----|----|------|----|
| Composition | 2.15 | 0.4 | 0.4 | 12.25 | 0.25 |

Table 3 Process parameters

| Trial No | Tool speed (rpm) | Traverse speed (mm/min) |
|----------|------------------|-------------------------|
| 1        | 1000             | 50                      |
| 2        | 1000             | 80                      |
| 3        | 1000             | 100                     |
| 4        | 1250             | 50                      |
| 5        | 1250             | 80                      |
| 6        | 1250             | 100                     |
| 7        | 1500             | 50                      |
| 8        | 1500             | 80                      |
| 9        | 1500             | 100                     |

Fig. 2: Schematic of FSW tool (All dimensions are in mm)
Fig. 3: Dimensions of tensile specimen (All dimensions in mm)

3. Results and discussions

3.1 Metallographic analysis

Microstructure analysis was performed in various zones of all the weldments. Based on the maximum tensile property yielded from the chosen window of process parameters carried out in this experiment, the microstructures were observed for samples 7 and 16 made with a tool speed of 1500 rpm and traverse speed of 50 mm/min with a constant axial force / load of 8 KN. It can be observed from Fig. 4 (a) the base metal grain structures were elongated and distributed evenly across the material. Fig. 4 (b-f) shows microstructures for the weldments without the addition of SiC powders. However, it can be observed from Fig. 4(c & f) the appearance of voids in the nugget zone. The reason for presence of voids is due to inadequate heat input in the process as reported by [13]. From Fig. 4 (b & d) it is understood that the grain structures were elongated and irregular due to inadequate bonding and irregular plasticization of material happened in the process. The unaffected base metal exhibited a nominal grain boundary as shown in Fig. 4 (e) when compared with other zones of weldments due to less heat dissipation. From Fig. 5 (a), one can understand that the bond line separates the nugget zone and thermomechanically affected zone. Also, the material flow is visible due to severe stirring and plasticization of parent material from retreating side to the advancing side. [5] reported SiC powder distribution was significantly even and it can be observed as dark spots in the optical image presented in Fig. 5 (c). [6] reported that the fine equiaxed recrystallized grains were formed due to the reinforcement of nano SiC powders in the weld area which leads for a better refinement in the grain boundaries. However, Fig. 5 (a) shows that the grains are coarser and recrystallized in the nugget zone when compared to that of base metal due to stirring process and addition of SiC powders. The grains were observed to be elongated due to the effect of heat input in the process as shown in Fig. 5 (b). In order to observe the flow of material and presence of SiC powders scanning electron microscopic analysis were carried out in the nugget zone of weldment as shown in Fig. 5 (d). It can be seen that distribution of SiC powders was uniform in the nugget zone due to continuous flow of tool material over the parent metal which showed a significant improvement in tensile property.
Fig. 4: Microstructures and SEM micrograph of weldment made with tool speed of 1500 rpm and traverse speed of 50 mm/min without SiC powders – (a) Base metal, (b) Thermo mechanically affected zone, (c) Nugget zone, (d) Heat affected zone, (e) Un affected base material, (f) SEM micrograph of nugget zone

Fig. 5: Microstructures and SEM micrograph of weldment made with tool speed of 1500 rpm and traverse speed of 50 mm/min with SiC powders - (a) Thermo mechanically affected zone and nugget zone, (b) Heat affected zone, (c) Un affected base material, (d) SEM micrograph of nugget zone

3.2 Tensile test

All the samples were made as per ASTM guidelines ASTM E8 M-04 [1]. The base metal AA 7075-T6 has a maximum Ultimate Tensile Strength (UTS) of 572 MPa [19]. The results were used to evaluate the effect of SiC powders with parent metal, tool speed and traverse speed on the mechanical properties for the weldments. Table 4 shows the maximum UTS values with corresponding joint efficiencies for all the fabricated joints.
Fig. 6 shows the schematic representation of UTS values for samples without and with SiC powders. The joint efficiency is defined as the ratio between the achieved tensile values with respect to maximum tensile value of base metal. It can be observed from results that the maximum ultimate tensile strength (427 MPa) and better joint efficiency (74.65 %) was obtained for sample 16 (with SiC) fabricated with higher tool speed (1500 rpm) and lower traverse speed (50 mm/min). The weldments with SiC expose superior strength and joint efficiency when compared to that of the one without SiC powder due to the development of good interfacial bonding between the parent material and powder. Also, one can understand that there is a homogenous distribution of SiC powders across the joints. However, the samples without SiC powders showed less tensile values due to improper material movement and absence of SiC powders which plays a major role in the enhancement of material property. There are variations in the mechanical properties of welded samples due to the presence of tunnel defects and voids [13] which are quite common in the friction stir welding process.

Table 4. Tensile values

| Trials | Tool speed (rpm) | Traverse speed (mm/min) | UTS (MPa) without SiC powders | Joint efficiency (%) | Trials | Tool speed (rpm) | Traverse speed (mm/min) | UTS (MPa) with SiC powders | Joint efficiency (%) |
|--------|-----------------|-------------------------|-------------------------------|---------------------|--------|-----------------|-------------------------|----------------------------|---------------------|
| 1      | 1000            | 50                      | 221                           | 38.63               | 10     | 1000            | 50                      | 321                        | 56.11               |
| 2      | 1000            | 80                      | 289                           | 50.52               | 11     | 1000            | 80                      | 331                        | 57.86               |
| 3      | 1000            | 100                     | 310                           | 54.19               | 12     | 1000            | 100                     | 247                        | 43.18               |
| 4      | 1250            | 50                      | 321                           | 56.11               | 13     | 1250            | 50                      | 298                        | 52.09               |
| 5      | 1250            | 80                      | 298                           | 52.09               | 14     | 1250            | 80                      | 267                        | 46.67               |
| 6      | 1250            | 100                     | 339                           | 59.26               | 15     | 1250            | 100                     | 382                        | 66.78               |
| 7      | 1500            | 50                      | 348                           | 60.83               | 16     | 1500            | 50                      | 427                        | 74.65               |
| 8      | 1500            | 80                      | 309                           | 54.02               | 17     | 1500            | 80                      | 378                        | 66.08               |
| 9      | 1500            | 100                     | 214                           | 37.41               | 18     | 1500            | 100                     | 398                        | 69.58               |
| Base metal | -    | -                       | 572                           | -                   | -      | -               | -                       | -                           | -                  |

Base metal
Fig. 6 Tensile values

3.3 Microhardness test

The microhardness values for samples across the nugget zone region for all the joints were shown in Table 5. Fig. 7 shows the schematic representation of microhardness values for samples without and with SiC powders. ASTM E384 [20] standard has been followed for the microhardness testing. The microhardness survey has been carried out, fifteen hardness values were taken in the nugget zone with different indentation gap and the average values were considered for the correlation. The hardness distribution is observed to be uniform across the nugget region for the weldments with addition of SiC powders, which proves uniform distribution of powders due to stirring process and attributed for refined grain boundaries. The material flow from retreating side to the advancing side in FSW process could be understood as reported by [7, 17]. The base metal has a hardness value of 160 HV as denoted by [13]. As reported by [13] that grain refinement plays important role in material strengthening and hardness value increases as grain size decreases according to Hall-Petch equation. The highest hardness values were 194 HV for sample with SiC powder and 141 HV for sample without SiC powder. However, hardness values were observed to be higher with maximum tool speed and lower traverse speed for the samples with SiC powders. Enhanced hardness value of 194 HV was observed for the joint fabricated with a tool speed of 1500 rpm and traverse speed of 50 mm/min, due to sufficient tool contact and better distribution of SiC powders. Also, it was observed from the results that hardness value reduces when the traverse speed increases, however higher traverse speed will lead for improper distribution of powders across the weld zone.
Table 5. Microhardness distribution

| Tool speed (rpm) | Traverse speed (mm/min) | Axial force (constant for all the trials) | Microhardness value (without SiC powders) | Microhardness value (with SiC powders) |
|------------------|-------------------------|-------------------------------------------|-------------------------------------------|----------------------------------------|
| 1000             | 50                      | 8 KN                                      | 131                                       | 156                                    |
| 1000             | 80                      | 8 KN                                      | 116                                       | 136                                    |
| 1000             | 100                     | 8 KN                                      | 108                                       | 121                                    |
| 1250             | 50                      | 8 KN                                      | 135                                       | 159                                    |
| 1250             | 80                      | 8 KN                                      | 129                                       | 142                                    |
| 1250             | 100                     | 8 KN                                      | 105                                       | 114                                    |
| 1500             | 50                      | 8 KN                                      | 141                                       | 194                                    |
| 1500             | 80                      | 8 KN                                      | 132                                       | 151                                    |
| 1500             | 100                     | 8 KN                                      | 101                                       | 109                                    |

4. Conclusions

In the present work, the joints were made between two similar aluminium alloys 7075-T6 without and with addition of SiC powders by single pass FSW process. The effect of tool speed, traverse speed on mechanical and microstructure properties for the weldments were evaluated. Based on the results obtained, the following conclusions were made.
It is observed that addition of SiC powders to the aluminium alloy 7075-T6 exhibits an enhanced mechanical and metallurgical property.

Good bonding was achieved between the parent metal and SiC powders during friction stir welding process.

As the distribution of SiC powders is uniform, the material flow in the nugget zone was successful and defect free welded joints were obtained.

Sample made with SiC powders, with a tool speed of 1500 rpm and traverse speed of 50 mm/min resulted in well refined grain structures, maximum UTS of 427 MPa and higher microhardness value of 194 HV. This reveals that a higher tool and lower traverse speed will lead for proper stirring of material for better weldment.

However, aluminium alloy without the addition of SiC powders exhibited defects such as voids and also resulted in reduced tensile strength and microhardness values.

From results a single pass friction stir welding process shows significant improvement / enhancement of alloy with proper setting of process parameters and tool design.

Still there is a scope for further improvement in mechanical and metallurgical properties by the addition of ceramic powders, etc., with the parent material for the FSW process.

Abbreviations:

NZ : Nugget Zone
TMAZ : Thermo Mechanically Affected Zone
HAZ : Heat Affected Zone
UA : Unaffected base material
AS : Advancing Side
RS : Retreating Side
SEM : Scanning Electron Microscope
SiC : Silicon Carbide
UTS : Ultimate Tensile Strength

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