Characterization of dissimilar friction stir welded joints of aluminium alloys by simulation and experimentation

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Abstract. The present work “Characterization of dissimilar friction stir welded joints of aluminium alloys by simulation and experimentation” is a combination of simulation and experimental work. In first part of the work friction stir welding (FSW) process is simulated in abacus software and then second part is based on the experimental work of friction stir welded joints of dissimilar aluminium alloys. In abacus, FSW process is well simulated. In this part heat generation profile during FSW is obtained in work-piece as well as in tool. In second part two alloys i.e. AA 5083 and AA 6061 is welded with friction stir welding process. Three process parameters were selected for welding. Three tool rotational speed is selected i.e. 500 rpm, 710 rpm and 900 rpm and one welding speed i.e. 25 mm/min. All the three welded samples were properly machined and different testing samples were prepared. Mechanical and micro-structural properties were studied on the variation of process parameters. From tensile test it can be concluded that with increase in tool rotational speed tensile strength increases. In all cases brittle fracture was observed. From microstructure study fine grains are observed in weld nugget zone.

1. Introduction

In the field of solid state joining process, Friction stir welding (FSW) has emerged rapidly as a reliable solution. It was developed and patented in the year 1991 at The Welding Institute (TWI) by Mr. Wayne Thomas. It has vast application in the field of automotive, railway, aerospace, maritime and lot more industries. As compared to other conventional fusion welding process this process it has lot of attractive advantages. Through this process, materials which are difficult to weld with conventional processes can be welded easily. Since it is a solid state joining process so, materials are joined below their melting point temperature. Therefore during this process defects like porosity, cracking, and difficulties raised due to second phase formation, embrittlement does not appear. During this process low distortion and low residual stresses are generated since it is a solid state joining process. It is observed that during process no filler material as well as no shielding gas is required, therefore it is an energy efficient process. Also during process no pollution, arc flash, spatter and fumes generated so it is an environment friendly process and also termed as green solid state joining process. Therefore, now these days, friction stir welding process is attracting the industry for its uses. [1]
Tang et al has performed the defect free friction stir welding for 316L stainless steel. They found excellent tensile properties for the welded samples and they are compared with the base metal. They also observed excellent bonding strength of weld interface [2]. Yan et al proposed a new calculating method based on fractal theory for frictional heat. They applied this method for the calculation of heat generated during FSW process. They correctly validated their results [3]. Zhang et al studied the effect of rotational speed on properties of dissimilar aluminium alloy welded joints. They observed that TMAZ on retreating side width is greater than that of advancing side width. They also concluded that with increase in rotational speed hardness value decreases. Dissimilar welded joints shows the mixed i.e. ductile brittle fracture mode [4]. Bertrand et al analysed the properties of two different alloy FSW joints i.e. AA2139 and AA7020. They concluded that these dissimilar alloy combination gives large range of process parameters fit for conservative mechanical properties of high performance structural components [5]. Ding et al studied the joint quality on friction stir welded joints due to ultrasonic vibration exerted at tool. They observed that the weld quality is improved due to ultrasonic vibration [6]. Cunha et al characterized the different properties of FSW GL E36 shipbuilding steel. They produced the joints at one rpm i.e. 500 rpm and at three different welding speed i.e. at 1, 2 and 3 mm/sec. They found that all tensile samples broke from the base material from which they concluded that joint achieved higher strength as compared to base metal [7]. Abrahams et al properties and microstructure of dissimilar FSW joints i.e. AA 5005 and AA 7075. They found greater influence of traverse speed as compared to rotational speed on mechanical properties. With increase in traverse speed micro-hardness and mechanical properties improves [8]. Pankaj et al studied the effect of pin profile and tilt angle of tool on FSW joints on brass. They tested samples for different mechanical properties. They found significant effect of pin profile and tilt angle on properties. They also correlated the mechanical testing results with micro-structural changes [9]. Donatus U et al investigated variations in stir zone and thermo-mechanically affected zone of dissimilar FSW joints of AA5083 and AA6082. They concluded that hardness profile changes in thermo mechanically affected zones of retreating side due to change in grain size [10].

From the above literature review it is found that researchers are working on friction stir welding of dissimilar alloys. Therefore this study is concentrated on FSW of dissimilar aluminium alloys. In this study modelling of the FSW process was done initially. Then, experimental was performed and welded joints mechanical and micro-structural properties were studied.

2. Abaqus modelling and simulation
At the start FSW tool model is drawn in abaqus software. Figure 1 shows the diagram of tool. Tool shoulder diameter is taken 30 mm and length of pin is taken 5.8 mm. Pin is selected as tapered profile pin. Length of shoulder is taken as 30 mm.

![Figure 1. Modelling of tool](image-url)
Two work pieces are selected of 6 mm thickness for welding simulation. First material is AA 5083 and second material is 6061 is selected. FSW tool and work-piece is assembled together as shown in figure 2. Figure 2 shows the assembly and meshing of tool and work piece together.

![Meshing of tool and work-piece assembly](image)

**Figure 2.** Meshing of tool and work-piece assembly

After meshing, simulation was done. Through simulation heat generation profile is generated. Figure 3 shows the simulation results. In which heat generation profile is shown. Maximum temperature generated is around the tool as shown in figure 3. This heat generated is due to the friction between tool and work-piece area.

![Heat generated profile](image)

**Figure 3.** Heat generated profile

### 3. Experimentation work

Friction stir welding was done on a setup made in vertical milling machine as shown in figure 4. Two aluminium plates having thickness 6 mm is selected. Two grades of aluminium i.e. one is AA 5083 and second one is AA 6061 is selected. Friction stir welding was performed at three process parameters. During the welding, welding speed is kept constant and tool rotational speed is varied. Welding speed is kept constant at 25 mm/min and three tool rotational speed is selected i.e. 500, 710 and 900 rpm. FSW tool is made of SS 410 material. Tool diameter is 25 mm and pin length is 5.7 mm which is slightly lower than the thickness of material. Pin is tapered profile pin.
3.1 Selection of samples

With friction stir welding three samples were prepared at three different process parameters. Detail of all process parameters are given in table 1.

| Sample No. | Material 1 | Material 2 | Tool rotational speed (rpm) | Welding speed (mm/min) |
|------------|------------|------------|----------------------------|------------------------|
| 1.         | AA 5083    | AA 6061    | 500                         | 25                     |
| 2.         | AA 5083    | AA 6061    | 710                         | 25                     |
| 3.         | AA 5083    | AA 6061    | 900                         | 25                     |

4. Result and Discussions

4.1 Tensile test

The FSW welded samples were cut and machined to specified dimensions to prepare samples for tensile test. Tensile test samples were prepared as per ASTM E8 standard. All specimens were tested at strain rate of 5.00 mm/min. Figure 5 shows the three specimens prepared for all three different parameters.
All specimens were tested on UTM machines for the tensile test. Figure 6 shows the image of all samples after testing.

For all the three samples as shown in figure 6, it can be observed that samples were fractured during the tensile test is from middle portion, which is required for good results for UTM. All samples were fractured from the weld zone. So, from this observation it can be concluded that it is a ductile fracture. So FSW samples after welding shows the ductile phenomenon.

All the results obtained from UTM are tabled in table 2.

| Sample no. | Ultimate tensile strength (MPa) | Percentage Elongation (%) |
|------------|--------------------------------|---------------------------|
| 1.         | 103.08                         | 9.7                       |
| 2.         | 105.58                         | 11.07                     |
| 3          | 163.23                         | 13.77                     |

Figure 7 shows the stress-strain graph for sample 2 during testing.
From figure 7, it is concluded that all FSW welded samples follows the ductile phenomenon during testing. For all three samples distinguished elastic region and plastic regions are observed from the stress-strain curve. For all test, clear ultimate tensile strength and clear fracture point is observed. In table 2 percentage elongations of all samples were shown, which also confirms the ductile phenomenon.

Figure 8 shows the variation of ultimate tensile strength for all three samples.

From figure 8 it can be observed that UTS is minimum for sample no 1 and maximum for sample no 2. So, UTS is increases from sample 1 to sample 3, i.e. with increase in rotational speed of tool ultimate tensile strength increases. As the increase in rotational speed, heat generated is increased. So, with increase in generated heat good weld quality is observed. Consequently with increase in rotational speed weld quality is increased. Standard UTS for AA 6061 is 115 MPa and for AA 5083 is 275 MPa. So, it is observed that UTS of welded sample is increased as compared to AA 6061 by 30% and become comparable to second aluminium alloy [11]. It is due to the grain refinement of the welded zone during friction stir welding. Since it is a solid state joining process so, materials are joined below the melting point of materials. Therefore grain refinement is better compare to other process due to formation of small heat affected zone.
4.2 Analysis of fractured surface

When samples are tested in UTM then fractured surfaces of samples are analysed in scanning electron microscope (SEM). After, tensile testing samples were cut in small size containing the fractured surface. Samples were studied under FESEM. Figure 9 shows the FESEM images of fractured portion. Figure 9 (b) is the magnified image of figure 9 (a), likewise figure (c) is magnified image of (b) and (d) is magnified image of (c) and also (e) is magnified image of (d). From figure 9 clearly circular dimples are visible, which also confirms the ductile fracture of FSW samples during tensile test.

![Figure 9. FESEM images of fractured portion](image)

Figure 10 shows the FESEM image of other fractured part of the same sample. From the figure it is cleared that fracture is of ductile phenomenon. Figure (a), (b),(c) and (d) are the consecutive magnified images of the sample. Peaks and valleys type structure is observed in this image.
4.3 Microstructure analysis

FSW samples were cut transversely along the weldment for the preparation of microstructure analysis samples. Samples were prepared on surface polishing machine and etched with keller’s reagent (95ml water, 2.5ml HNO$_3$, 1.0 ml HF). In SEM analysis mixing of two different aluminium alloy can be observed. In figure 11, separating boundary layer between two materials can be observed.

As shown in table 2 and figure 8, comparable tensile strength with parent material is observed. This can be explained with microstructure study. Fig 12 and 13 shows the equiaxed grains and fine grains of FSW samples. Since, during FSW materials are uniformly joined under frictional heat and pressure.
Materials are joined below melting point temperature. So, formation of second phase is absent here. Therefore fine grain and grain refinement can be achieved in weld zone. This type of grains can be observed in figure 12 and 13.

![Figure 12. SEM images showing equiaxed grains](image1)

![Figure 13. SEM images showing fine grains](image2)

Figure 14 shows the centre part of the welded samples. It is called weld nugget zone. In this part shoulder pin rotates and give stirring action to the material. Due to the movement of pin of tool this part has more refined grains as compared to other part of the welded samples. As in figure 14, small circular grains can be observed which is due to the heat generated and pressure applied by tool and stirring action of tool pin.

Figure 15 shows the SEM image of thermo mechanically affected zone (TMAZ). It is adjacent to weld nugget zone. It is not affected by the stirring of tool pin. Therefore very less circular grains are observed in this region.
5. Conclusion

Above study is based on the friction stir welding of dissimilar alloys. In this study at the staring FSW process is simulated on abacus software. After that experimentation work is done on two dissimilar alloy i.e. AA5083 and AA6061. After experimentation tensile strength, fracture study and micro-structural analysis is done on the FSW joints. On the basis of above study following conclusion is made.

i. FSW process can be well simulated on abacus software. As the time increases temperature generated in work-piece and tool is increased.

ii. From experimentation tensile strength of joint increases with the increase of rotational speed of tool.

iii. All fractures in tensile test follows the ductile phenomenon.

iv. From micro-structural study fine grains are observed in the nugget zone as compared to other weld zones.
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