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ScienceDirect
Procedia Technology 23 (2016) 543 – 550
Procedia Technology

3rd International Conference on Innovations in Automation and Mechatronics Engineering, ICIAME 2016

An experimental investigation of temperature distribution and joint properties of Al 7075 T651 friction stir welded aluminium alloys

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Abstract

The 7xxx series aluminum alloys provides the highest strength of all aluminum alloys and are considered to be a family of high strength aerospace alloys. Its weldability with conventional fusion welding techniques is extremely poor. The development of friction stir welding (FSW) process has made these aluminum alloys join satisfactorily in a reliable manner. The heat generation during the process dictates the weld quality, the tool life and the residual stresses in the workpiece. The tool geometry plays a vital role in the determining the amount of heat generation during FSW. In the present work, different tool shoulder diameters were used to practically explore the thermal histories in the workpiece during the FSW process of Al 7075 T651 joints. The transient temperatures during FSW were measured with different thermocouple layouts. A detailed discussion on temperature distributions in the workpiece is presented. Evaluation of the tensile strength of the welded joints was carried out alongwith the metallographic characterization and they were put in relation with the temperature data recorded during the friction stir welding process.

Peer-review under responsibility of the organizing committee of ICIAME 2016
Keywords: Solid state welding, mechanical characterization, metallography, joint efficiency, friction stir welding

1. Introduction

Aluminium alloys are mainly classified into two major categories viz. non heat treatable and heat treatable alloys. Non heat treatable alloys do not respond to strengthening by heat treatment whereas heat treatable alloys respond to strengthening by heat treatment. The enhanced strength properties in all the heat treatable alloys depend on the phenomena of age-hardening. Based on the strength properties the heat treatable alloys are classified into two

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Peer-review under responsibility of the organizing committee of ICIAME 2016
doi:10.1016/j.protcy.2016.03.061

categories: those with medium strength which are easily weldable and those with high strength which have very limited weldability. These high strength alloys have been primarily developed for aircraft constructions [1]. Aluminum alloy 7075 falls into this category. It is one of the strongest aluminium alloys with high strength to weight ratio. Apart from the high strength, the alloy has particularly high response to natural age hardening which makes it a natural choice for a number of aircraft structural applications, military vehicles, earth moving equipment, bridges and other highly stressed defence applications [2-4]. Al 7075 alloy has zinc, magnesium and cooper as its major alloying elements. The alloy derives its strength from precipitation of Mg_2Zn and Al_2CuMg phases [2]. Fusion welding of these alloys is extremely difficult as it is highly sensitive to weld solidification cracking. While it is possible to overcome the problem of weld solidification cracking using a suitable nonheat-treatable aluminium alloy filler (for example, Al–Mg or Al–Si), the resulting joint efficiencies are unacceptably low [2, 5]. Hence use of Al 7075 is currently limited to applications that do not involve fusion welding [6-8].

A relatively new process of joining materials, friction stir welding process was invented by Wayne Thomas in 1991 at TWI (The Welding Institute) in the United Kingdom [9]. The entire welding process takes place in solid state. The process is regarded as highly energy efficient and environment friendly. It exhibits many advantages over conventional fusion welding processes. Some most important of these advantages are low distortions and residual stresses, no fumes and spatters and no arc flash. As the entire operation takes place in solid state, it features the most significant advantage in welding of alloys which are difficult or impossible to weld by fusion welding techniques. The precipitation hardenable series of aluminium alloys (2XXX and 7XXX series) are such kind of alloys which are extremely sensitive to weld solidification cracking and are thus welded by FSW. The process is an autogenous process and does not require any kind of filler metal or shielding gases. It can operate in almost all positions with exception of fillets joints. The process finds its commercial applications in several industries, such as aviation industry and space technology [10, 11], marine and ship building [12], automotive industry [10, 11].

Due to high strength and high commercial acceptability of Al 7075, FSW of this material is a subject of interest both for the academicians and researchers. From the literature survey and the papers published related to FSW it can be observed that many researchers have focused on mechanical properties and microstructure evloution of the FSW weld joints. FSW of 7xxx-series aluminum alloy is extensively studied by many researchers which mainly includes studies on mechanical properties [2, 13], microstructure behavior [13-15], failure behavior [16, 17], superplasticity [18], peening effects [19, 20] and post weld heat treatment effects [4, 21] on friction stir welds.

Though friction stir welding is a solid state welding process, the temperatures that develop during the process are very vital in dictating the grain size, the weld joint efficiency, the tool life and the residual stresses produced in the material. By and large the temperature distributions and the thermal histories determines the successful implementation of the friction stir welding process. Studies on temperature distribution and thermal histories have been done on different combinations of materials. Many researchers have resorted to numerical methods and simulation techniques inorder to predict the thermal behavior during FSW. Yeong-Maw Hwang et al. [22] have used regression analysis to predict the temperature at the joint line during FSW of Al 6061-T6. Z. Zhang et al. [23] have used ABAQUS/Explicit software in order to simulate the effect of on the temperature rise and the material deformation in friction stir welding. X.K. Zhu et al. [24] numerically simulated transient temperature and residual stresses in friction stir welding of 304L stainless steel.

As discussed in the preceding part, the temperature generation plays an important role in friction stir welding. It becomes more important in welding of precipitation hardenable alloys like 2xxx and 7xxx series aluminium alloys. A lower heat input results in defects like pin holes and tunnel defects. With higher heat input the strengthening precipitates tend to dissolve in the matrix and clustering of the precipitates resulting in poorer mechanical strength of the resulting joint. The tool geometry plays a vital role in the determining the amount of heat generation during FSW. It has been observed that very few attempts to have been made in the past to indentify the thermal histories at various positions during FSW and to correlate the same with the joint properties of Al 7075 T651. This research is an attempt to understand the thermal histories in friction stir welding of Al 7075 T651 aluminum alloy with various shoulder diameters and to evaluate the corresponding joint strengths.

2. Experimental Procedure

2.1. Material, weld setup and testing procedure

Commercial Al 7075-T651 rolled plates 6.5 mm thick were cut to the required size (100 mm long and 50 mm wide) with the help of power hack saw and milling machine. The tensile testing of the base metal was done on 50 KN computer controlled universal testing machine (Make: Tinius Olsen) at room temperature with a constant head speed of 0.5 mm/min. The tested ultimate tensile strength of the base material was found to be 568 MPa. Non consumable tools made from M2 grade high speed steel with a cylindrical threaded pin were used to fabricate the joints. The tools were machined and then subjected to the standard heat treatment cycle for high speed steels to induce an hardness of upto 60 HRC. Close square butt joints were friction stir welded using a conventional vertical milling machine. The welding was done with a specially designed fixture made from SS304.The values of prominent parameters like welding speed and tool travel speed were selected on the basis of optimum values reported in the available literature. A tool tilt angle of 2^0 on the backward side is given to the welding tool. Providing a tilt angle to the tool mainly promotes recoalescence of the material in the stir zone at the rear of the tool. The experiments were carried out with three different shoulder diameter tools. The dimensions of the tools are shown in Figure 1. The process parameters selected for welding are shown in Table 1. During the welding process temperature data were continuously recorded at various locations in the plates using K-type thermocouples. After welding, all the welds were allowed to naturally age for the same period of time. The welds were visually inspected. This was followed by mechanical characterization which consists of tensile testing.

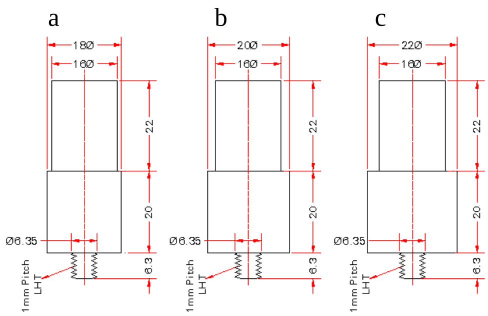


Fig. 1. Dimensions of the tool (a) 18mm (b) 20mm (c) 22mm shoulder diameter

Table 1. Process parameters

Sample ID	Shoulder Diameter (in mm)	Tool Rotation Speed (in rpm)	Welding Speed (in mm/min)	Tool Tilt Angle (in degrees)	Tool Plunge Depth (in mm)	Thermocouples Used (in nos.)
S1	18	1500	50	2^0	6.5	2
S2	20					2
S3	22					2
S11	18					4
S22	20					4
S33	22					4

2.2. Thermocouple Layouts

In the experimentation the plates were welded in a single pass and temperature history is recorded during the FSW process by K- type thermocouples having sheath diameter of 1.5mm. Maximum measuring capacity of this type of thermocouple is around 1100^0c. The analysis for temperature study is carried out using ENVADA make multi loop scanner with 16 channels. The scanner was connected to a personal computer that contained a data acquisition software ESCAN installed for recording temperatures. The temperature histories during FSW are recorded at a time interval of 2 seconds. Two different types of thermocouple layouts are used to measure the temperature distribution in the transverse direction of the weld joint and the thermal histories in the weld direction. The two different types of thermocouple layouts are shown in Figure 2 below.

a b

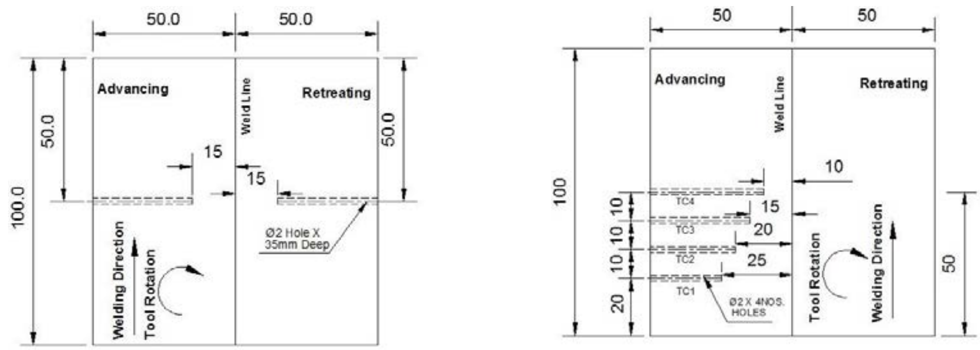


Fig. 2. Thermocouple Layouts (a) Both sides and equidistance type (b) Same side and unequal distance

2.3. Temperature data for both sides and equidistance type layout

In this type of layout two thermocouples were placed; one on the advancing side and other on the retreating side of the weld joint. Two holes with a diameter of 2mm and depth of 35mm are drilled on both the sides to accommodate the thermocouples. The distance between the tip of the thermocouple and the weld line is 15mm on each side. The holes are drilled at the center in the thickness direction of the workpiece's side edge side. This type of layout is called "both sides and equidistance type layout" and is mainly used to record the temperature data on the advancing and the retreating sides. This type of layout is shown in Figure 2(a). The temperature data are recorded for three different shoulder diameters tool viz. 18mm (S1), 20mm(S2) and 22mm(S3). Various other FSW parameters were kept constant. The tool rotational speed is 1500 rpm, the welding speed is 50 mm/min and the tool tilt angle is taken as 2^0. The temperature data is recorded for a cycle of 1000 seconds. Figure 3 below shows the temperature profiles recorded for S1, S2 and S3 shoulder diameters on the advancing and the retreating sides.

a b

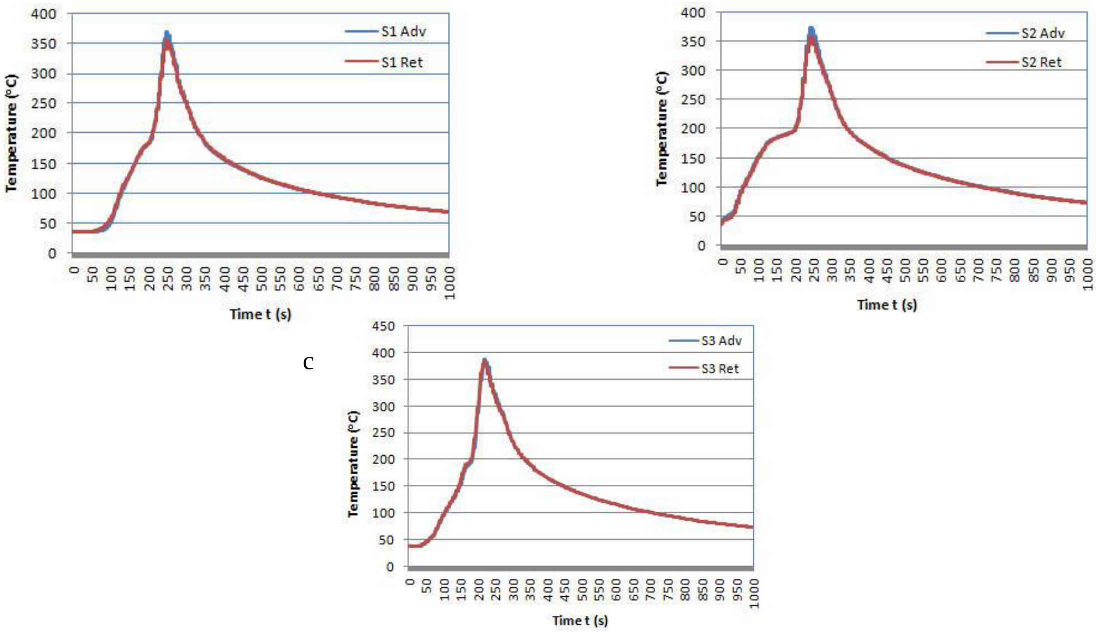


Fig. 3. Temperature profiles on advancing and retreating side (a) S1 (b) S2 (c) S3

The maximum temperatures recorded on the advancing and the retreating sides for all the three shoulder diameters are shown in table 2 below.

Table 2. Maximum temperatures recorded for both sides and equidistance type layout

Sample ID	Shoulder Diameter (in mm)	Max. Temp. on Advancing Side (°C)	Max. Temp. on Retreating Side (°C)
S1	18	370.4	355.3
S2	20	374.4	358
S3	22	387.6	382.7

2.4. Temperature data for same side and unequal distance type layout

In this type of layout four thermocouples were placed; all on the advancing side weld joint. Four holes with a diameter of 2mm are drilled on the advancing side to accommodate the thermocouples. In this layout the distances from their tips to the weld line are different. The tip of the first thermocouple TC1 is at a distance of 25mm from the weld line. However the distances for the second (TC2), third (TC3) and fourth (TC4) thermocouple tips are 20mm, 15mm and 10mm respectively from the weld line. The distances of the thermocouples' tips in the weld direction also vary in the welding direction as shown in Figure 2(b) above. This type of layout is called "same side and unequal distance type layout" and is mainly used to record the temperature data in the transverse direction of the weld joint. The temperature data are recorded for three different shoulder diameters tool viz. 18mm (S11), 20mm(S22) and 22mm(S33). Various other FSW parameters were kept same as the both sides and equidistance type layout. The temperature data is recorded for a cycle of 1000 seconds. Figure 4 below shows the temperature profiles recorded for S11, S22 and S33 shoulder diameters on the advancing side.

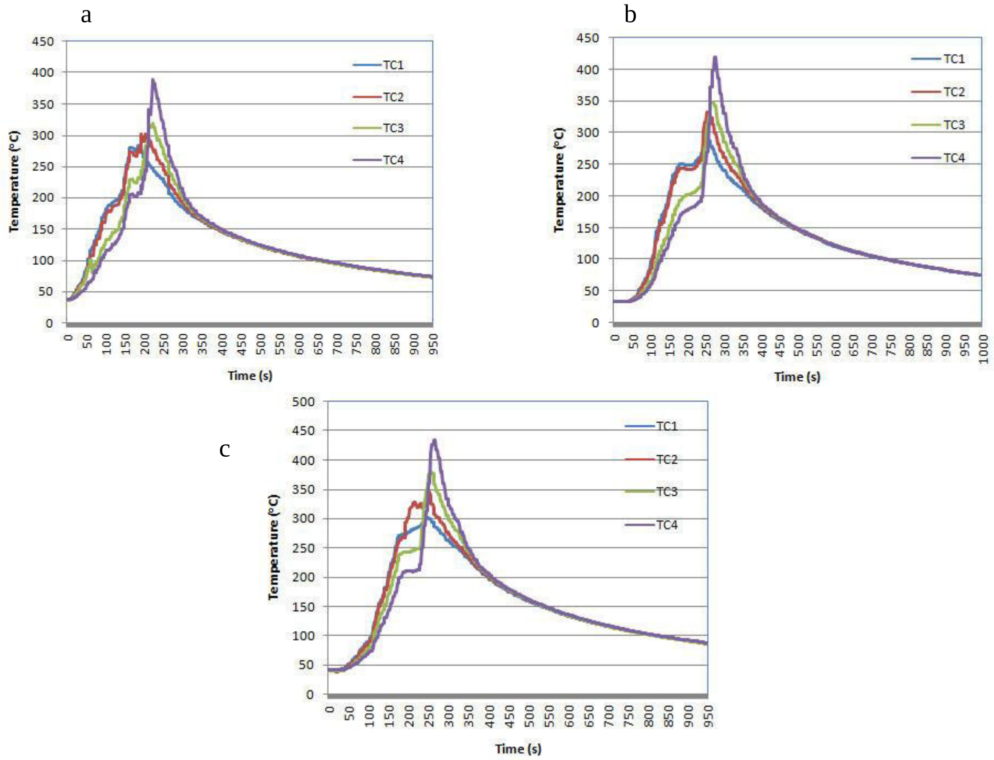


Fig. 4. Temperature profiles for same side and unequal distance type layout (a) S11 (b) S22 (c) S33

The maximum temperatures recorded on the advancing side of the same side and unequal distance type layout for all the three shoulder diameters are shown in table 3 below.

Table 3. Maximum temperatures recorded for same side and unequal distance type layout

Sample ID	Shoulder Diameter (in mm)	TC1 (ºC)	TC2 (ºC)	TC3 (ºC)	TC4 (ºC)
S1	18	283.20	301.78	318.59	389.46
S2	20	290	331.5	347.6	418.4
S3	22	301.2	245.86	380.7	433.80

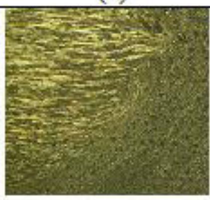
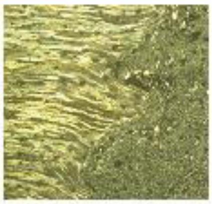
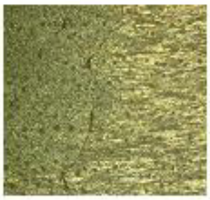
3. Tensile strength properties

After welding, all the welds were allowed to naturally age for the same period of time. The welds were visually inspected. This was followed by mechanical characterization which consists of tensile testing. The welded joints were cut using a power hacksaw and then machined to get the tensile specimens. The weld region was taken in the center of the specimen. The tensile specimens were prepared as per ASTM E8 M-04 standards. The transverse tensile strength tests of the joints welded with all the three diameters were undertaken. Three specimens for each weld condition were tested and the average results are presented. The maximum strength of the weld was exhibited by the weld made with 20mm shoulder diameter. The maximum strength of the weld was 262MPa with an elongation of 8.66%. The joint welded with 18mm diameter showed the least tensile strength of 192 MPa and that with 22mm shoulder diameter had a tensile strength of 242MPa.

4. Microstructure Analysis

Optical microscopy examinations were undertaken to study the influence of the shoulder diameter on the microstructure of FSW joint. The microstructures of the friction stir welded samples have been studied at various magnification levels. The transverse cross-sections around the joint line were observed. The microstructure evolutions were studied by optical microscope (Make: Olympus GX51).

Table 4. Microstructural analysis of samples welded with different shoulder diameters

Sample ID (1)	Stir (Nugget) Zone (2)	Advancing Side (TMAZ - WN) (3)	Retreating Side (WN - TMAZ) (4)
S1			
S2			
S3			

Standard procedures for preparing metallographic samples were followed. Table 4 shows typical cross-sectional microstructures of the friction-stir-welded AA7075-T651 joints obtained in different welding conditions. Three zones, i.e., a weld nugget (WN) zone, advancing side thermomechanically affected zone (TMAZ), and a retreating side thermomechanically affected zone, are shown in table 4. In table 4 the micrographs of the centre of the nugget zones are shown in column 2. From the results obtained it is evident that both the advancing and the retreating side have a boundary with the weld nugget but the interface on the advancing side of the tool is different from that on the retreating side. The interface between the WN and TMAZ in the advancing side is more distinctly visible than that on the retreating side.

5. Results and Discussion

From the experiments performed it is very much evident that the heat generated during the friction stir welding is directly proportional to the tool shoulder diameter. From the both sides and equidistance type layout it is known that the maximum values of temperature recorded on the advancing side are 370.4^0C, 374.4^0C and 387.6^0C for 18mm, 20mm and 22mm shoulder diameters respectively. The temperatures recorded on the retreating side are slightly lesser than compared to the advancing side. They are 355.3^0C, 358^0C and 382.7^0C respectively. The same side and unequal distance type layout indicates that the temperatures increases along the direction of the weld and towards the centre of the weld.

The microstructure of base metal consists of very fine insoluble second phase precipitates dispersed in various locations. The base metal grains are elongated in the rolling direction. The figures in the table 4 above clearly show that FSW converts the initial flat grains in the parent metal to fine equiaxed recrystallized grains in the weld nugget zone. This is a result of high temperature and high rate of stirring action due to the pin of the tool. Column 2 in the table 4 shows the weld nugget zone. In the TMAZ region the bending of the grains is observed which is due to the plastic deformation resulting by the stirring action. From the microstructural study it has been observed that the larger is the shoulder diameter, the wider is the TMAZ due to increased contact area between the tool and the workpiece. This has resulted in the deterioration of the strength of the joint fabricated with 22mm shoulder diameter. On the other side the smaller shoulder diameter of 18mm resulted in lesser contact area and thus a lesser frictional heat generation. The microstructure shows poor weld metal consolidation is the stir region resulting into the lowest joint efficiency. The joint fabricated with 20mm shoulder diameter exhibited superior strength than the other two. The temperatures recorded near the shoulder rim at half of the plate thickness ranged from 375 - 420^0C approximately.

5. Conclusions

In this paper the temperature distributions in the workpiece Al 7075 T651 were determined experimentally during the FSW process. It was observed that the temperatures on the advancing side of the weld are bit higher than that of the retreating side of the weld. Though it is extremely difficult to measure the temperatures at the weld line, an attempt has been made to determine the temperatures around the rim of the tool shoulder. From the study it can be concluded that the appropriate temperature for a defect free friction stir weld of Al 7075 T651 can be within the range of 375 - 420^0C. The joints fabricated with 20mm shoulder diameter yield maximum joint efficiency. The experimental results obtained can be helpful to control various process parameters during FSW of Al 7075 T651 to achieve defect free, sound and good quality welds.

Acknowledgements

The authors wish to place their sincere thanks to Indian Space Research Organisation (ISRO), India, for financial support rendered through a R&D Project No. E33011/60/2010-V.The authors are grateful to the Elecrical Research and Development Association (ERDA), Vadodara, India for extending the facilities of Material Testing Laboratory to carry out this investigation. Authors would like to thank Pandit Deendayal Petroleum University (PDPU), Gandhinagar, India for their help in providing a platform for conducting the experimental work required for the investigation.

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