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Improving the Fatigue Strength of Friction Stir Welded AA7075 Aluminium Alloy Joint through Heat Treatment

P.Sivaraj[1], M. Vinoth Kumar[2], V.Balasubramanian[3] and A. K. Lakshminarayanan[4]
Center for Material Joining and Research (CEMAJOR), Department of Manufacturing Engineering, Annamalai University, Chidambaram – 608002, India.[1,3]
Department of Mechanical Engineering, Hindustan Institute of Technology and Science, Chennai - 603103, India.[2]
[4]Department of Mechanical Engineering, SSN College of Engineering, Chennai - 603110, India. [4]
Email : cemajorsiva@gmail.com[1], mvinothk@hindustanuniv.ac.in[2], visvabalu@yahoo.com[3], lakshminarayananak@ssn.edu.in[4]

Abstract-This paper reports the effects of post weld heat treatments on fatigue (S-N) behaviour of friction stir-welded AA7075 aluminum alloy joints. Rolled plates of 12-mm thick AA7075-T651 aluminum alloy were used to fabricate the joints. Two different post weld heat treatment were given to the joints. They are: (1) Solution treatment followed by aging, (2) Artificial aging. A 100kN servo hydraulic controlled fatigue testing machine was used to test the specimens under constant amplitude uniaxial tensile load with a stress ratio of 0.1 and a frequency of 15 Hz. Microstructures of the welded joints were analyzed using optical microscopy. The scanning electron microscope was used to characterise the fracture surfaces. It is found that the joint treated with the solutionizing followed by artificial aging cycle is showed superior fatigue life compared to as- welded joint and artificially aged joints of friction stir welded of AA7075-T651 Aluminium alloy.

Index Terms-AA7075 alloy, Post weld heat treatment, Friction stir welding, Fatigue behaviour, Microstructure, Fracture surfaces.

1. INTRODUCTION

The 7xxx series (Al–Zn–Mg–Cu) aluminium alloy thick plates have been extensively used in aerospace industry to produce the components of airplane such as skeleton parts, bulkhead, longeron and so forth [1]. This alloy derives its strength from precipitation of Mg_2Zn and Al_2CuMg phases [2,3]. A major problem with Cu containing 7xxx series alloy is that it is not fusion weldable [4]. Friction Stir Welding (FSW) is technique results in low distortion and high joint strength compared with other welding procedures, and is able to join all aluminium alloys, that are considered as virtually not weldable with classical liquid state techniques [5]. Although the FSW process can eliminate defects of crack and porosity associated with fusion welding, the softening problem of the joints also exists. Therefore, it is necessary to search some effective remedial measures to further improve the mechanical properties of FSW joints. To recover the loss of strength in the joint caused by over-ageing due to the welding thermal cycle, one option is to fully post-weld re-heat-treat welded components [6].

However, studies in this area [7-13] have shown that the fine grains in the weld zone (WZ) are not stable during solution treatment (ST), which results in undesirable coarsened grain structures. For the aircraft components fatigue performance was known to be one of the crucial assessment qualities, therefore many efforts have been made to investigate the fatigue properties of friction stir welded aluminum alloy joints [14]. However, up to now the fatigue data for the heat treated FSW joints of various AA7075 alloys was relatively deficient. The aim of this work is to investigate the effect of post-welding heat treatments namely the artificial ageing, solution treatment followed by aging on fatigue properties of 12 mm thick friction stir welded joints of AA7075 alloy.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

Rolled plates of 12 mm thick aluminium alloy (AA 7075 in T651 condition) were used as the parent material in this investigation. The chemical composition of parent metal is presented in Table 1. Fig.1 shows the experimental details. Fig.1a represents the FSW tool diagram. Prior to welding, the abutting faces of the plates were finely milled in order to avoid surface scaling intruded with the tool. The FSW tool with tapered threaded pin profile of shoulder diameter of 36 mm, pin diameter of 12 mm and pin length of 11.6 mm was used in this study.

Table 1 Chemical composition (wt %) of Parent Metal (AA7075-T651)

Zn	**Mg**	**Cu**	**Fe**	**Si**	**Mn**	**Cr**	**Ti**	**Al**
6.1	2.9	2.0	0.50	0.4	0.30	0.28	0.20	Bal

Few trial experiments were made to identify the parameters which give the defect free welds and those parameters were taken as the optimized welding parameters in this investigation. Tool rotation and welding speeds were taken as 350 rpm 25 mm/min, respectively. Necessary care was taken to avoid joint distortion during welding. The welding was carried out normal to the rolling direction of the base metal. Fig. 1.b show the fabricated joint photograph. The welded joints were sliced using power hacksaw to prepare fatigue and tensile test specimens. Two different fatigue specimens were prepared to evaluate the fatigue properties as per ASTM E467-08 specifications. Unnotched specimens were prepared to evaluate fatigue limit. The fatigue testing experiments were conducted at six different stress levels (100,150, 200, 250, 300 and 350 MPa) and all the experiments were conducted under uniaxial tensile loading condition (stress ratio = 0.1, Frequency=10Hz) using servo hydraulic fatigue testing machine (Make: INSTRON, UK; Model: 8801). The unnotched tensile specimens were prepared as per Fig.1c to evaluate yield strength, tensile strength, percentage elongation and notch tensile strength. Hardness measurement was done across the weld center line by Vickers micro hardness tester (SHIMADZU, Japan Model: HMV-2T) with 0.05 kg load and 15 sec dwell time. Metallographic specimens were prepared by standard metallographic technique and were etched with Keller's reagent. The etching solution was cooled to 0°C and specimens were etched for about 20 s in order to study the grain structure of the weld zones and to allow for optical microscopy characterizations reveal the macro and microstructure. The micro structural analysis was done using optical microscope (MEIJI, Japan; Model: ML7100). The HRSEM analysis was carried out to identify the fracture mode of tested specimen.

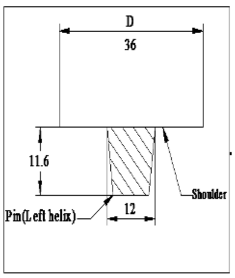
3. RESULTS

3.1 Fatigue properties

Fig. 2 shows the S-N curves of unnotched fatigue specimens of unwelded parent metal and friction stir welded AA 7075 aluminium alloy joints. The S-N curve in the high cycle fatigue region is generally described by the Basquin equation [15].

$$S^n N = A \qquad (1)$$

Where 'S' is the stress amplitude, 'N' is the number of cycles to failure, and, 'n' and 'A' are empirical constants. Each S-N curve can be represented by the above equation. From those equations, the empirical constants 'n' (slope of the curve) and 'A' (intercept of the curve) were evaluated and they are presented in Table 2. When comparing the fatigue strengths of different welded joints subjected to similar loading, it is convenient to express fatigue strength in terms of the stresses corresponding to particular lives, for example 10^5, 10^6, and 10^7 cycles on the mean S-N curve. The choice of reference life is quite arbitrary. For these reasons, in this investigation, fatigue strength of welded joints at 2 X 10^6 cycles was taken as a basis for comparison. The stress corresponding to 2 X 10^6 cycles was taken as an indication of the fatigue strength and it was evaluated for all the joints and is presented in Table 2.



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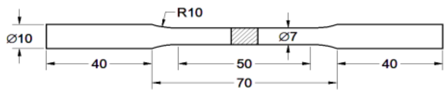
a. FSW tool diagram

b. Photograph of fabricated joint



c. Dimension of unnotched fatigue/tensile specimens

Fig. 1 Experimental details

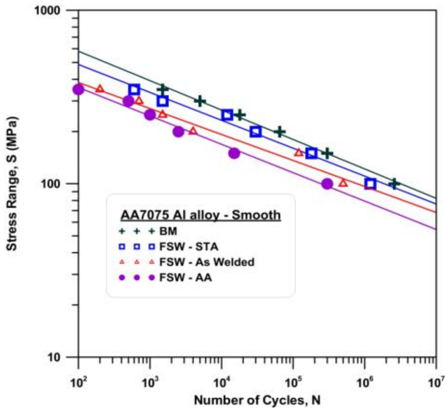


Fig. 2 S-N curves of parent metal, As-welded joint, Artificially aged joint, and Solution treated & Artificially aged joint of AA7075 Aluminium alloy

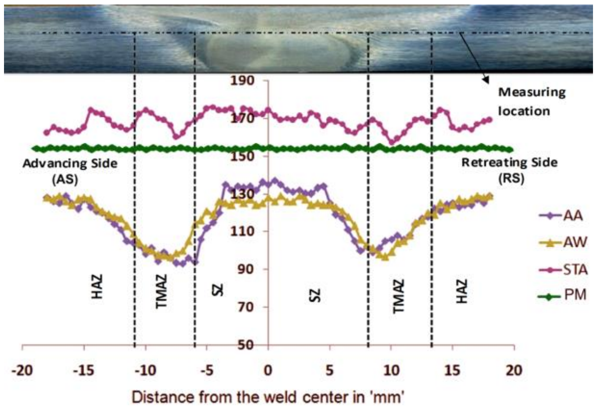


Fig.3 Microhardness Survey across the center line of FSW joint

Table 2 Fatigue properties of Parent Metal and FSW joints

Joint Type	Slope of the S-N curve (m)	Intercept of the S-N curve (C)	Fatigue strength of the unnotched specimens at 2 x 10^6 cycles (MPa)
PM	3.22	2.39 x 10^{11}	115
AW	2.90	7.14 x 10^{10}	86
AA	2.88	2.04 x 10^{10}	70
STA	2.97	9.37 x 10^{10}	100

3.2 Tensile Properties

The results of the transverse tensile test carried out for the FSW joints in AW, AA and STA conditions along with the PM are presented in Table 3. In each condition three specimens were tested and the average value is presented. The yield strength and tensile strength of the un-welded PM are 510 MPa and 563 MPa respectively with an elongation of 16%. However, the FSW joint exhibited lower tensile and yield strength of 315 MPa and 394 MPa respectively in comparison with the PM, in the as-welded (AW) condition. This suggests that FSW has caused a huge reduction in tensile strength (30%) in AA7075-T651 aluminium alloy, similar results were reported elsewhere [10,11]. The artificial aging treatment performed on the FSW joint has further lowered the yield strength and tensile strength to a value of 251 MPa and 314 MPa respectively resulting in reduction of joint efficiency by 14 % in comparison to AW joint. However the the AA treatment has also caused an increase in elongation by 2 % in comparison with the AW joint. STA treatment has increased the yield strength and tensile strength value to 346 MPa and 445 MPa respectively resulting in increase of joint efficiency by 9 % in comparison to AW joint. However, the STA treatment has caused a decrease in elongation by 1% to the AW joint.

3.3 Hardness

The hardness survey across the weld cross section was conducted along the mid thickness of the joint using a Vickers micro hardness testing machine and the hardness profile was presented in Fig. 3. The stir zone (SZ) of AW joint does not show any considerable hardness difference in comparison with the PM hardness. The hardness value for the AW joint shows a drop in the TMAZ region on both sides of the joint. The lowest hardness in AW joint was observed at the AS-TMAZ. The AA treatment resulted in increase of hardness value in the stir zone region and decrease in TMAZ region.

The STA joint recorded the highest hardness in all the regions of the weld in comparison with AW, PM and AA joints.

Table 3 Transverse tensile properties of Parent Metal and FSW joints

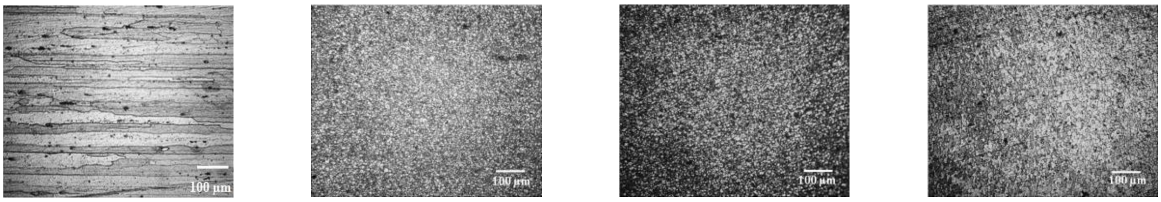
Joint type	0.2 % Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation in 50mm gauge length (%)	Joint efficiency (%)	Failure location
PM	510	563	16	-	
AW	335	394	12	70	AS-TMAZ
AA	251	314	14	56	AS-TMAZ
STA	346	445	11	79	AS-TMAZ

3.4 Microstructure

The optical micrograph of parent material and stir zones of AW, AA and STA joints are shown in Fig.4. The SZ region of AW joint (Fig. 4b) reveals fine and equiaxed grains structure, due to the dynamic recrystalization that occurred during FSW. The stir zone of AA joint (Fig. 4c) reveals no alteration in the size of fine equiaxed grains when subjected to the AA treatment. The stir zone of STA joint (Fig. 4d) reveals the marginal increase in grain.

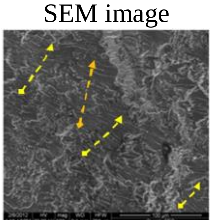
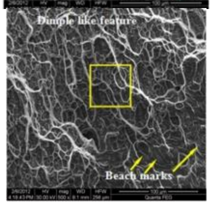
3.5 Fracture surfaces

Fig. 5 represents the fracture surfaces of the unnotched fatigue specimens tested at the stress level of 100 MPa. Fig. 5a the scanned image of the parent metal shows the very fine fatigue beach marks. The arrow mark indicated in this fractograph reveals that the probable crack initiation and propagation direction.
Fig. 5b of the unnotched AW joint fatigue specimen shows irregular path of fracture surface which indicates the lower stress levels resulting in multiple crack initiation sites. Fig. 5c of the AA joint shows faster propagation of the crack growth fracture surface which indicates the lower stress levels resulting in quick failure of the specimen. Fig. 5d of the scanned image of the STA joint clearly shows the fatigue crack propagation and very fine fatigue beach marks. The fracture pattern of STA unnotched fatigue specimen reveals the presence of very fine striations could be the reason for the higher fatigue strength of this STA joints.



a. Parent material b. AW Joint c. AA Joint d. STA Joint

Fig. 4 Optical micrograph of stir zone

S.no	Condition	Scanned image	SEM image
a.	PM		
b.	AW Joint		

c. AA Joint

d. STA Joint

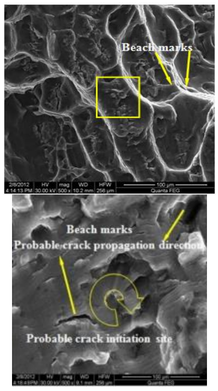


Fig. 5 Fracture surface of fatigue specimen

4. DISCUSSION

The solution treatment followed by artificial aging cycle is used to be beneficial to enhance the fatigue strength of friction stir welded AA7075 aluminium alloy joints. The reasons for the better fatigue performance of the STA joints are: (i) superior tensile properties of the joints, (ii) uniformly distributed finer precipitates in the stir zone. The tensile properties (yield strength, tensile strength and elongation) of STA joints are superior compared to AW and AA joints. Higher yield strength and tensile strength of the STA joint is greatly used to enhance the endurance limit of the joints and hence the fatigue crack initiation is delayed [16]. Larger elongation (higher ductility) of the STA joints also imparts greater resistance to fatigue crack propagation and hence fatigue failure is delayed. The combined effect of higher yield strength and higher ductility of the STA joint offers enhanced resistance to crack initiation and crack propagation and hence the fatigue performance of the joints is superior as compared to their counterparts.

5. CONCLUSIONS

- Rolled thick plates of 12 mm, precipitation hardened, high strength AA7075-T651 aluminium alloys were successfully friction stir welded without any defects using single pass welding procedure.
- The solution treated followed artificial aging (STA) joints exhibited 30% higher fatigue strength than artificially aged (AA) joints and 16% higher fatigue strength than as-welded FSW joints.
- The superior tensile properties, higher hardness and uniformly distributed finer precipitates are the main reasons for superior fatigue properties of STA joints compared to AA joint and AW joints.

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