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Post-weld heat treatment effect on dissimilar friction stir welds (AA 2024-t6 and AA 6351-t6)

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ABSTRACT

Post weld heat treatment and subsequent aging (PWHTA) effect on dissimilar friction stir welding (DFSW) (AA2024-T6 to AA6351-T6) were investigated in the present study. The micro structural measurement techniques (Optical, SEM- EDS) have been employed to understand the precipitate distribution and the elements distribution in the Stirred zone (SZ). PWHTA on dissimilar FSWs shows better mechanical properties and pitting corrosion than as welded specimens. A post weld solution treatment at 520^0 C for 1 hr and subsequent ageing at 180^0 C for 12 hrs and 8 hrs aging time resulted in better mechanical and corrosion properties respectively than other conditions.

Introduction

The friction stir welding (FSW) is a very important new tool in the aircraft and automotive industry solving more of the problems related to the need of high performance joints [1]. FSW was invented in 1991 at The Welding Institute (TWI) of UK, and initially useful for the joining of aluminum alloys traditionally difficult to weld (2XXX & 6XXX series) materials in which the fusion welding techniques produce brittle dendritic structures producing a strong decrease in the mechanical properties [2]. Many scientists demonstrated the lower distortion and presence of residual stresses in FSW joints with respect to the traditional welding techniques [3–5]. Post weld heat treatment (PWHT) is an option to recover the loss of strength in the heat affected zone (HAZ) caused by averaging due to the weld thermal cycle. Recent studies on the effect of PWHT on FSW of Al alloy 2219 (in T6 temper) showed significant improvement in the mechanical properties of the weldment [6].The PWHT following FSW of 2219 (in O temper) has significant effect on the fracture locations of the joints. The tensile strength of the joints is increased with increasing solutionising temperature [7]. The PWHT (solutionising and ageing) following FSW of 6061 (in O temper) resulted in increase in hardness across the whole weldment [8]. Studies on AA6082 (in T6 temper) showed that when the material was under T6 condition, the HAZ had lower hardness after post weld ageing, while the rest of region regained the hardness [9]. On the other hand, when the material was under T4 condition, there was recovery of hardness across the entire weldment. Post weld ageing and post weld solution treatment and ageing of 6063-T5 restored the strength of the weld to the level of base metal [10]. From the above studies it can be seen that PWHT would minimize the HAZ softening problem and improve the strength of the weld. Though there has been lot of research on FSW of similar aluminium alloys like AA 2219 and AA 6061 [2-10], very few studies deal with dissimilar metal/alloy welds. The tensile and fatigue behavior of FSW weldments of 2024 and 7075 Al alloys and observed that the failure in the tensile test was on 2024 side(which has lower hardness) and the dissimilar joint exhibited a decrease in fatigue life with respect to 7075 FSW joint [11]. Ageing improved the hardness at the interface of FSW joint (5083 to 6061-T6) but did not improve the hardness of soft HAZ [12]. The Polarization tests and electrochemical impedance spectroscopy showed a nobler behavior of weld bead with respect to parent alloy of AA2024-T3 using FSW and TIG techniques [13]. The effect of post weld surface laser treatment led to a remarkable improvement of the corrosion resistance of FSW aluminum welds in 2024Al-T351 and 7010Al-T7651 [14]. A torch treatment (exposing each side) of 7075 alloy FSW welds to a torch flame for 1min at a distance of ~20 mm and quenched in water resulted in a slight disappearance of the intergrannular precipitates and the general disappearance of the grain boundary phase, in particular for the HAZ, thereby decreasing the intergrannular corrosion susceptibility and increasing the stress corrosion cracking resistance [15]. Naturally aged FSW joints of 7050 Al-T7651 had better SCC resistance, but some aged joints caused unacceptable loss in mechanical properties under ambient conditions [16]. The local heat treatment (solutionising heat treatment, retrogression and re-ageing) was the most promising type of heat treatment to restore SSC resistance [17].

The present study aims to investigate the effects of PWHTA (post weld solutionising at 520^0 C for 1h and subsequent ageing at 180^0 C for 4,8,12 hr) on the properties of dissimilar FSW of 2024-T6 and 6351-T6 aluminum alloys.

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2. Experimental Details

The material used in this study of PWHTA (Table 4) was a friction stir welded samples at weld condition shown in the Table 3. The base materials selected for this investigation were AA6351-T6 and AA2024-T6 aluminum alloys sheets of 5mm thickness having chemical composition and mechanical properties shown in the table 1and 2. The welds for the present study were prepared by friction stir welding (FSW) with sheets of AA6351 and AA2024 and then cut for welding. The AA6351-T6 alloy sheet was located on the retreating side and AA2024-T6 was placed on the advancing side. The rotating tool used in this study was made of high-speed tool steel. From the FSW sheets, some samples were cut for metallographic observations, Vickers hardness measurements, tensile tests and polarization measurements.

Surfaces were prepared by standard metallographic techniques i.e. the grinding process utilized SiC papers that started from 80 grit down a series of 220, 320, 500, 800, and finally 1200 grit. Polishing consisted of a 1.0 and 0.3 micron size alumina slurry. Final polishing was performed by using diamond paste and etched with Keller's reagent and grain structure of the weld zone was characterized by optical microscopy.

The Vickers hardness across the weld nugget (WN), thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ) and base metal was measured on a cross-section, perpendicular to the welding direction using MM-112, Micro-Vickers hardness testing Machine at a load of 100g for 10 seconds

To determine the tensile strength of the stir zone, tensile test specimens were sectioned as per ASTM E8 in the transverse direction perpendicular to the weld line with an electrical discharge machine (EDM). Transverse tensile tests were performed on UTM Dak Inc series 9000 of 5 ton capacity machine to evaluate the mechanical properties of the joints of as welded and PWHTA. SEM-EDS was employed for both as welded and PWHTA at SZ as well as for tensile fracture surfaces of the FSW specimens.

For performing the polarization tests, the plates had dimensions of about 5 mm thick and 15 mm wide to be fitted in special holder supplied with such apparatus. One $1cm^2$ area of the weld joint which consisted SZ of as welded, PWHTA samples (heat treatment parameter shown in the Table 4) and base metal were individually exposed to 3.5%NaCl solution. The potentiodynamic scan was performed with scan rate of (1mV/sec) by using Basic electrochemical system (Princeton Applied Research) supported by corrosion measurement software.

3. Results and Discussions

3.1 optical microstructures

In the present study, FSW joints were successful produced. The obtained joints showed no porosity or other defects in both top and root weld surface in the all welding conditions. The Stirred Zone (Fig.1a) is the region that experienced the highest strain and undergoes recrystallization. Its microstructure is due to mechanical action of the tool probe that generates a continuous dynamic recrystallization process. The higher temperature and the severe plastic deformation during the welding in the SZ result in a new equiaxed fine grain structure. This indicates that the stir zone experienced high temperatures resulting in coarsening/dissolution of the precipitates leading to lower hardness/strength. Post weld heat treatment will generally result in a modification of the microstructure of both the stir zone and heat affected zone. Optical micrographs of the stir zone show the presence of coarse precipitates throughout the matrix**.** PWHTA (Fig.1b) led to the homogeneous re-precipitation**.**

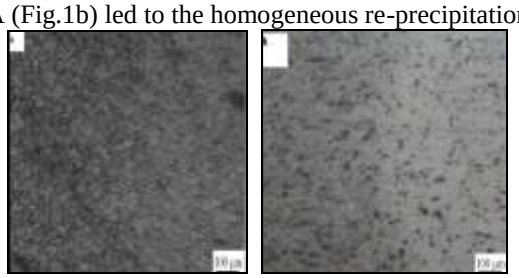

Fig 1 Optical micrographs of FSW joint at SZ (a) as-welded (b) after PWHTA at 12hrs ageing time

3.2 SEM-EDS analysis of weld joints

The SZ contains two different layers of materials. These layers were distinct in their appearance and composition. The composition of each layer was found to be exactly the same as that of the base metal. Energy dispersive spectroscopy (EDS) analysis at the interface indicated that there is no intermixing between the two materials. It was reported in the literature that the SZ experienced a temperature above 450ºC [18-19]. This indicates that the residence time at high temperatures achieved during FSW is not sufficient for diffusion. But during PWHT treatment at 520°C for 1 h diffusion took place and this was observed by SEM-EDS (Fig 2). SEM-EDS analysis in the region of AA2024 side shows that the copper by weight percentage and precipitates of Al_2Cu were higher and which cause for more number of pit formation (shown in Fig 5a, b). On the other hand in the region of AA6351 side shows that magnesium, silicon elements and precipitates of Mg2Si causes more corrosion resistance than the advancing side (Fig 5a, b)

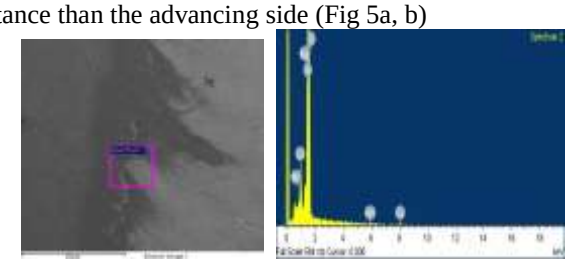

Fig 2 SEM-EDS of FSW joint at SZ of 12hrs aging time

3.3. Hardness profile

Micro Vicker's hardness profiles of as welded and PWHTA in the transverse direction are summarized in Fig.3. It indicates the cross-sectional hardness profile from retrieving side metal through centre of the weld to advancing metal. Micro hardness profiles provide an overview of anticipated mechanical behavior of the weldment. Hardness of the stir zone was lower than both the base metals (AA2024 and AA6351) in both the as welded and PWHTA conditions. In a precipitation hardened Al alloy, the mechanical properties of the weld zone mainly depended on the precipitates behavior during the weld thermal cycles. This result could be attributed to the reason why lower hardness than that of base metals. The PWHTA resulted in significant improvement in hardness throughout the weldment (Fig 3). It is because of uniformly dispersed Mg_2Si and Al_2CuMg particles in the SZ with aging time. The solutionising treatment resulted in dissolution of precipitates throughout the SZ. Rapid cooling following solutionising is expected to result in supersaturated state with large number of quenched in vacancies throughout the weldment. Ageing following quenching resulted in homogeneous precipitation of strengthening phases throughout the SZ (Fig. 3).

Table 1: Chemical Composition of AA2024-T6 and AA6351-T6

Material	*Si*	*Fe*	*Cu*	*Mn*	*Mg*	Al
AA2024-T6	0.118	0.209	3.99	0.53	1.28	Bal.
AA6351-T6	1.040	0.372	1.20	0.65	1.14	Bal.

Table 2: properties of AA2024-T6 and AA6351-T6

Material	UTS (Mpa)	YS (Mpa)	(%) Elongation	Micro Vickers Hardness(VHN) (0.1kgf)	E_{corr} (mV)	E_{pit} (mV)
AA2024-T6	496	348	10.54	122.2	-1343	-702
AA6351-T6	329	272	11.7	98.34	-1125	-630

Table 3 Welding Parameters and Tool Dimensions

S.No.	*Process Parameters*	*Values*
1	Rotational Speed(rpm)	1200
2	Welding Speed(mm/sec)	1.2
3	Axial Force(N)	5000
4	Pin Length(mm)	3.5
5	Tool Shoulder Diameter(mm)	15
6	Pin Diameter(mm)	5

Table 4: Heat Treatment Parameters

S.No.	*Heat treatment parameters*	*Values*
1	Solutionising Temperature,0^C	520
2	Solutionising Time, hr	1
3	Ageing Temperature , 0^C	180
4	Ageing times, hr	4, 8,12

Table 5 Tensile properties of FSW joints

S.No	*Condition*	*UTS (Mpa)*	*YS (Mpa)*	*% Elongation*
1	As welded	238	182	5.69
2	Solutionising at 520 ^{0}C for 1 hr and subsequent ageing at 180^{0}C for 4 hr	249	190	4.5
4	Solutionising at 520 ^{0}C for 1 hr and subsequent ageing at 180^{0}C for 8 hr	268	219	3.2
4	Solutionising at 520 ^{0}C for 1 hr and subsequent ageing at 180^{0}C for12 hr	285	232	2.4

Table 6 Pitting Potential values of FSW joints

S.No	*Condition*	E_{corr} *(mV)*	E_{pit} *(mV)*
1	Base metal AA 2024-T6	-1336	-702
2	Base metal AA 6351-T6	-1125	-630
3	As welded	-1197	-686
4	Solutionising at 520 ^{0}C for 1 hr and subsequent ageing at 180^{0}C for 4 hr	-1231	-715
5	Solutionising at 520 ^{0}C for 1 hr and subsequent ageing at 180^{0}C for 8 hr	-1181	-661
6	Solutionising at 520 ^{0}C for 1 hr and subsequent ageing at 180^{0}C for12 hr	-1189	-682

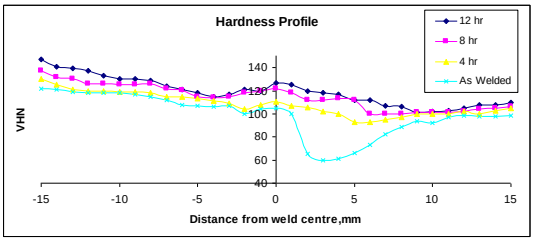

Fig.3. Micro Hardness profiles the FSW joints

3.4 Tensile strength

The tensile properties of the joints are shown in Table 5. This indicates a 26-27% reduction in strength for DFSWs compared with that of the BM (AA6351). PWHTA joints revealed that significant improvements in the tensile properties of SZ. Out of all, after solutionising, 180^0C aging temperature and 12 hrs aging time shows significant improvement in tensile properties than other conditions.

There is consequent reduction in ductility in both as welded and PWHTA conditions as However, the as-welded joint exhibited better elongation than the PWHTA joints. This was an approximately 51.4% reduction in the elongation of the as-welded joint compared with the base metal of AA6351-T6. Elongation values of the ageing time 4 hr, 8 hr, 12 hr temper joints were 4.5%, 3.2% and 2.4%, respectively.

In all the cases, the fracture location in tensile specimens was with minimum hardness side (AA6351). As welded fractured specimens revealed very good plasticity properties and shown the ductile behaviors by the presence of very fine dimples in SZ (Fig.4a) but brittle fracture behavior observed in PWHTA welds (Fig.4b). Owing to the optical microscopy observations, it can be affirmed that the mechanical behavior of the welds is a strong function of PWHTA.

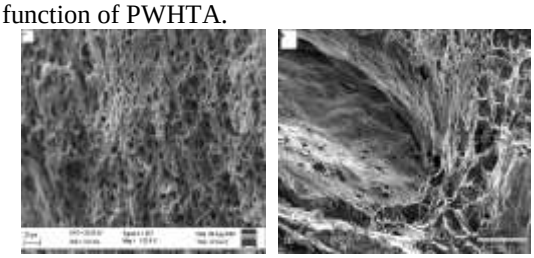

Fig 4 fracture surface of tensile tested specimen (a) as welded (b) after PWHTA at 12hrs aging

3.5 pitting corrosion

Table 6 shows typical E_{corr} and E_{pit} values of BMs, as-welded and PWHTA samples. It has found that the corrosion potential E_{corr} and E_{pit} values (shown in Fig 6) of AA 6351 are more (less negative value) than AA 2024. The pitting corrosion E_{corr} and E_{pit} values of as welded had intermediate to both the BMs because of presence of the precipitates from both the metals at SZ. It has shown that the position of polarization curves (Fig 7) for the ageing samples shifts towards the positive direction and 8 hr ageing time has high corrosion resistance than the other conditions. The over ageing tends to lead to a decrease in breakdown potential, an increase in passive current density prior to breakdown, which is probably associated with an increase in the number of copper-rich precipitates of Al_2CuMg

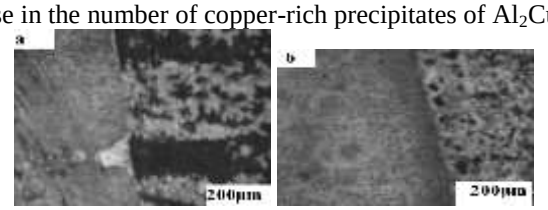

Fig 5 Optical micrographs of FSW joints at SZ (a) as - welded (b) after PWHTA at 8 hrs aging time

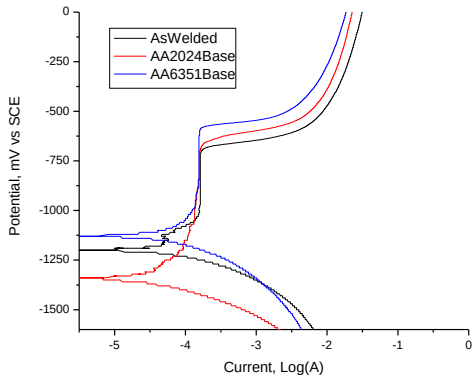

Fig 6 Potentiodynamic polarization curves of as welded and base metals in 3.5%NaCl solution

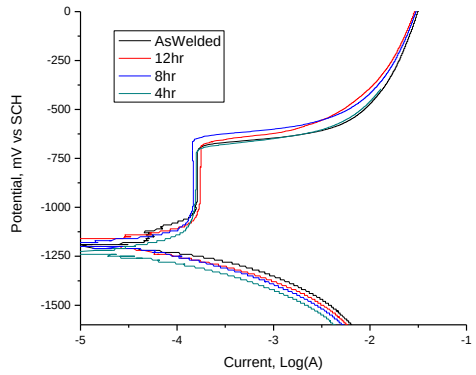

Fig 7 Potentiodynamic polarization curves of as welded and aged samples in 3.5% NaCl solution.

4. Conclusions

In the present study, the effect of post weld heat treatment on friction stir welded dissimilar Al alloys (AA 2024 and AA 6351 in T6 condition) is studied and based on the results the following conclusions are arrived at

1. DFSW (AA 6351-T6 and AA 2024 -T6) was successfully carried out using friction stir welding
2. The hardness, UTS and YS of the DFSWs were increased by the PWHTA process. The maximum hardness, UTS and YS of the DFSWs were obtained with PWHTA of 520^0C for 1 hour and subsequent ageing at 180^0 C for 12 hours than the other conditions.
3. There was reduction in ductility of as welded and PWHTA joints.
4. Corrosion resistance increased with PWHTA, especially its significant effect of corrosion resistance improvement was apparently observed with PWHTA of 520^0C for 1 hour and subsequent ageing at 180^0 C for 8 hours than the other condition.

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