Post corrosion tensile strength and failure of dissimilar friction stir welded aluminium alloys

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Abstract. The present study efforts towards appraising the effects of corrosion on the tensile and fracture behaviour of dissimilar friction stir welding (FSW) of aluminium alloys. Three different dissimilar FSW joints obtained between AA6061-T6 and AA7075-T651, AA6061-T6 and AA2014-T6, AA7075-T651 and AA2014-T6, using threaded pin profile with three flat faces (TIF) tool at rotational speed of 1200 rpm and welding speed of 98 mm/min. The maximum joint tensile strength was achieved for AA7075-AA2014 joints followed by AA6061-AA2014 and least recorded for AA6061-AA7075 for as obtained FSW joints (non-corroded). The joints are further immersed into a corrosive solution for 1, 2, 7 and 14 days duration. The corrosion occurred all over the joint but much accelerated rate of exfoliation corrosion exists away from stir zone near the confluence of heat affected zone and base material irrespective of the advancing or retreating side. With increase in corrosion time the location of tensile failure shifted towards corroded region (AA6061-T6) instead of stir zone in dissimilar weld joint AA6061-AA2014, whereas it remained unchanged for other two joints. The fractured surfaces of AA6061-AA2014 FSW joints reveals the articulated view of pits and fracture morphology advocating the loss in YS, UTS and % elongation with increases in immersion duration.

1 Introduction

Aluminium alloys due to their low weight to strength ratio make them excellent for aerospace, marine and other applications. Along with the optimized mechanical properties, corrosion susceptibility of these alloys is also required to be reduced and worth investigation. Friction stir welding (FSW) evolved as a promising solid-state joining process for aluminium and other alloys. A non-consumable, rotating tool plastically deforms the work piece material generating sufficient heat for desired material flow, mixing and joining predominantly through solid state diffusion. Srinivasan et al. [1] studied corrosion susceptibility to stress corrosion cracking (SSC) of friction stir welded AA7075-AA6056 by performing tensile test in air and NaCl solution (3.5%). They reported that TMAZ/HAZ of AA7075 is susceptible to SCC, although fracture location is governed by both mechanical stresses as well as corrosive environments. Birbilis et al. [2] investigated the electrochemical and metallurgical behaviour of Al₇Cu₂Fe particles in AA7075-T651 alloys. They found that 65% of the constituent particle population is of Al₇Cu₂Fe and are of comparatively large size. Mentioned particles served as a local cathode during localized corrosion of AA7075-T651, developing large pits at the particle-matrix interface. Aluminium alloys of 7XXX series are more susceptible to corrosion in comparison to 2XXX and 6XXX series appealing several researchers to find the cause and remedy to its corrosion behaviour. Marlaud et al. [3] quantified corrosion susceptibility of

7XXX series with different heat treatment conditions using EXCO test and electrochemical test. They suggested over aging as the remedy to reduce localized inter-granular corrosion however found no considerable change in the results between two different test methods. Lahovary et al. [4] studied the galvanic behaviour between copper rich intermetallic and its adjacent matrix within AA2024-T351 alloy. For corrosion test, the test coupons were immersed in NaCl solution of 1 M for 24 hours. The probable cause for intergranular corrosion was found to be the dissolution of copper rich precipitates like Al₂Cu and Al₂CuMg. Difference in galvanic behaviour of constituent particles can't be apprehended as lone reason for corrosion as the studies proven grain or constituent particle size can also affect corrosion behaviour. Yan et al. [5] put forward their idea of grain boundary optimization to control corrosion resistance in Al-Mg alloys. Their study witnessed that better corrosion resistance and precipitation in Al-Mg alloy is controlled by grain boundary (GB) misorientation angle. They concluded that low angle GBs are immune and high angle GBs are prone to grain boundary acid attacks. In the similar context, Zuo et al. [6] recognized changes in corrosion susceptibilities of Al-Zn-Mg-Cu alloy by bringing changes in rolling process. They found that controlling grain structure can change corrosion behaviour. The corrosion potentials (E_{corr}) reported for AA2014 is -768 mV [7], for AA6061 is -807 mV [8] and for AA7075 the value is -831 mV [9]. The E_{corr} value signifies the potential at which

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corrosion begins and more negative value notifies the poor resistance to corrosion.

In FSW process, by virtue of the process, regions in-and-around the weld nugget zone undergo different magnitude of deformation and/or thermal cycle thereby leading to grain size variations. Microstructural inhomogeneity at different regions in FSW joint is expected to exhibit variation in corrosion behaviour. Thus, the present work is conducted to analyse the behavioural change in corrosion for three dissimilar FSW joints by changing the adjoining alloy combinations and corrosion periods. The study is successively completed by first obtaining friction stir welds between AA6061-T6 and AA7075-T651, AA6061-T6 and AA2014-T6, AA7075-T651 and AA2014-T6. The dissimilar welds obtained then are investigated for susceptibility and extent of corrosion with increasing immersion time and its effect on the tensile strength and fracture behaviour.

2 Materials and methods

The three different friction stir welds AA6061-AA7075, AA6061-AA2014 and AA7075-AA2014 obtained by keeping earlier in advancing side (AS) and later in retreating side (RS). Each alloy plate of 6.1 mm thickness was joined on a vertical milling machine by clamping on a suitably designed fixture. The tool made from H13 material having pin of right-hand thread with intermittent flat surfaces (TIF) (3 flat faces cut at 120° apart) was used for FSW. The tool shoulder diameter is 20 mm whereas the pin major diameter and length are 6 mm and 5.9 mm respectively. Shoulder penetration of 0.1-0.2 mm was provided for all joints. The friction stir joining is done at 1200 rpm tool rotation and 98 mm/min welding speed for all joints. Total ten tensile samples were obtained from each dissimilar joined weld plate and two samples each were kept for different immersion timings in corrosive solution. Figure 1(a) portrays the schematic representation of the order in which samples are being obtained for tensile test and for optical micrographs. The tensile samples (transverse to weld line) cut as per (ASTM E8) dimension from the welded plates. The samples were then dipped in NaCl solution for 1, 2, 7 and 14 days for observing the site, extent of corrosion and later tested for its effect on joint tensile strength. The samples were cleaned using etch cleaner and concentrated HNO₃ to decontaminate the surface before dipping in the saline solution of NaCl (57 g) + H₂O (1 L) + H₂O₂ (10 mL) prepared for corrosion. For the tensile samples, only the gage length portion was exposed to the corrosive environment from all four sides and rest is masked using spray paint. The samples which were dipped for more than 2 days the corrosive solution is changed after every two days. The samples were then taken out of the solution after the decided time period and cleaned for corrosive residues. For removing the corrosion products samples were washed using distilled water and then dipped in cleaning reagent prepared from H₃PO₄ (50 mL) + CrO₃ (20 g) + H₂O (1 L) at 90 °C for 5 to 10 minutes and then were taken out, washed using

distilled water and air dried. Afterwards the samples were dipped in heated concentrated HNO₃ for 1 minute as a counter measure to remove corrosion product (if any) and washed using distilled water and air dried. The samples were then ultrasonicated in ethanol. The fresh (without any corrosion) and corroded tensile samples were tested for yield strength (YS), ultimate tensile strength (UTS) and % elongation. Uniaxial tensile tests of transverse specimens were conducted at cross head speed of 0.5 mm/min on ultimate tensile testing machine (Zwick/Roell Z50, capacity 50 kN). Contact type extensometer was used to record YS at 0.2% offset strain. Macroscopic observations of failure of the joints were performed using an optical microscope and fractographic studies were carried out on field emission scanning electron microscope (Zeiss Gemini500).

Table 1. YS, UTS and % elongation of friction stir welds before and after immersion for different time periods

FSW	Immersion time	YS (MPa)	UTS (MPa)	Elongation (%)
AA6061-AA7075	Without immersion	133±11	193±1	4.1±0.3
	1 day	109±3	189±5	4.15±0.05
	2 days	108±3	183.5±0.5	4.1±0.4
	7 days	113.5±0.5	192±1	3.9±0
	14 days	118.5±0.5	193.5±1.5	4.3±2
AA6061-AA2014	Without immersion	108.5±0.5	182.5±3.5	4.15±0.15
	1 day	106.5±1.5	177.5±1.5	3.95±0.25
	2 days	105±2	172±1	3.65±0.15
	7 days	105±0	175.5±0.5	4.05±0.25
	14 days	103±1	164±4	3.5±3
AA7075-AA2014	Without immersion	189±6	291.5±25.5	2.3±0.4
	1 day	181.5±4.5	252±2	1.7±0
	2 days	162±9	238.5±6.5	1.55±0.15
	7 days	176.5±1.5	270.5±7.5	1.7±0.2
	14 days	190±2	273±4	1.9±1

3 Results and discussion

The tensile properties of the FSW joints before and after immersion for different duration are given in Table 1 and

Fig. 1. (a) Schematic of samples cut from friction stir welded plates, micrographs of three dissimilar friction stir welds before and after tensile test of samples without immersion; tensile stress-strain plot for FSW joints between (b) AA6061-T6 and AA7075-T651 (c) AA6061-T6 and AA2014-T6 (d) AA7075-T651 and AA2014-T6 before and after immersion for different duration

the stress-strain plots are provided in Fig 1. Figure 1 also represents the optical microscopic images of the joints (nugget region) before and after tensile tests for the samples without immersion. As inferred from Table 1 and stress-strain plots (refer Fig 1. (b), (c), (d)) that the maximum UTS and YS was achieved for AA7075-AA2014 as compared to AA6061-AA2014 and AA6061-AA7075 dissimilar welds pre-corrosion. However, % elongation is noted minimum for AA7075-AA2014 joints compared to other two cases. For AA6061-AA7075 and AA7075-AA2014 there is no specific trend followed for different corrosion periods. Whereas for

AA6061-AA2014 FSW joints loss in YS as well as UTS is noted with increase in corrosion period. The tensile failure of the joints (pre-corrosion) initiated and propagated from the stir zone for AA7075-AA2014 and AA6061-AA2014 FSW joints whereas failure in AA6061-AA7075 weld occurred from the advancing side (AA6061-T6). Figure 2 represents the corroded micrographs for all three dissimilar FSW joints after immersion for 1, 2, 7 and 14 days. The corrosion takes place all over the joint however minimum corrosion is observed at core of the nugget stir zone (SZ). There exists a region away from SZ, near the confluence of

Fig. 2. Optical micrographs of corroded dissimilar friction stir welds after four different immersion periods for (a) AA6061-T6 and AA7075-T651 (b) AA6061-T6 and AA2014-T6 (c) AA7075-T651 and AA2014-T6 FSW joints

heat affected zone (HAZ) and base metal which experienced much accelerated rate of exfoliation corrosion (EFC). Once the weld joints are exposed to corrosive solution the extensive EFC is particularly observed on the AA7075-T651 side in two dissimilar welds (refer Fig.2 (a) and (c)). Whereas, for the dissimilar weld of AA6061-AA2014 it was observed in the AA6061-T6 side (refer Fig.2 (b)). Figure 2(a) shows the progressive corrosion after four different immersion durations for AA6061-AA7075. The extent of pitting corrosion can be observed increasing with the immersion time in the retreating side (AA7075-T651) of the weld. It may also be noted that the distance between SZ and extensive corrosion zone is more as compared to that of other two set of welds.

Thus, in AA6061-AA7075 FSW joints, the SZ and surrounding thermo-mechanically affected zone (TMAZ) is less prone to corrosion attack in NaCl solution. Whereas the extensive pitting is noted beyond HAZ till immersion for 2 days and HAZ regions also gets corroded after 7 days of immersion. In AA6061-AA2014 FSW joint the excessive pitting and EFC was observed on AS (AA6061-T6) with its extent increasing with immersion duration whereas on RS (AA2014-T6) metallic lusters are noted. Thus, it can be inferred from both cases that exfoliation corrosion sight is independent

of the side in which alloy is placed. The corrosion took place as per the galvanic series in which 7XXX series is more anodic than 6XXX series and least is 2XXX series among all three. The AA7075 alloy with higher negative E_{corr} value justifies its extensive corrosion trending towards base metal. The lowest negative value of E_{corr} in AA2014 alloy conserves it from substantial material loss due to EFC as in other two alloys. Figure 2(c) shows the progressive corrosion of AA7075-AA2014 place in the AS (AA7075-T651) of the joint in regions beyond TMAZ and HAZ with increasing immersion time. However, the SZ of the nugget remains unattacked till 2 days of immersion and mild corrosion are observed in this zone after 7 or 14 days of immersion. The source of the $\text{Al}_7\text{Cu}_2\text{Fe}$ particles in AA7075-T651 is due to the presence of iron impurities and their large size makes them prone to corrosion. The progressive corrosion in AA6061-AA2014 (refer Fig.2 (b)) dissimilar weld shows excess pitting and exfoliation corrosion in the advancing side (AA6061). The Mg_2Si is the common precipitates in AA6061-T6 and possess low corrosion potential compared to Al-matrix and acts as anode. During localized galvanic corrosion these particles get corroded fast leaving pits that further get exfoliated, although the rate of EFC is comparatively low in AA6061-T6 as compared to that of AA7075-T651. Figure 3 (a) shows the fracture location of tensile samples after immersion

Fig. 3. Optical micrographs showing fractured locations of corroded dissimilar friction stir welds after different immersion periods of (a) AA6061-T6 and AA7075-T651 (b) AA6061-T6 and AA2014-T6 (c) AA7075-T651 and AA2014-T6 FSW joints

and progressive corrosion for different durations of AA6061-AA7075 FSW joints. With the increase in immersion duration the extent of corrosion gets increased but still the fracture location remains same. The UTS and % elongation is also same after corrosion and thus it can be inferred that advancing side (AA6061) participated maximum in the gage length elongation and remains the weakest among SZ and extensively corroded region. For the specific combination and the time duration for which the immersion was employed, the base metal (AA6061) is the weakest portion and thus it can sustain corrosive environment for longer periods without getting compromised on strength. However, the tensile testing of AA6061-AA2014 FSW joints after corrosion as shown in Fig. 3 (b) narrates a different nature with shifting in fracture location. The change is brought in even after getting exposed to the corrosive environment for 1 day i.e. least time period in this study. It can also be observed that with increase in immersion time the extent of corrosion is increasing and the EFC morphology is growing in AA6061-T6 (AS) side towards the HAZ. Prominent pitting and metallic lustres are noted on AA2014-T6 after 1 week immersion period. It can be also observed that from Fig 3 (b) that the AA6061 portion present in the SZ starts corroding after

2 days of immersion. UTS and % elongation tend to decrease with corrosion time as the populating pits accelerated the fracture propagation in AA6061 side of the joint. In AA7075-AA2014 dissimilar weld the extent of EFC is much higher than any of the other two combination as can be noted from Fig 3 (c). Observing the black region in AS (AA7075-T651) indicates EFC getting populated and lastly covering the whole width and narrowing the overall cross section from all four sides. Even after the narrowing of section due to corrosion, the fracture occurs from the SZ, although the side of fracture shifted from AA2014 towards AA7075 side of the SZ. This might be possibly due to the very narrow void at the bottom through which the corrosive solution sieved in, affecting the strength of joint at the SZ. Thus, for AA7075-AA2014 dissimilar weld, SZ remains the region of minimum strength possibly due to the presence of micro-voids in the SZ and the larger immersion duration will be required to weaken the joint from other location.

Figure 4 represents the SEM fractographs obtained for tensile fractured surface after the progressive corrosion of the dissimilar welds of AA6061-AA7075. The fracture occurred on the same location in AA6061-T6 for all the specimens irrespective of sample without

Fig. 4. FE-SEM micrographs of fractured surfaces of corroded AA6061-AA7075 dissimilar friction stir weld for four different immersion periods

(a)

(b)

Fig. 5. FE-SEM fractographs of (a) corroded AA6061-AA2014 dissimilar friction stir weld for four different immersion periods (b) fracture morphology near the deep pitted region

or with corrosion for different durations. Thus, it can be inferred that corrosion time for which specimens are being exposed didn't affect the weld strength or fracture morphology. The fracture morphology and behaviour only get effected either due to the alloy constituents or due to the heating effects produced during welding and the metallurgical consequences. The fracture morphologies for all corrosive conditions show similar equiaxed dimple distributions and cup-cone failure can

be observed for all the joints. The presence of secondary phase reinforcing particles of Mg_2Si is evident from different studies that work as the stress raisers in the weld joint [10-12]. The high magnification fracture images show broad population of microscopic voids of differing shape and size which resulted in local ductile mechanisms. These typical fracture surfaces are the evidence of existence of ductile failure with sufficient necking before failure.

Fig. 6. FE-SEM micrographs of fractured surfaces of (a) corroded dissimilar AA7075-AA2014 friction stir weld for four different immersion periods (b) fracture morphology of highlighted regions at higher magnifications

Figure 5(a) represents the SEM fractographs obtained for tensile fractured surface after the progressive corrosion of the dissimilar welds of AA6061-AA2014. The location of fracture is on the advancing side (AA6061-T6) as for AA6061-AA7075 and thus similar fracture mechanisms have taken place. Although there is compositional similarity and thus failure morphology, mechanism might be similar but the difference can be noted in the existence and extent of pits and EFC (refer Fig. 5 (b)) that possibly is the crack initiation site. Thus, multiple fracture initiation took place from all the corners which is due the pits formed during corrosion. The representative pit depth is measured around 480 μm , 644 μm , 747 μm in three fractured surfaces obtained after the immersion time of 1, 7 and 14 days respectively. With immersion time, depth of pits increased at certain locations and subsequently, loss in strength recorded. These fractured sample also reveals that the pitting is more progressive from the sides and less from the top or bottom of the joint cross section.

Figure 6(a) shows extremely dense and uniformly distributed dimples with very narrow intermittent zone. All the fractures occurred near the SZ for all AA7075-AA2014 dissimilar welds. The fracture location is fine grain dominated region and thus very dense dimple region can be expected. The density of dimples can be compared as all are under same magnifications. Region 'A' spotted in the fracture surface shows stepwise failure and this region is common to all the fractured surfaces in Fig. 6 (a), signifying shear failure. Although a very

different fracture morphology at the bottom of every joint can be observed due to the presence of small voids at the bottom due to insufficient joining. Figure 6(b) helps in observing the fracture morphology with dimples of low depth and separated by bright, narrow ridges at some intermittent locations.

4 Conclusions

- The maximum UTS and YS was achieved for AA7075-AA2014 as compared to AA6061-AA2014 and AA6061-AA7075 dissimilar welds without any corrosion treatment whereas minimum % elongation is noted for AA7075-AA2014 joints compared to other two cases.
- The corrosion takes place all over the joint but the much accelerated rate of corrosion exists away from stir zone near the confluence of HAZ and base metal. From the welds it is inferred that exfoliation corrosion sight is independent of the side in which alloy is placed.
- In AA6061-AA2014 weld combination the excessive pitting and exfoliation corrosion is in the advancing side (AA6061) and its extent increases with increase in immersion duration. Also the extent of pitting corrosion increased for AA7075 irrespective of the side in which it is placed.
- The corroded and tensile tested dissimilar weld of AA6061-AA2014 shows the shifting of fracture

location after getting exposed to the corrosive environment for the least time period whereas it remains unchanged for the other two welds.

Declaration

Authors declare no potential conflict of interest.

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