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Effect of Post Weld Heat Treatments on Mechanical and Stress Corrosion Cracking Behaviour of Aa7075 Friction Stir Welds

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Abstract

The high strength aluminium alloys exhibits low weldability due to poor solidification microstructure, porosity in the fusion zone and lose their mechanical properties when they are welded by fusion welding techniques. Friction stir welding (FSW) is a promising technique to retain the properties of the alloy as the joining take place in the solid state. Even though mechanical properties of the welds are better, corrosion resistance of welds gets affected by the microstructural changes that occur during welding. In the present work the effect of post weld treatments viz. peak ageing (T6), overaging (T73), retrogression and retrogression & reaging (RRA) on the mechanical properties and stress corrosion resistance is studied. It was observed that Retrogression and RRA treatments improved the resistance to stress corrosion cracking and maintained the mechanical properties. The resistance to stress corrosion is improved in RRA and Retrogression condition with the minimum loss of weld strength. This is attributed to the dissolution, re-precipitation and re-distribution of precipitates.

Keywords: *Friction Stir Welding, AA7075 alloy, Post Weld heat Treatments, Stress Corrosion Cracking.*

1. Introduction

Friction stir welding (FSW) is energy efficient, environment friendly solid state welding process. Because of the absence of parent metal melting and related problems such as brittle dendrite structure, porosity, distortion and residual stresses, this process can be used for joining most of the aluminium alloys [1]. FSW of aluminum alloys offers the advantages of low heat input, reduced distortion, therefore, low residual stresses and higher mechanical properties compared to conventional fusion welding methods [2].

In FSW process the material is subjected to intense plastic deformation at elevated temperatures due to the stirring action of a rotating tool [3]. Friction stir welding achieves solid phase joining by locally introducing frictional heat and plastic flow by rotation of the welding tool with resulting local microstructure change in aluminum alloys [4]. The welding temperatures in FSW ranges between 425^0C–480^0C. The welding temperature never exceeds 80% of melting point and does not cause melting but high enough to cause dissolution/overaging of strengthening particles in heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and the nugget zone (NZ) leading to the formation of a

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softened region with degraded mechanical properties generally in heat affected zones [2, 3]. FSW causes grain refinement in the weld zone due to which the tensile strength of the joint increases with little loss of ductility [1].

The microstructure of the welded joint is formally divided into four zones: base material (BM), heat HAZ, TMAZ and NZ. Paglia et al. [5] was reported that the microstructure in the HAZ, TMAZ and WN varies particularly in precipitation hardenable aluminium alloys like 7xxx series alloys. The variation in microstructure leads to variation of hardness and corrosion resistance in 7075 aluminium welds. The softening of HAZ is one of the reasons for poor corrosion resistance in 7075 aluminium welds. As the FSW process induces a dramatic change in microstructures, there is every need to understand the microstructure and corrosion behaviour of friction stir welds [5].

A number of techniques are being considered currently for minimizing the softening and to improve the properties of FSW weld joints such as optimization of process parameters, post weld heat treatments, in process cooling using external coolants, and under water or submerged FSW. Many authors reported that post weld heat treatment of 7075 alloys at T73 temper improves the corrosion resistance. However, the strength is 10 – 15% less in case of T73 temper when compared to T6 temper. The RRA treatment of 7xxx series alloys recovers the strength without impairing the corrosion resistance of the material. Post weld heat treatment is a viable option to restore the strength of the joints by modifying the size, shape and distribution of secondary strengthening particles [6].

It was reported that the micro structural characterization of 7075 aluminum alloy in the RRA temper revealed that the retrogression treatment resulted in dissolution of the less stable precipitates (GP zones and η’) inside the grains, while the grain boundary precipitates grow and are more spaced. The re-aging enhances the re-precipitation of η’ precipitates.

Stress corrosion usually occurs in the presence of mild corrosive atmospheres and the surface products are almost non-detectable. If extensive corrosion occurs the component usually fails due to the loss of cross sectional area. It is fortunate that corrosion occurs only under certain combinations of material and environment. In the early stages of stress corrosion cracking the cracks are microscopic and cannot be detected by visual examination. These cracks can be either intercrystalline or transcrystalline, depending on the alloy environment combination [6, 7]. It is noteworthy that aluminium alloys with appreciable amounts of soluble alloying elements, of copper, magnesium, silicon and zinc, are susceptible to stress corrosion cracking in marine atmospheres or wherever salt is present in the environment. The complexity of variables entering the phenomena of stress corrosion cracking provides sufficient evidence that the mechanism is not simple nor is it easily derived. Several theories have been proposed [9, 10], but all contain elements of speculation are usually resolved into one of two mechanisms: (a) Electrochemical including oxide film rupture or tubular corrosion pit modification and (b) stress sorption cracking, involving surface energy condition or weakening of adjacent metal atom bonds by adsorbed components of the environment. It is worth mentioning that the mechanism of stress sorption cracking plausibly accounts for many fractures of stress corrosion cracking and it also relates stress corrosion cracking to the mechanism of similar fracture in metals and non-metals from environmental causes not involving electrochemical reactions. On the other frontier, fracture mechanics and mechanisms have provided considerable insight into fracture resulting from pre-existing defects, particularly when the fracture is not preceded by net section yielding [2, 3]. A concept like this is applied to stress corrosion especially for those materials which tend to fail with little strain even when tested in air. Although the SCC phenomena is not completely understood on AA7075 alloys, its occurrence in metals can be associated with electrochemical energy releasing as an additional term in the general energy balance approach of the fracture mechanics [11]. Structural features of the material, like galvanic cells arising from segregation, grain boundary precipitation or passive film breaking due to plastic deformation are the common SCC phenomena that comprise both chemical and mechanical effects.

Keeping in view above problems related to stress corrosion cracking resistance of the aluminium alloy welds, the present investigation was undertaken to determine the effects of T6, T73, retrogression and re-aging (RRA) heat treatment on hardness, tensile properties and resistance to stress corrosion of the 7075- T7351 aluminum alloy friction stir welds.

2. Experimental Details:

Materials and heat treatment: The material used in this study was a 7075aluminum alloy in plate form, was friction stir welded in butt joint position at Defence Metallurgical Research Laboratory (DMRL), Hyderabad using 3-axis CIMTRIX make computer numerical controlled milling machine with FANUC controller. The process parameters used for the welding are in Table 2.1. Welds were done on the plate of 240mm X 150mm X 8 mm size. Chemical composition of the base metal is given in the Table 2.2. The FSW machine and the obtained weldments are shown in the Figure 2.1 a) & b).

Table 2.1. Process Parameters of Friction Stir Welding

Process parameters	Spindle Speed (rpm)	Tool Down Feed (mm/min.)	Depth (mm)	Initial Heat Time (Sec.)	Tool Axial Feed (mm/min.)	Tool Longitudinal Travel (mm)
Values	750	40	7.25	3	25	240

a) b)

Figure 2.1. a) Friction Stir Welding Setup b) Welded AA7075 Alloy Plates

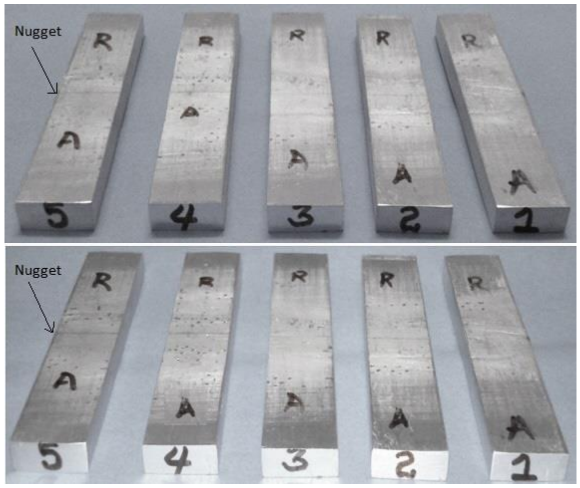


Figure 2.2. Samples for Microstructure and Hardness Measurements

Table 2.2. Chemical Composition (wt. %) of the 7075 Aluminium Alloy

Material	Zn	Mg	Cu	Fe	Si	Ti	Mn	Cr	Al	Other
AA7075	5.1-6.1	2.1-2.9	1.2-2.0	Max 0.5	Max 0.4	Max 0.2	Max 0.3	0.18-0.28	87.1-91.4	Max 0.15

Table 2.3. Heat Treatment Procedures Done on the Welded Samples

Temper	Condition	Ageing Temperature
T6	Near peak aged	Solution heat treatment at 515^{0}C for 1.5hrs with cold water quench and heating at 120^{0}C for 24hr.
T73	Over aged	6hrs/10^{0}C + 24hrs/163^{0}C.
Retrogression	Peak aged	Heat treatment at 220^{0}C for 5mins and then water quenched.
Retrogression and Re-ageing	Peak aged	Heat treatment at 220^{0}C for 5mins then water quenched and again aged at T6 condition.

Figure 2.3. a) Tensile Samples Prepared from Friction Stir Welded AA7075 Plates

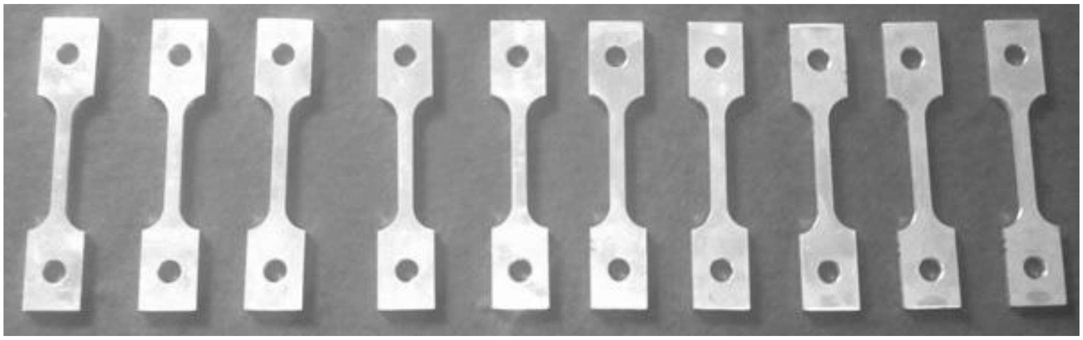


Figure 2.3. b) SCC Samples Prepared from Friction Stir Welded AA7075 Plates

After welding the plates, the specimens were cut from the butt joints for microstructural analysis, SEM analysis and hardness measurement of various regions of the joint i.e. nugget, TMAZ, HAZ and Base Metal. The samples were shown in the Figure 2.2. The tensile and SCC samples were prepared as per the ASTM E-8/E8M-09 standards. Wire cut - EDM was used to cut the samples from the welded plates. The tensile samples were cut across the direction of the tool travel direction and the cut specimens were shown in the Figure 2.3 a) & b). The samples were heat treated to change the temper conditions. The details of post weld temper conditions are shown in the Table 2.3. After changing the temper conditions of the welded samples, the microstructures were recorded with Image analyzer attached to the metallurgical microscope of Olympus (Model: C–5060–G X 4-Japan). The hardness of the specimens was measured using Vickers hardness tester (LV700-USA) with 1kgf load and 15 Seconds as dwelling time. The tensile testing was performed and based on the tensile test results, the SCC tests were performed on the SCC specimens.

3. Results and Discussions

3.1. Microstructure

Figure 1 show the nugget microstructures of 7075 alloy friction stir welds in various temper conditions. The nugget microstructure consists of recrystallized equiaxed fine grains. A majority of the large grains are recrystallized to the fine equi-axed grains due to the FSW process. A trace of the abnormal grain still exists in the nugget. The microstructure revealed the typical appearance with grains with the presence of some intermetallics.

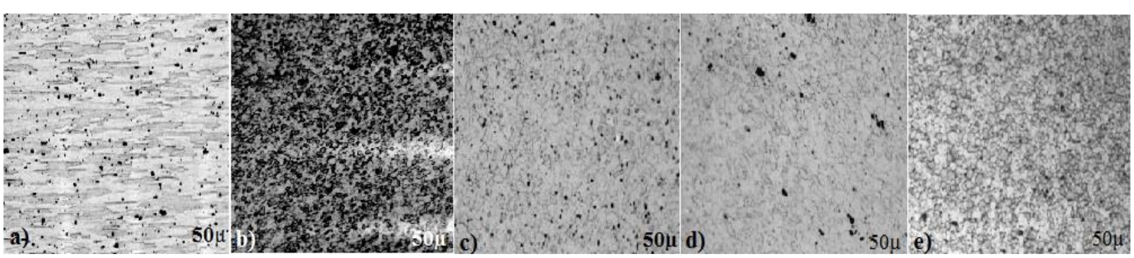
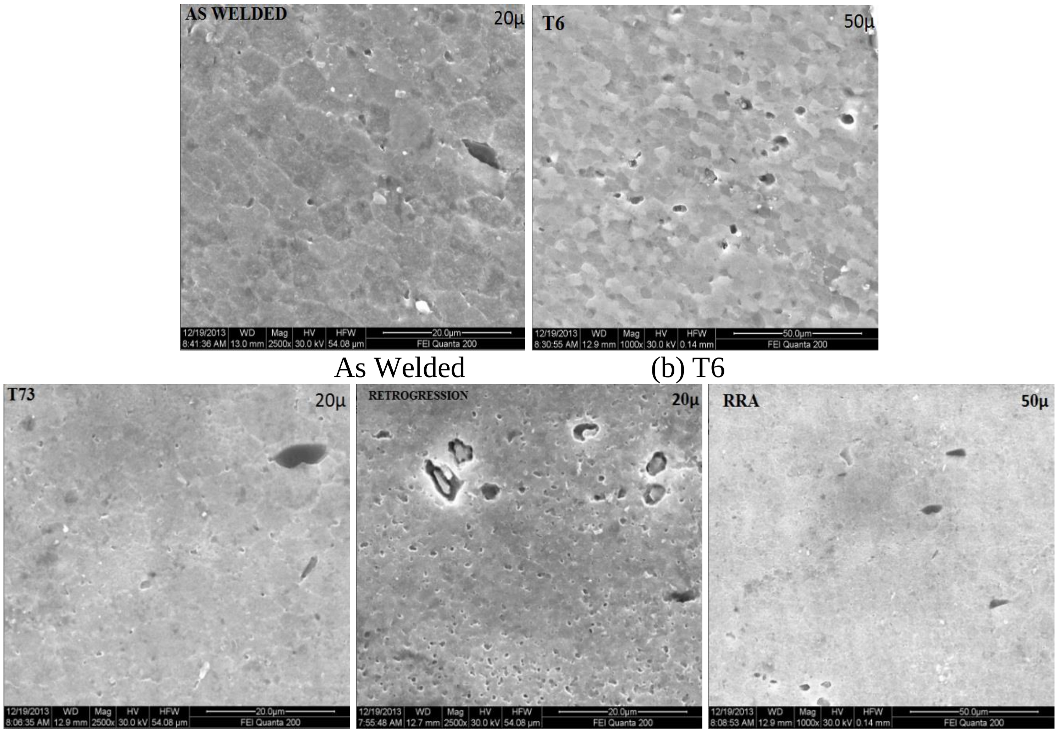


Figure 3.1.1. Microstructures of the nugget zone a) Base Metal, b) T6, c) T73, d) Retrogression e) Retrogression and Re-aging conditions

These intermetallics have been previously identified as mainly Al_7Cu_2Fe, $(Al, Cu)_6$ (Fe,Cu), and Mg_2Si. Characteristic micro structural constituents formed following T6 temper consist of GP zones, semi coherent ή (MgZn2), and incoherent η (MgZn2) precipitates.



As Welded (b) T6

c) T73 d) Retrogression e) RRA

Figure 3.1.2. SEM Images of the Nugget Zone a) T6, b) T73, c) Retrogression d) Retrogression and Re-aging conditions at 100x magnifications

The high strength of T6 microstructure is mainly due to GP zones and ή precipitates, but the contribution of ή precipitates to the strength is reported to be higher. Because retrogression and reaging treatments mainly affect the size, type, and distribution of the microstructural constituents (GP zones, η’and η precipitates).

3.2. Hardness testing

The hardness values measured at various points from the weld centre are presented in the Table 3.2.1. From the results it was observed that the variation of hardness is greatly influenced by the post weld heat treatment processes. The hardness profiles of the welded joints under different heat treated conditions are presented in the Figure 3.2.1 the hardness measurements were taken at 2mm below the weld surface of the plates. The average hardness values at weld nugget (WN) and heat affected zone (HAZ) are 158.2 H_V and 160.8 H_V respectively. These are less than the hardness of base metal (BM) hardness. It was observed that the hardness is high under T6 condition when compared to other post weld heat treatments. The average value of base metal hardness is 150 H_V.

Liu [12] reported that that overaging and dissolving of the metastable precipitates lead to the decrease in the hardness in the WZ. But the presence of the fine equiaxed grains and the resolution of the dissolved precipitates partially remedy the loss of hardness. The improved hardness in the WN is attributed to the recovery of the dissolved precipitates and the fine equiaxed grains in the WN. Friction stir welding of 7075 aluminium alloy generates a region of relatively low hardness value around weld centre. This zone extends up to the transition of TMAZ and HAZ. The reason for the same is the softening of the weld in the region due to coarsening/ dissolution of the strengthening precipitates. The maximum hardness occurs in

HAZ because aging strengthen the welds. Hardness again decreases on approaching the base metal.

Table 3.2.1. Hardness Measurements at Various Zones of Welds Under Different Temper Conditions

	Distance from Weld Centre, mm	As Welded	T6	T73	Retrogression	RRA
BM	-25	149	152	147	148	152
HAZ	-20	155	156	158	154	158
	-15	158	162	159	158	161
TMAZ	-10	176	180	178	178	179
Nugget	-5	157	160	153	157	158
	0	155	159	154	156	157
	5	158	162	156	168	160
TMAZ	10	178	181	177	177	180
HAZ	15	159	163	162	161	162
	20	156	156	160	152	155
BM	25	150	152	149	147	152

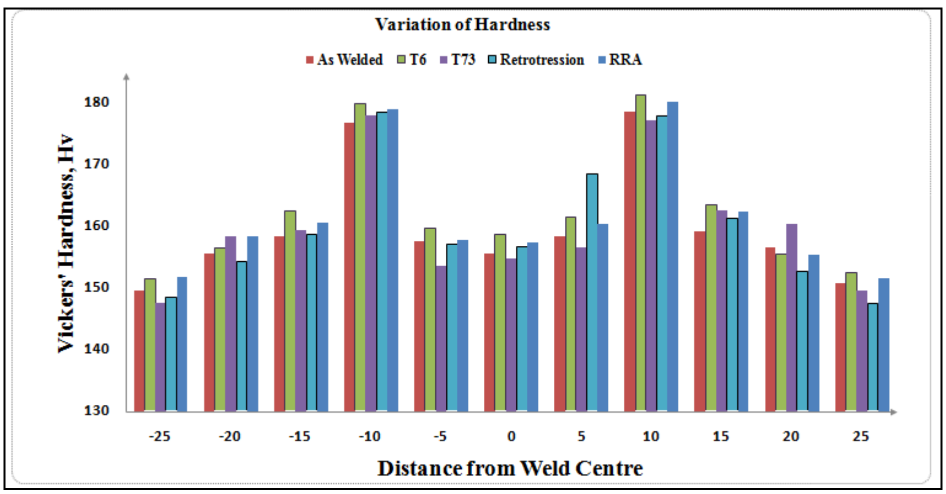


Figure 3.2.1. Hardness Profile of Weld Zones Under Various Temper Conditions

3.3. Tensile Testing

The Tensile properties of the FSW joints are dependent on microstructure which in turn depends on welding conditions, base metal initial temper conditions and post weld treatments. The tensile properties of the joints in post weld heat treated and as welded conditions are summarized in Table 3.3.1 and Figure 3.3.1.

Table 3.3.1. Tensile Properties of Weld Zones Under Various Temper Conditions

S.No.	Sample Temper Condition	Y.S. MPa	UTS MPa	% Elongation
1.	Base Metal	421	482	8.4
2.	As welded	227	346	4.6
3.	T6	373	494	10.4
4.	T73	452	540	11.1
5.	Retrogression	341	553	11.4
6.	RRA	420	536	11

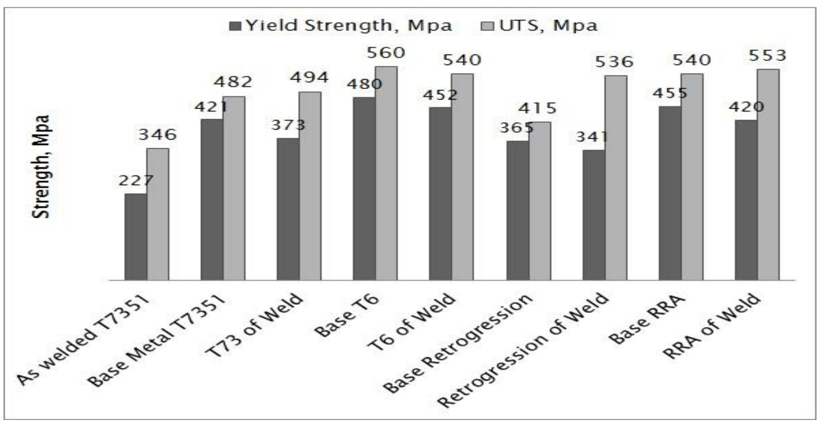


Figure 3.3.1. Tensile Properties of Welded Joints under Different Post Weld Conditions

The post weld heat treatments significantly influenced the tensile properties of FSW joints as evident from Table 3.3.1. The RRA treatment improved the tensile properties of the FSW joint when compared to the as welded condition. The Yield Strength(Y.S.), Ultimate Tensile Strength (UTS) and % elongation of FSW joints under RRA treatment are increase by 45 %,35 %, 48and % respectively when compared to as welded condition. The strength and elongation of the joints were also improves in T6, T73 and Retrogression conditions.

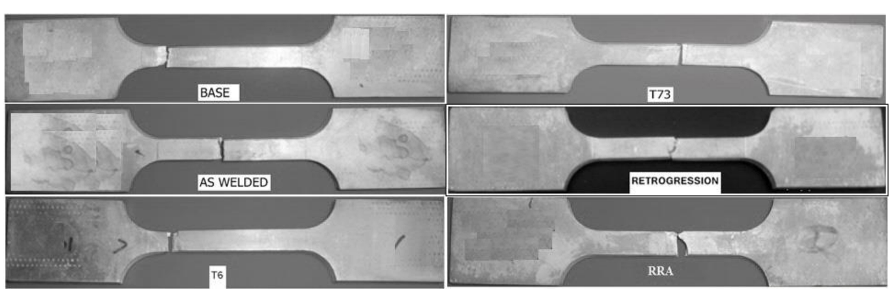


Figure 3.3.2. Fracture Locations of Welded Tensile Specimens Under Various Temper Conditions

3.4. Stress corrosion Cracking Tests

Stress corrosion cracking tests were conducted on constant load type SCC testing setup as per ASTM E-8/E8M-09 standards. The load applied on the test specimens were based on tensile test results is presented in the Table 3.4.1. Specimens were immersed in a 3.5 wt. % NaCI solution (pH 6.5-7.0) and the solution was periodically circulated to maintain a constant pH. The loading arrangement of specimens is shown in the Figure 3.4.1. The load applied and the time to failure is recorded for each specimen and is represented in the Table 3.4.1. The SCC tests revealed that the as welded specimen has poor resistance to stress corrosion. The RRA and retrogression specimens had shown good resistance to stress corrosion. The time to failure for the specimen under retrogression treatment was 184 days, which maximum when compared to other post weld treated specimens.

Figure 3.4.1. Stress Corrosion Cracking Test Setup

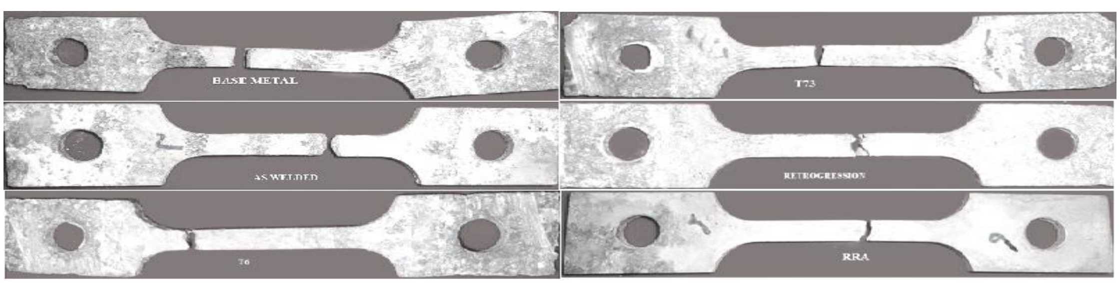


Figure 3.4.2. Fractured Welded SCC Samples under Various Temper Conditions

The time to failure for the specimen under RRA condition is 175 days. These results clearly showed that RRA and Retrogression treatments after friction stir welding greatly improved the stress corrosion resistance. The failed SCC specimens were shown in the Figure 3.4.2. From Figure 3.4.2 it can be seen that the fracture locations are same when compared to tensile test specimens which were shown in the Figure 3.3.2. Figure 3.4.3 shows the time to failure of welded SCC specimens under different conditions.

Swanson *et al.* [4] have studied the SCC behaviour of the RRA-treated aluminium alloy 7075 and concluded that the RRA treatment is only beneficial to crack initiation but not to crack propagation. Wallace *et al.* [5] have measured the crack growth rate as a function of stress intensity using double-cantilever-beam specimens and contrarily concluded that the crack growth rate significantly decreases as a result of the RRA treatment, confirming the original claim of Cina and Ranish. Rajan *et al.* [9] and Danh *et al.* [10] have reported that the reversion of Guinier-Preston (GP) zones is responsible for the initial decrease in strength during the retrogression treatment. The retrogression behaviour is shown to be determined by competition between the dissolution of small η' particles and the precipitation of η1 phase.

Hence improvement in resistance to SCC might be due to re-distribution of precipitates in the matrix of friction stir welds of AA7075 alloy.

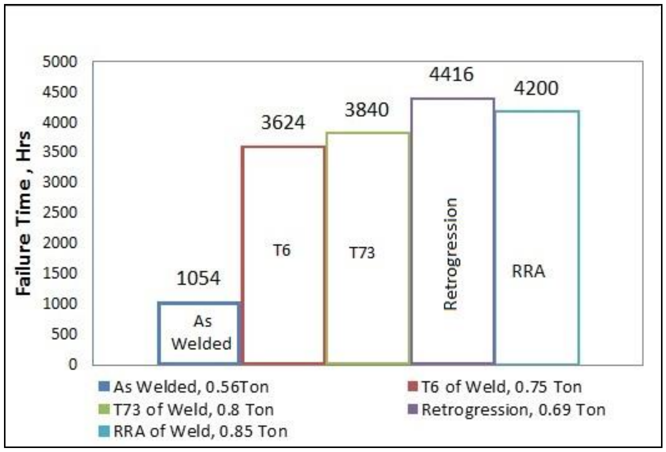
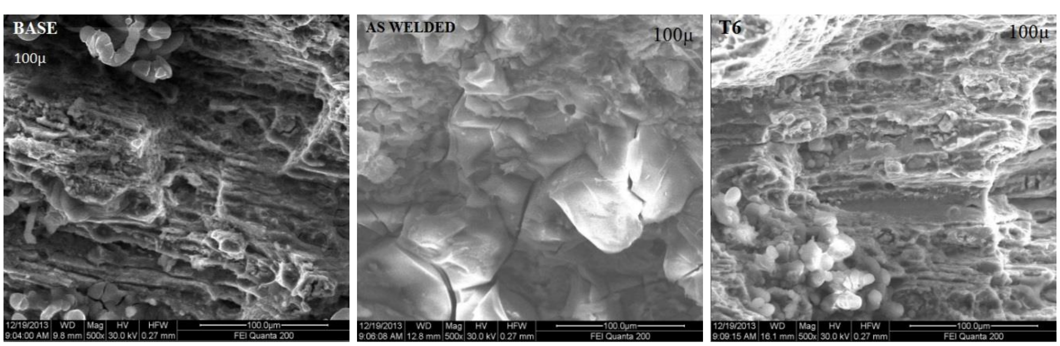


Figure 3.4.3. Graphical Presentation of Failure Times during SCC Testing

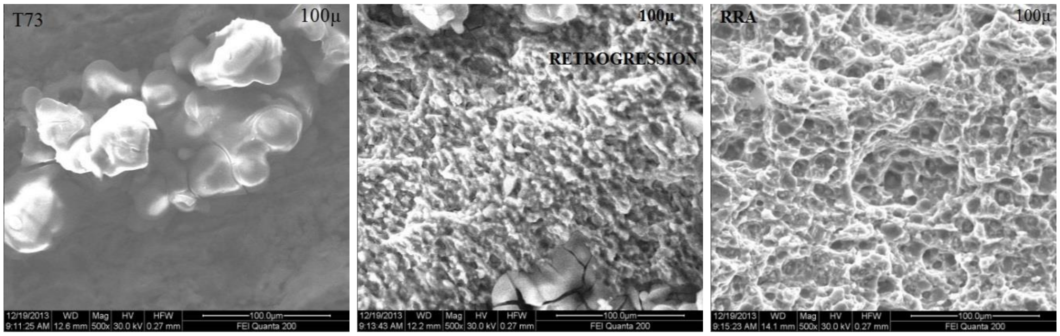
3.5. Fractography

The SEM analysis of the fractured SCC samples obtained from the friction stir welded aluminium 7075 alloy was performed and is shown in the Fig.3.5.1. SEM fracture surface micrographs showed deep grooves on the specimen edges where the elongated grains pulled out when decohesion occurred in the grain boundaries.

It is demonstrated that the fractures of RRA and Retrogression are all in transgranular-intergranular combined mode and both conditions represent fibrous ductile fracture, with many small dimples inside the surface of fibrous fracture. There are more transcrystalline fractures, and fewer intergranular fractures caused by the second phases within the dimples. The fracture behavior of alloy is due to the reduction of un dissolved coarser phase and the increase of precipitated phase (the increase of yield Strength) [20].



a) Base b) As Welded c) T6



d) T73 e) Retrogression f) RRA

Figure 3.5.1. SEM Fractographs of Fractured welded SCC Samples under Various Temper Conditions

4. Conclusions

1. When joining the higher strength 7075 aluminum alloys, post weld heat treatment is necessary to stabilize the microstructure in the friction stir welded regions.
2. Post-weld heat treatment of friction stir welds has the potential to restore the corrosion resistance in sensitized weld zones to that of the parent metal.
3. Overaging (T73) from Peak aged (T6) condition (RRA) improves the SCC resistance with minimum loss of strength. This may be due to the reversion of micro structure to original state and reprecipitation of coarsened strengthening precipitates.
4. The peak aged condition (T6) shown better mechanical properties than other post weld treatments. T6 treatment can be applied to the welds when corrosion is not a concern.
5. The Failure time and yield strength under Retrogression treatment condition was 184 days and 341MPa respectively. Whereas it was 175 days and 420MPa in case of RRA condition. The results show that the SCC resistance was more in retrogression but the strength was slightly inferior as compared to RRA. In RRA the SCC resistance was good and also the strength was recovered nearer to the base metal strength.

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