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Stress Corrosion Cracking Behaviour of GMAW-GTAW welded 7004-T75311 Aluminium alloys

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Abstract

Stress corrosion cracking (SCC) behaviour of GMAW-GTAW welded 7004-T75311 Aluminium alloys was investigated by using Slow Strain Rate Tensile Testing immersed in6.0 NaCl solution. Room temperature Tensile behaviourand Stress Corrosion Cracking behaviour were characterized by using Instron Universal Testing Machine at slow strain rate of 2.54 x10^{-3} s^{-1}. The time to failure ratio, plastic elongation ratio and area reduction ratio were measured for both the welded and base metal specimens by immersing them in 6.0 % NaCl solution. Experimental observations revealed thatthe parent materialoffers superior corrosion resistance to stress corrosion cracking when compared to that of all the welded specimen, but GMAW specimens shows comparatively higher susceptibility to SCC than GTAW specimens. Role of welding process and corrosive environment (dry, wet and hot medium)on SCC behaviour of the welded joints were discussed.

1. Introduction

The unique combinations of properties provided by aluminium and its alloys make aluminium one of the most versatile, economical, and attractive metallic materials for a broad range of uses from soft, highly ductile wrapping foil to the most demanding engineering applications [1]. Between the highly competitive field of commercial shipping and the expanding uses of the naval military force, there is a need to increase marine vessel efficiency. Rising fuel costs and the requirement to carry larger loads over greater distances is the chief motivation for improving ship design and construction. Specifically, advancements in the design and fabrication of the new Littoral Combat Ship were completed with an emphasis on the optimization of speed, mission flexibility and shallow draft. One such way to improve ship design is decreasing the weight of building materials in marine vessels while maintaining the strength of the materials currently in use. This conundrum has resulted in the research and development of materials with high strength, low weight, good weldability, and good corrosion resistance for marine and military applications. Aluminium is approximately one third the density of steel with comparable strength and weldability, making it a viable material choice. Specifically, the 7xxx series aluminium alloys have been considered a good choice for marine applications due to their high general corrosion resistance compared to other aluminium alloys [1].A variety of welding processes can be used to join Aluminium including the fusion methods GMAW (standard MIG, plasma and pulse) and GTAW (standard TIG and plasma) giving high quality, all-position welding, manual, mechanized or fully automatic. Choice of process is based on technical and/or economic reasons. For most structural economical and quality welds, TIG and MIG are recommended for Aluminium [2-3].

Stress corrosion cracking (SCC) is a failure mechanism that is caused by environment, susceptible material, and tensile stress. Temperature is a significant environmental factor affecting cracking (or) a structure under static tensile stress, much below the yield stress, in contact with corrosive environment may fail due to SCC. Three conditions must be present simultaneously to produce SCC: a critical corrosive environment, a susceptible alloy and some component of tensile stress [4]. The stress corrosion cracking initiation and propagation is a very complex degradation process, which depends on several parameters; these can be classified in micro structural, mechanical and environmental, and its intricate relationship which causes the failure.Aluminium alloy AA7004 (Al-Zn-Mg) with temper condition T75311 is generally characterized by high strength, but they are prone to SCC. However, the tendency of these alloys to SCC changes depending on the content of alloying elements and other treatments. Maximum strength of the alloy is achieved, when there is a mixture of GP zones & η-I precipitates. In the state of maximum strength, the alloys are prone to SCC and exfoliation corrosion [5]. In the over-aged state, the alloys are characterized with a good resistance towards both SCC and exfoliation corrosion, while in the partially overaged state the alloys show a slightly lower resistance to SCC and high resistance to exfoliation corrosion [6]. Susceptibility of the alloy depends on the heat treatment. PWHT is not recommended for this alloy, so natural aging treatment for 28days is followed to retain the mechanical properties [6].

Lee et al. [6] investigated the effects of environment concentration and strain rate on the stress corrosion cracking (SCC) behaviour of 5083-H131 and 7075-T6 aluminium alloys were studied, conducting electrochemical measurement and slow strain rate test. The employed environments were pH 7.3 aqueous solutions of 0 to 20% NaCl, and the applied strain rate ranged from 10^{-8} s^{-1} to 10^{-4} s^{-1}. A comparative test was also carried out in air. After the tests, the fracture surface morphology was examined by scanning electron microscopy and the microstructure in the vicinity of the fracture by light microscopy to clarify the SCC mode. Compared to 7075-T6, 5083-H131 had inferior mechanical strength (UTS, YS, and hardness) in air and greater SCC susceptibility in NaCl solution. Crack was initiated at the junctions of grain boundaries with the specimen surface and grown inward along grain boundaries under slow straining in a NaCl solution. The SCC mechanism is simultaneous anodic dissolution and hydrogen embrittlement of grain boundaries.Eltaiet al. [7] investigated the effects of TIG welding on the corrosion and mechanical properties of Al alloy 6061 T6. The findings made by the experimental examination of welded and un-welded specimens are, the heat affected zone is more susceptible to corrosion than the rest of the base metal due to thermal alteration that resulted from the welding process. The corrosion potential of the HAZ has fluctuated and it was more negative than the potential of the BM. The ultimate tensile strength of the TIG welded AA 6061 T6 specimens was 193.107 MPa which is 54% that of the base metal. The size and the spacing between the grains close to welded area were bigger compared to that located away from the weld.Emilyet al. [8] examines the effect of sensitization on the stress corrosion cracking behaviour of marine grade aluminium alloys (Al-Mg). These alloys can be sensitized during operation, promoting their susceptibility to intergranular stress corrosion cracking (IGSCC). Aluminium alloy 5456-H116 (also identified as Al-Mg5.1) samples were sensitized at 175ºC for varying durations of time and then mechanically tested in salt water. Mass loss tests quantified the degree of sensitization (DOS) as a function of sensitization time. Dual cantilever beam tests were used to measure the SCC growth rate and cyclic fatigue tests were conducted to determine the corrosion fatigue behaviour. DOS increased as sensitization time increased with little difference in mass losses above 336 hours. Stress corrosion crack growth rate increased as sensitization time increased. Although the sensitization rates for AA5456-H116 were higher than for AA5083, the stress corrosion crack growth rates were significantly lower. The stress corrosion fracture surfaces showed clearly showed a clearly intergranular fracture path with extensive crack branching and delamination in the transverse direction. The main objective of this present work is to understand the stress corrosion cracking behaviour of GMAW-GTAW welded 7004-T75311 Aluminium alloys. Role of different welding conditions and corrosion medium on SCC behaviour has to be explored. Such findings can be applied to optimize the welding and corrosion parameters for 7004-T75311 Aluminium alloys which can be used in marine applications.

2. Materials and Methods

The alloy taken in to consideration for this study was Aluminium alloy 7004 in T73511 temper condition, where zinc & Magnesium are the major alloying elements with trace amount of copper in it, where little amount of copper imparts resistance to Stress Corrosion Cracking (SCC)& exfoliation corrosion. It is an overaged, heat treatable, wieldable and self-aged (or) Natural aged alloy [9]. It takes 28 days of natural aging time after welding to regain mechanical properties. For this investigation 9.52 mm flat extruded plate is taken in to consideration. The chemical composition of this alloy is shown in Table 1

Element	Min. (%)	Max. (%)
Zn	3.80	4.60
Mg	1.00	2.00
Mn	0.20	0.70
Zr	0.10	0.20
Cr	0.00	0.05
Si	0.00	0.25
Fe	0.00	0.35
Ti	0.00	0.05
Cu	0.00	0.05
Al	Remainder	Remainder

Table 1: Chemical composition of AA7004-T73511

Eight parent material coupons are prepared to make four welded coupons from 9.50mm extruded flat plat. Welding of these coupons are carried out based on the standard & approved WPS (Welding Procedure Specification). Schematic representation of weld test coupon is shown in

Figure 1 andthe dimensions of the same are shown in Table 2.GMAW & GTAW welding processes are channelled using ER5356 filler wires (chemical composition is shown in Table 3). The different operating parameters and welding data sheets are mentioned in Table 4 to Table 7 [10].

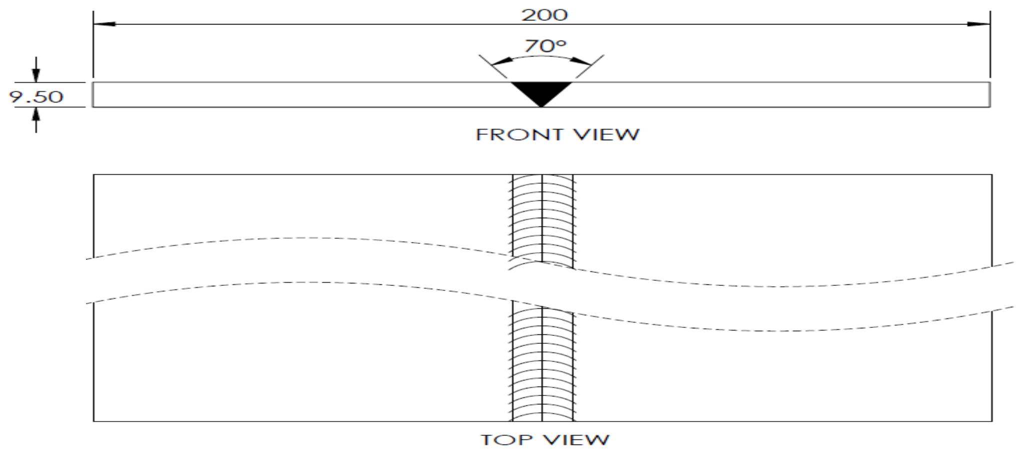

Figure 1: Schematic representation of weld test coupon

S.no	Type of welding	Dimensions (in mm)	Weld coupon Id
1	GMAW	300X200X9.50	W1-GMAW-1
2	GMAW	250X200X9.50	W1-GMAW-2
3	GTAW	250X200X9.50	W2-GTAW-1
4	GTAW	250X200X9.50	W2-GTAW-2

Table 2: Dimensions &IDs of weld test coupons

S.No.	Alloy Element	ER5356
1	Mg	4.5-5.5
2	Cu	0.1Max
3	Si	0.25 Max
4	Fe	0.40 Max
5	Mn	0.05-0.20
6	Zn	0.10 Max
7	Cr	0.05-0.20
8	Ti	0.06-0.20
9	Al	Remainder
10	Beryllium	0.0008 Max
11	Unspecified	Each0.05 & Total 0.15

Table 3: ER5356 filler wire composition

Weld data sheet for plate Id – (W1- GMAW-1)

S.no	Weld passes	Time (T) in sec	Amps	Volts	Travel speed (mm/min)	Heat input (KJ/mm)
1	Root	95	125	18.2	189	9.62
2	1	58	160	20.9	310	8.62
3	2	48	170	21.4	375	7.76
4	3	46	170	21.6	391	7.51

Table 4: weld data sheet for Gas Metal Arc Welding (GMAW) plate 1

Weld data sheet for plate Id – (W1- GMAW-2)

S.no	Weld passes	Time (T) in sec	Amps	Volts	Travel speed (mm/min)	Heat input (KJ/mm)
1	Root	104	130	17.2	172	10.4
2	1	63	160	20.3	285	9.11
3	2	52	165	22.2	346	8.46
4	3	45	170	23.8	400	8.09

Table 5: weld data sheet for Gas Metal Arc Welding (GMAW) plate 2

Weld data sheet for plate Id – (W2- GTAW-1)

S.no	Weld passes	Time (T) in sec	Amps	Volts	Travel speed (mm/min)	Heat input (KJ/mm)
1	Root	184	185	15.1	97	17.2
2	1	141	185	15.3	127	13.3
3	2	138	185	14.5	130	12.3
4	3	170	175	15.6	105	15.6
5	4	162	175	15.3	111	14.4
6	5	142	165	15.1	126	11.8

Table 6: weld data sheet for Gas Tungsten Arc Welding (GTAW) plate 1

Weld data sheet for plate Id – (W2- GTAW-2)

S.no	Weld passes	Time (T) in sec	Amps	Volts	Travel speed (mm/min)	Heat input (KJ/mm)

1	Root	280	172	13.2	64.28	21.19
2	1	164	176	12.3	109.75	11.83
3	2	106	168	12.7	169.81	7.53
4	3	87	165	13.2	206.89	6.31
5	4	62	160	12.9	290.32	4.26
6	5	61	158	12.8	295.08	4.11

Table 7: weld data sheet for Gas Tungsten Arc Welding (GTAW) plate 1

Round direct tension test specimens were machined to ASTM B557M standard as shown in the Figure 2. CNC milling machine is used to cut the specimen in to required dimensions. Those specimens were subjected to tensile testing, constant load testing (continuous immersion in 6% boiling NaCl solution) & SSR testing [11-12].

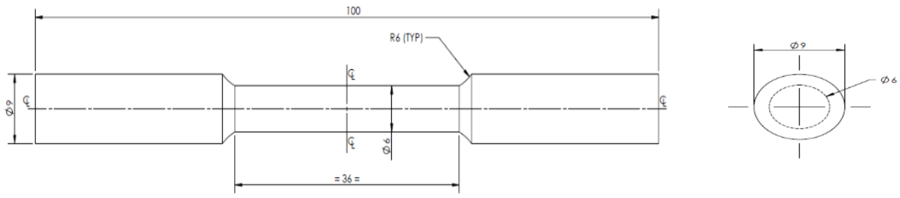

Figure 2: Specimen geometry of round direct tension specimen (as per ASTM B557M)

Universal Testing Machine (INSTRON 300DX) was used to conduct tensile testing on round tension specimens. Machine with a capacity of 250 KN and with a cross head speed of 3 mm/min is used for testing. Nine specimens (i.e. 3 no's of specimens from each Parent Material, GTAW& GMAW respectively) is considered for testing. Ultimate tensile strength, 0.2% of proof strength and percentage elongation is measured for the purpose of study.INSTRON – 5586 tensile testing machine is used to conduct SSRT to evaluate SCC behaviour of AA7004. Eighteen specimens were prepared to conducting SSRT, out of which 9 specimens (3 PM + 3 W1 +3 W2) were tested under controlled environment (Dry Air) and the rest of them (3 PM, + 3 W1 + 3 W2) were conducted in an environmental test cell filled with 3.5% NaCl solution. The gauge section of the specimen is completely immersed inside the test environment during the test period. The specimen is pulled in tension to fracture, by maintaining a slow extension rate of $2.54X10^{-3}$ mm/sec. a comparative evaluation is carried out between the two different test environments (i.e. Dry air and solution) to check the material resistance to SCC under evaluation. In the analysis of test results, the time to failure, elongation and reduction in area is taken as the measures of SCC susceptibility.

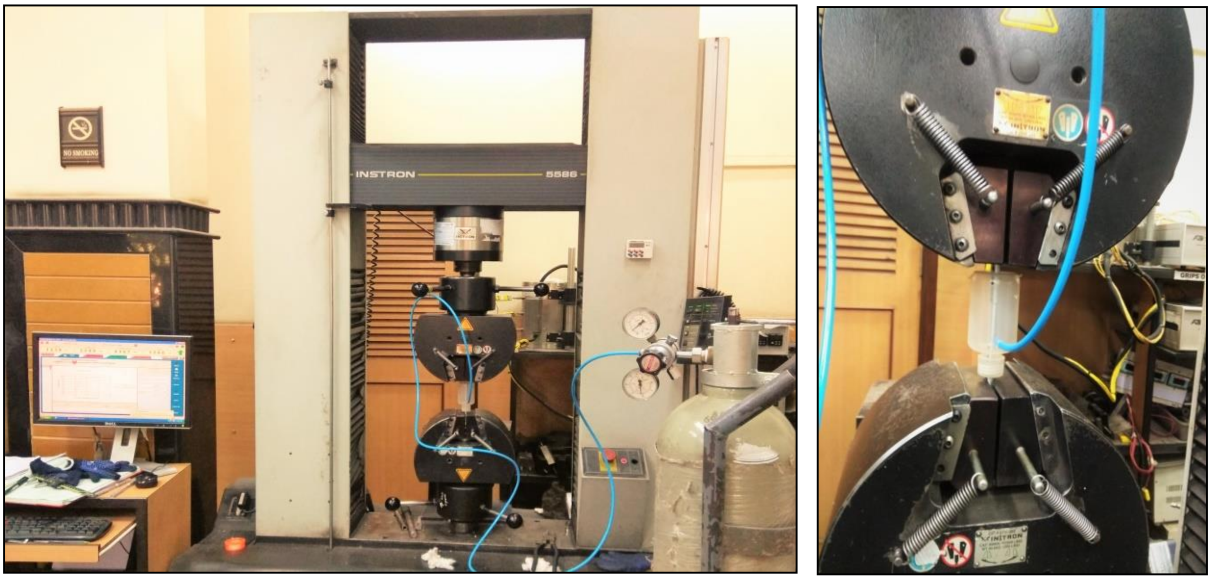

Figure 3: Specimen loaded in SSRT machine under controlled environment (Dry Air)

SSRT in controlled environment:Metaphors of SSR Testing is shown in Figure 3, where a chamber is arranged in which the gauge section is completely enclosed, then dry air is passed in to the chamber with a pressure of 30 psi. In such a case entire gauge length will experience a controlled environment with uniform rate. There will be a continuous circulation of dry air throughout the entire testing period [11-12].

SSRT in corrosive environment: The specimens are cleaned and immersed in a corrosive medium. Specimens are placed in an environmental test cell (made of acrylic), where its ends are inserted into the holders of displacement gauges. Then 3.5% sodium chloride solution is allowed to fill the environmental test cell (as shown in Figure 4) followed by inducing very slow extension rate ($2.54X10^{-3}$ mm/sec) on to the specimen. In such a case gauge length of the specimen will be completely immersed inside the solution till failure [11-12].

Figure 4: Specimen loaded in environmental test cell with 3.5% NaCl solution

The test results to be used for the evaluation of resistance of the material to SCC in SSR testing may depend largely on the intended application and service performance. As a minimum, the following ratios shall be utilized in evaluating SSR test data for a particular extension rate.

Time to Failure ratio: The ratio of time to failure determined for the material in the test environment (*TTFe*) to the corresponding value determined in the control environment(*TTFc*).

Plastic Elongation ratio: The ratio of plastic elongation determined for the material in the test environment (*Ee*) to the corresponding value determined in the control environment (*Ec*)

Reduction in Area ratio: The ratio of reduction in area after fracture for the specimen in the test environment (*RAe*) to the corresponding value determined in the control environment (*RAc*).

In all cases, evaluation of the SSR ratios and for indication of SCC shall be based on the decrease in the value of the SSR ratios from unity. Therefore, to maximize SCC resistance, it is desirable to obtain values of SSR ratios as close to unity as possible. Lower values of SSR ratios generally indicate increasing susceptibility to SCC.Two specimens (i.e. one GMAW & one GTAW specimen) were used to conduct constant load test in which specimens were stressed to 90% of yield strength and then immersed in boiling 6% NaCl solution continuously for about 168hrs. Temperature of the solution is maintained between 92ºC to 95ºC.The 6% NaCl solution is heated to boiling by means of quartz immersion heaters. The power stat controls the heat output of the quartz heater. Cold water circulating glass condenser tube is placed to prevent evaporation losses as shown in Figure 5. Stressed specimens are placed to the test cell after the solution comes to boil. Specimens are examined in place for visual evidence of cracking.

Figure 5:SCC Test – Continuous immersion of specimen in boiling 6% NaCl solution.

The 6% NaCl solution is prepared by using distilled water conforming to the purity requirements of Specification D 1193, Type IV reagent water, except that values for chloride and sodium shall be disregarded. Concentration of the salt solution is prepared by dissolving6.0 ± 0.1 parts by weight of NaCl in 94.0 parts of water.Solution is maintained between 6.4 and 7.2. The pH is adjusted by the addition of dilute reagent grade HCl solutions [11-12].

3. Results and Discussions

The results of the tensile tests conducted on AA7004-T75311 specimens are shown in Table 8. Nine specimens were considered for testing (i.e., 3 Nos machined from Parent Material coupon, GTAW coupon & GMAW coupon respectively). The specimens were degreased before the testing. The speed of the displacement gauges is maintained constant as 3mm/sec till failure.

Specimen ID	Yield strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
Parent Material (PM)			
PM-TT-1	373	423	15.93
PM-TT-2	368	418	14.67
PM-TT-3	351	402	16.53
Average	**364**	**414**	**15.71**
GMAW (W1)			
W1-TT-1	220	298	8.47
W1-TT-2	223	299	7.00
W1-TT-3	211	295	10.33
Average	**218**	**297**	**8.6**
GTAW (W2)			
W2-TT-1	207	306	8.83
W2-TT-1	205	298	12.13
W2-TT-1	199	297	9.63
Average	**207**	**300**	**10.2**

Table 8: Tensile properties of Parent Material, GMAW & GTAW specimens

Tensile properties of the PM specimens are higher when compared with the W1 & W2 specimens. The coupons are welded by using ER5356 filler wire. Strength and elongation of ER5356 is lower when compared with AA7004.The ultimate tensile strength of the welds got reduced to ~72% when compared with Parent material (i.e. AA7004 T75311).The yield strength of W1 specimens is slightly higher than W2 specimens. The ultimate tensile strength is almost similar, but the elongation of W2 specimens is higher than W1. The results of SSR Testing for parent material, GMAW & GTAW is shown in table 16. A comparative evaluation is drawn between controlled environment (Dry Air) and corrosive environment (3.5% NaCl solution). Load was imposed on specimens through the shifting cross-head of the testing device at quite slow but constant speed. SSRT was carried out with uniform extension rate of $2.54x10^{-3}$ /sec till failure.Evaluation of the SSR ratios and for indication of SCC shall be based on the decrease in the value of the SSR ratios from unity. The obtained SSR ratios are shown in Table 9. Therefore, to maximize SCC resistance, it is desirable to obtain values of SSR ratios as close to unity as possible. Lower values of SSR ratios generally indicate increasing susceptibility to SCC.

SSR Ratios			
	Time to failure	**Elongation**	**Reduction in area**
Parent material	Unity	Unity	Unity
GMAW (W1)	0.87	0.85	0.6
GTAW (W2)	Unity	Unity	0.8

Table 9: SSR ratios for parent material and weldments

SSR ratios are calculated based on the values obtained from SSR Testing in both controlled and corrosive environment. The obtained results are tabulated in Table 10. As per the ratios, parent material and GTAW specimens shows good resistance to SCC, but GMAW specimens shows lower values of SSR ratios from unity. This shows that GMAW welds are susceptible to SCC when compared with parent material and GMAW specimens.

SSRT (Dry Air)				**SSRT (3.5% NaCl solution)**			
Parent Material (PM)				**Parent Material (PM)**			
Specimen id	Time to failure (Min)	% Elongation	% Reduction in area	Specimen id	Time to failure (Min)	% Elongation	% Reduction in area
PM-A1	32.36	15.50	29.59	PM-B1	34.85	16.43	37.73
PM-A2	34.23	15.56	31.10	PM-B2	35.94	15.23	33.28
PM-A3	35.60	15.33	33.06	PM-B3	36.75	15.57	40.56
GMAW (W1)				**GMAW (W1)**			
Specimen id	Time to failure (Min)	% Elongation	% Reduction in area	Specimen id	Time to failure (Min)	% Elongation	% Reduction in area
W1-A1	16.4	8.00	31.61	W1-B1	12.37	5.83	19.80
W1-A2	17.7	8.23	35.36	W1-B2	16.47	7.77	20.76
W1-A3	17.4	7.77	33.75	W1-B3	6.34	3.00	9.06
GTAW (W2)				**GTAW (W2)**			
Specimen id	Time to failure (Min)	% Elongation	% Reduction in area	Specimen id	Time to failure (Min)	% Elongation	% Reduction in area
W2-A1	19.6	8.47	40.34	W2-B1	24.98	11.07	26.86
W2-A2	21.7	9.73	35.89	W2-B2	24.57	10.77	35.15
W2-A3	25.0	10.83	34.94	W2-B3	23.88	11.33	26.73

Table 10: SSRT results for Dry Air and 3.5% NaCl solution

Optical micrographs of SSR testing for parent material and welds in dry air environment and in 3.5% NaCl environment are shown in Figure 6. Magnification used for observations is of 500X and HF is used as an etchant.Micro graphs of Parent material specimens and GTAW specimens haven't revealed any type of cracking on the surface, but on the other hand GMAW specimens shows a river branched structure (cracking) on its surface. This implies that GMAW welds have higher susceptibility to SCC when compared with parent material.

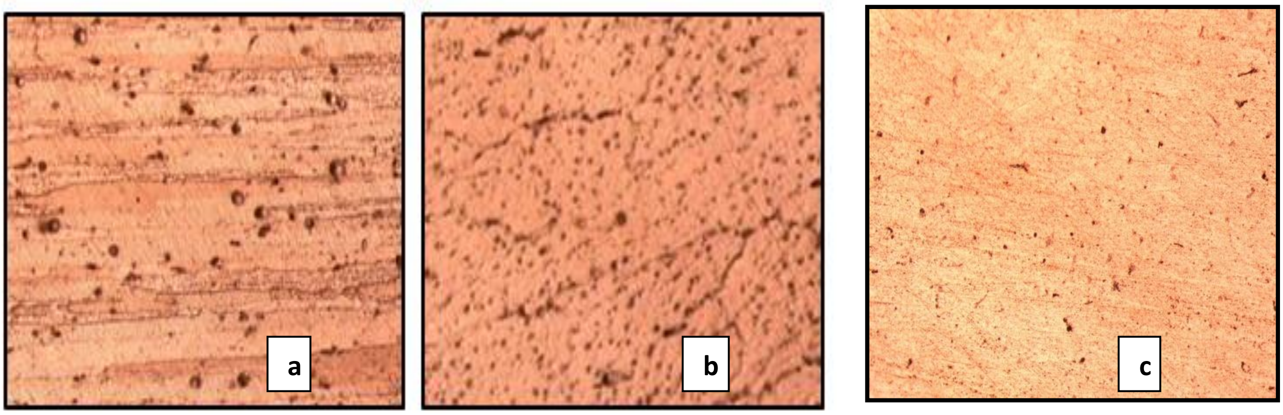

Figure 6: Micrographs of SSRT specimens in Dry Air environment a) parent material b) GMAW weld c) GTAW weld

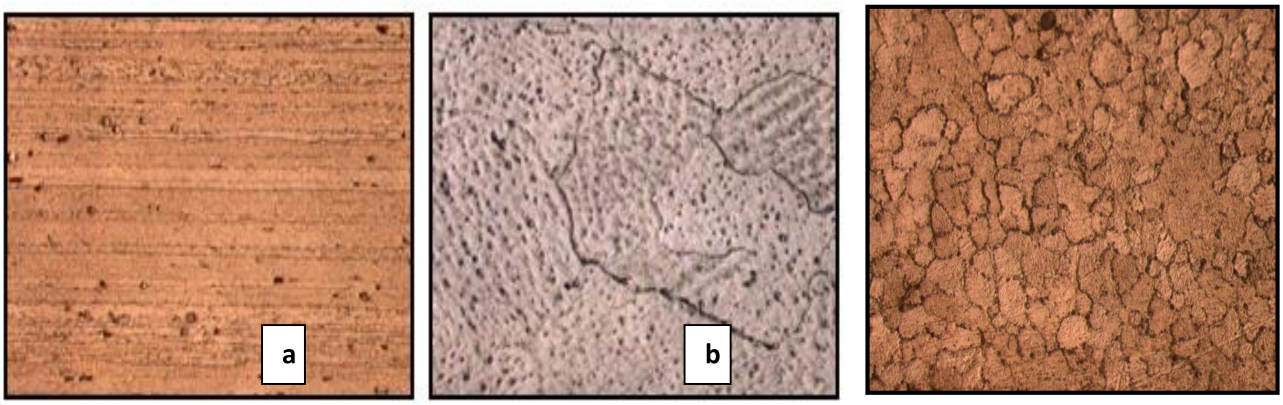

Figure 7: Micrographs of SSRT specimens in 3.5% NaCl solution a) parent material b) GMAW weld c) GTAW weld

By observing the micrographs [Figure 6 and Figure 7]and SSR ratios the results reveal that GMAW welds have higher susceptible to SCC when compared with GTAW welds and Parent material. There is no evidence of pitting on the surface of the specimens as well.Parent material (AA7004 T73511) shows good resistance to SCC. Filler wire ER5356 also shows good resistance to SCC but comparatively lesser than AA7004.It has been understood that the surfaces of aluminium alloys tend to be covered with oxide film in corrosive environment; this is the reason behind increasing in time to failure, when tested in corrosive environment when compared with controlled environment. As the SCC susceptibility changes with strain rate, it was concluded that, at high strain rates the corrosion process cannot keep up with the staining process and the influence of corrosion is negligible.Test results reveals that GMAW specimen failed (failure happened in parent material area) after 68 hours of test duration in boiling 6% NaCl solution, whereas on the other hand GTAW specimen failed (failure happened in parent material area) after 74 hours of test duration as shown in Figure 8. Observations on the surface of the specimens by using 10X magnification lens revels pitting in parent material area. As per ASTM G103 standard if the surface of the specimen shows the evidence of pitting or pitting with Trans granular or Intergranular attack may not be considered as SCC failure.

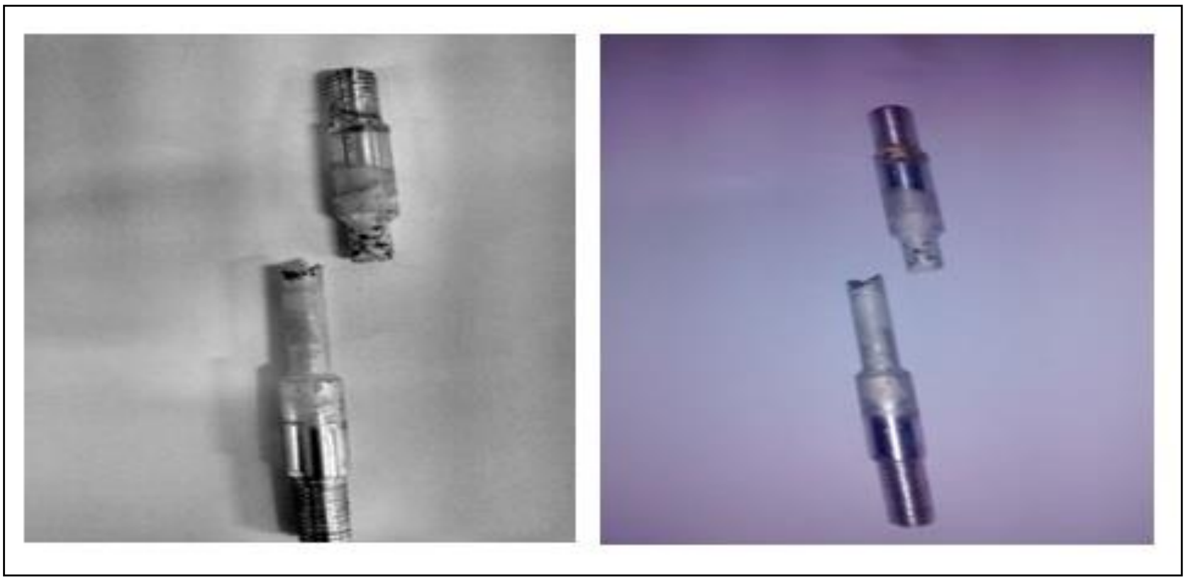

Figure 8: Failed GMAW and GTAW specimens after boiling NaCl solution test

There is no evidence of cracking or pitting on the surface of the welds, this shows ER5356 has good resistance to SCC and exfoliation corrosion. Since there is evidence of pitting on the surface of parent material, it can be concluded that AA7004 T73511 also have good resistance to SCC (As per ASTM G103), but alloy need resistance to pitting and exfoliation corrosion.

4. **Conclusions**

1. GMAW specimens shows comparatively higher susceptibility to SCC than GTAW specimens.It was found that the surfaces of aluminum alloys tend to be covered with oxide film in corrosive environment. This is the reason behind increasing in time to failure, when tested in corrosive environment when compared with controlled environment.

2. It was experimentally observed that for the specimen tested at high strain rates, the corrosion process cannot keep up with the staining process and the influence of corrosion is negligible.
3. In constant load test (Boiling 6% NaCl test), only pitting is evident on the surface of the specimen, and the welds are even safer without any evidence of corrosion on its surface. It was observed thatboth the parent material&welded specimen with ER5356 filler wire show good resistance to SCC when compared to their counterparts. However, AA7004 T73511 has superior mechanical strength of about 72% greater than ER5356.

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