Analysis and Test for Optimal Pitting Corrosion and Mechanical Properties of AA 6061- T6 for Marine Applications

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Abstract – Aluminium and its alloys play crucial role in engineering materials field. The predominance of this is attributed to the excellent corrosion properties owing to the tenacious oxide layer, easy fabricability and high specific strength coupled with best combination of toughness and formability. In the domain of joining processes of aluminium and its alloys, the Tungsten Inert Gas (TIG) welding process continues its apex position due to its versatility and flexibility in adaptation. The superior weld quality obtained in TIG weldments differentiates the TIG process in comparision with other competing and emerging joining processes. TIG welding plays an important role in the joining processes as it provides high and superior quality welds. In aerospace applications, one of the major problems faced is corrosion. The corrosion resistant is one of the controlling parameter for selection of materials and welding process. As the aluminium alloys are keen on reducing the weight of the aircrafts, it is much preferred. The corrosion resistance is also one of the parameter for selecting AA6061 and TIG welding process. In the present work the parent metal and weldment taken as samples for corrosion tests. The corrosion protection performance of aluminium materials was investigated in 3.5% NaCl solution for time ranging between 1-60 days. Free immersion techniques were used to check and study the corrosion behaviour. Microstructure and mechanical properties were analysed and tested before and after corrosion. After the test we conclude that the amount of corrosion is almost nill because of the usage of ER4043 filler in the weldment. This ensures that the welding parameters are optimal. In NaCl solution corrosion attack is uniform. No localized pitting has been observed. It is observed from the microstructure the pits are deeper and more in number in case of demineralised water than 3.5% salt solution. Hence we can recommend AA 6061-T6 can be used for all kinds of marine applications and even in high altitude applications.

Key Terms— Corrosion, AA6061-T6, TIG welding, Heat treatment, Immersion techniques, Fusion zone.

I. INTRODUCTION

Aluminium Alloy 6061-T6 has excellent corrosion properties, easy fabricability and high specific strength coupled with best combination of toughness and formability. Due to its light weight, high thermal conductivity, high strength ratio and ultimate tensile strength it is used in aerospace and marine applications for making storage tanks. Temper T4 designate Solution heat treated and naturally aged, T6 for Solution heat treated and artificially aged. AA6061-T6 has excellent properties like melting point of 660^{o} C, Light weight, density is about 1/3 that of steel or copper alloys, have a better strength to weight ratio than that of high strength steel, have good malleability and formability, high corrosion resistance and high electrical and thermal conductivity. Strength can be increased by cold working. It has ability to resist corrosion very effectively due to the phenomenon of passivation. The chemical composition of AA 6061-T6 is shown in table 1.

Table 1 Chemical composition (in wt %) of AA 6061-T6.

Element	Mg	Fe	Si	Cu	Mn	V	Ti	Al
Weight %	1.08	0.17	0.63	0.32	0.52	0.01	0.02	Remainder

Alloys composed mostly of the two light weight metals aluminium and magnesium have been very important metal in the aerospace manufacturing. Aluminium-magnesium alloys are both lighter than other aluminium alloys and much less flammable than alloys that contain a very high percentage of magnesium.

II. WELDING PROCESS

Gas Tungsten-Arc Welding (GTAW), also known as Tungsten Inert Gas (TIG) welding, shown in figure 1 uses tungsten electrodes as one pole of the arc to generate the heat required. The gas is usually argon, helium, or a mixture of the two. A filler wire provides the molten material if necessary. The GTAW process is especially suited to thin materials producing welds of excellent quality and surface finish. Filler wire is usually selected to be similar in composition to the materials being welded. TIG-welding uses a permanent non-melting electrode made of tungsten. Filler metal is added separately, which makes the process very flexible. It is also possible to weld without filler material. The most used power source for TIG-welding generates Alternating Current (AC). Direct current can be used, but due to high heat generation on the tungsten electrode when DC-EP (electrode positive) welding, that particular polarity is not feasible. In some cases DC-EN (electrode negative) is used, however, this requires special attention before welding, due to the arc's poor oxide cleaning action. AC TIG-welding usually uses argon as a shielding gas. The process is a multipurpose process, which offers the user great flexibility. By changing the diameter of the tungsten electrode, welding may be performed with a wide range of heat input at different thicknesses. AC TIG-welding is possible with thicknesses down to about 0.5 mm. For larger thicknesses, greater than 5 mm, AC TIG-welding is less economical compared to MIG-welding due to lower welding speed. DC TIG-welding with electrode negative is used for welding thicknesses greater than 4mm. The negative electrode gives a poor oxide cleaning compared to AC-TIG and MIG, and special cleaning of joint surfaces is necessary. The process usually uses helium shielding gas. This gives a better penetration in thicker sections. DC TIG-welding is applicable for welding thicknesses in the range 0.3 - 12 mm. More and more popular is also pulsed DC TIG-welding, which makes it possible to weld uniform welds with deeper penetration at the same heat input. Pulse frequency is usually in the range 1 - 10 Hz. Figure 1 shows the typical TIG Welding setup for welding Aluminium Alloys.

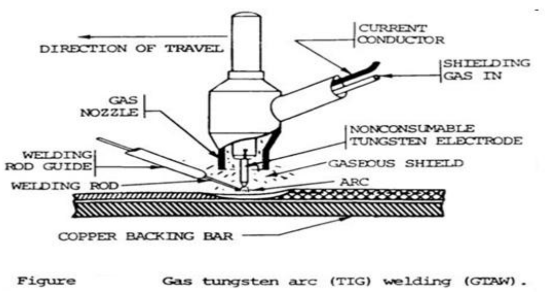

Fig. 1 TIG welding Setup.

TIG welding has superior quality weld can be obtained with TIG welding process. Loss of properties near the weld is less compared to other conventional welding processes on AA 6061-T6 in TIG welding. In case of as-welded aluminium alloys, the loss of properties in the weld zone and the heat affected zone due to TIG welding is much lesser than other welding processes. In the construction of pressure vessels and storage tanks, the weldability play unique role in selection of material and the type of welding operation.

III. CORROSION OF ALUMINIUM ALLOYS

Aluminium has a natural corrosion protection from its oxide layer, but if exposed to aggressive environments it may corrode. Still, if correctly fabricated, constructions of aluminium may be reliable and have long service life. Heat treatable aluminium alloys are widely used in aircraft structural applications and are susceptible to localized corrosion in chloride environments, such as pitting, crevice corrosion, intergranular corrosion, exfoliation corrosion and stress corrosion cracking. This article reviews the some aspects of passivity and pitting of Al–alloys. Specifically, metastable and stable pits, pitting mechanism, effect of intermetallics and effect of welding parameters on pitting corrosion of age hardenable Al-alloys.

3.1 Pitting

Pitting is a highly localized type of corrosion in the presence of aggressive chloride ions. Pits are initiated at weak sites in the oxide by chloride attack [8,1]. Pits propagate according to the reactions

$$Al = Al^{3+} + 3e^- \qquad (1)$$

$$Al^{3+} + 3H_2O = Al(OH)_3 + 3H^+ \qquad (2)$$

while hydrogen evolution and oxygen reduction are the important reduction processes at the inter-metallic cathodes, as sketched in the figure 2.

$$2H^+ + 2e^- = H_2 \qquad (3)$$

$$O_2 + 2H_2O + 4e^- = 4OH^- \qquad (4)$$

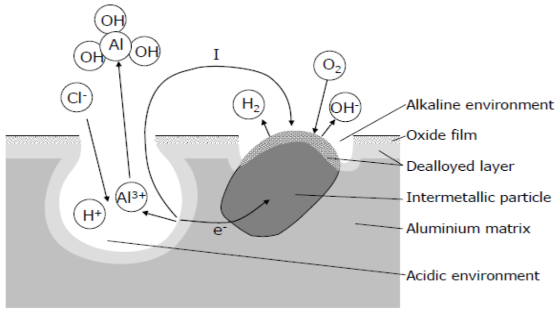

Fig. 2 Generalized illustration of pitting corrosion of aluminium alloys.

As a pit propagates the environment inside the pit (anode) changes. According to reaction 2 the pH will decrease. To balance the positive charge produced by reaction 1 and 2, chloride ions will migrate into the pit. The resulting HCl formation inside the pit causes accelerated pit propagation.

The reduction reaction will cause local alkalinisation around cathodic particles. As previously mentioned aluminium oxide is not stable in such environment, and aluminium around the particles will dissolve (alkaline pits). The active aluminium component of the particles will also dissolve selectively, thereby enriching the particle surface with Fe and increasing its cathodic activity. Etching of the aluminium matrix around the particles may detach the particles from the surface, which may re-passivate the alkaline pits. This may also reduce the driving force for the acidic pits causing repassivation of some in the long run. Figure 3 show pitting on an Al-Mg-Si alloy.

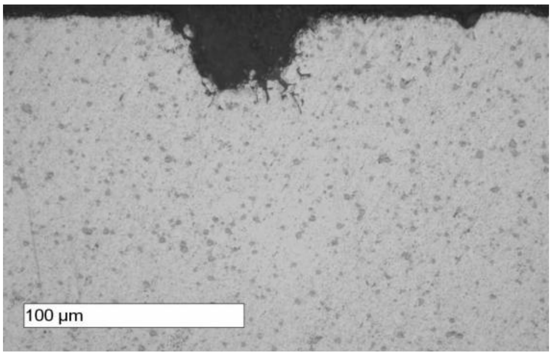

Fig. 3 Cross section of pitting attack on AA6061 aluminium alloy after exposure to marine atmosphere for 6 months. The dark spots are inter-metallic particles.

Pitting corrosion is defined as "localized accelerated dissolution of metals that occurs as a result of a breakdown of the protective passive film on the metal/alloy surface. In an aggressive environment, typically containing halide ions, pits initiate and grow in an autocatalytic manner, where the local environment within the pits becomes more aggressive because of decrease in P^H and increase in chloride concentration, which further accelerates the pit growth. Pit shapes can be simply divided into isotropic and anisotropic groups. If are anisotropic and are called microstructural orientated pitting. The variation in pit shape could mainly depend on the microstructure of metals or alloys such as alloy composition and aspect ratio of grains. Even though there are some differences in pitting corrosion between stainless steels and Al alloys, e.g., hydrogen bubbles form at the active pit surface in Al alloys both materials basically share a similar mechanism.

IV. CORROSION OF WELDS

Welding is an important method of fabrication and leads to physical, chemical and metallurgical changes in aluminium alloys. One of the reasons for the chemical changes in the welds is due to the different chemical compositions of the filler materials used. Weld thermal cycle also causes micro-structural changes in the weld metal and Heat Affected Zone (HAZ).These alloys after welding will be subjected to either post-weld natural aging (T-4) or post weld artificial aging (T-6).

The literature survey also indicated that there were no detailed and comparative studies available on corrosion behavior of welds of heat treatable aluminium alloys with respect to changes in welding and heat treatment conditions. When localized corrosion does occur in aluminium welds, it may take the form of preferential attack of the weld bead, pitting, intergranular attack or exfoliation may occur in a HAZ a short distance from weld bead. Welds in Al-Mg-Si alloys (AA6061) generally have a good resistance to atmospheric corrosion, but in specifically corrosive environments like seawater localized corrosion may occur. Reheat treatment of the welded part might restore the original corrosion resistance, but this is rarely possible. Some of the heat treatable alloys particularly those containing substantial amounts of copper and zinc, may have their resistance to corrosion lowered by the heat of welding. These alloys exhibit grain boundary precipitation in the HAZ and of this zone is normally anodic to the remainder of the weldment. In a corrosive environment selective corrosion on the grain boundaries may take place and in the presence of stress this corrosion can proceed more rapidly. Post weld heat treatment provides a more homogeneous microstructure and improves the corrosion resistance of these alloys. Welds in Al-Zn-Mg alloy were seen to be attacked preferentially in an area adjacent to the weld bead when exposed to a corrosive environment in the as welded condition. Post weld aging for a sufficient at a high enough temperature eliminated this preferential attack. Insufficient aging resulted in a knife-edge attack parallel to at some distance from weld.

Gas tungsten arc welding (GTAW) and Gas Metal Arc Welding (GMAW) processes are widely used for joining aluminium alloys for various applications like aerospace, defence and automotive industries. The resistance to corrosion of aluminium alloy welds is affected by the alloy being welded and by the filler alloy and the technique used. Galvanic cells that cause corrosion can be created because of the corrosion potential differences among the base metal, the filler metal and the heat-affected regions where microstructure changes have been produced. In the Aluminium-copper alloys, the heat-affected zone (HAZ) becomes cathodic, where as in aluminium zinc alloys; it becomes anodic to the remainder of the weldment. Selection of proper filler wire is important to avoid cracking during welding and to optimize corrosion resistance. When the solution potential of the filler is same as that of the base metal (4043 for 6061-T6 alloy), optimum corrosion resistance is obtained. In some cases inter-metallic phase formed by the base metal and filler wire determines the final corrosion resistance of the weld, for example magnesium silicate formed during welding 5xxx alloy with 4043 filler can be highly anodic to all other parts of the weldment. In general, the welding procedure that has the least influence on microstructure has the least chance of reducing the corrosion resistance of aluminium weldments. The alloy with the more negative potential in the weldment will attempt to protect the other part. Thus if the weld metal is anodic to the base metal (5356 weld in 6061-T6), the small weld can be attacked preferentially to protect the larger surface area of the base metal.

V. METHODOLOGY AND EXPERIMENTATION

Figure shows the procedure adapted for corrosion tests and mechanical properties tests before and after corrosion.

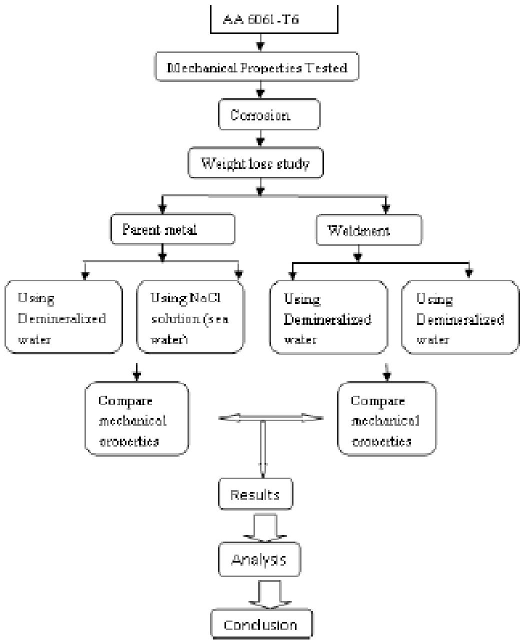

Fig. 4 Work flow diagram

5.1 Welding Parameters for joining

AC-TIG welding, 140-150 amp, 17-18 v, Gas flow rate is 14-16 lpm, Filler wire ER4043 of 2.4mm diameter, Helium 20% Argon 80% in arc6, Water cooled torch, Nozzle diameter 12m, Shield 11-standard number, Preheated up to 60%.

5.2 Weight loss corrosion test

The corrosion behaviours of Al 6061 alloy were studied by immersion test. The static immersion corrosion method was adapted to measure corrosion loss. 200cm^3 of sea water collected from the Arabian Sea, Malpe beach, Karnataka state, India was used as corrodent to characterize the corrosion behaviour. The sea water sample was subjected to different tests; the results were given in the table 2. NaCl–3.5% Sodium Chloride solution, DW – De-mineralized water. To minimize the contamination of the aqueous solution and loss due to evaporation, the beakers were covered with paraffin during the entire test period. Samples were suspended in the corrosive medium for different time intervals, up to 96hrs in steps of 24hrs. After the corrosion test, the specimens were cleaned mechanically by using brush in order to remove the heavy corrosion deposits on the surface. Different parameters of sea water measured are shown in Table 2.

Table 2 Parameters of Sea water

Test Parameter	Result mg/L
pH	6.18
Turbidity	2.3
Total dissolved solids (TDS)	4400ppm
Total Alkalinity CaCo3	120
Total Hardness CaCo3	7750
Calcium	4008
Magnesium	1634.8
Chloride	13739.5

5.3 Effect of test duration

The corrosion rate and potential measurements as a function of exposure time in the weight loss. In all the cases it is observed that the corrosion rate decreases in the beginning with increase in test duration and remains constant towards the end due to passivation. It is clear from the graph that the resistance of the composite to corrosion increases as the exposure time increases. The phenomenon of gradually decreasing corrosion rate and potential indicates the possible passivation of the matrix alloy. Visual inspection of the specimens after the tests revealed the presence of a black film covering the surface and that might have retarded the corrosion. De Salazar et al, who studied alumina reinforced Al-based MMC, observed that a protective black film is formed on the surface consisting of hydrogen hydroxyl chloride, which apparently retards the corrosion [11].

5.4 Types of weight loss corrosion test

Weight loss corrosion study is commonly carried out by two methods:

i) Continuous immersion test

ii) Alternate immersion test

5.4.1 Continuous Immersion Test

Continuous immersion test is subjecting the metal to corrosion continuously for a suitable duration of time in aqueous solution. Weight lost due to corrosion is measured by observing the difference in weight of the materials before and after it has been subjected to corrosion.

5.4.2 Alternate immersion test

According to ASTM standards, the metals are subjected to corrosion for a particular duration of time in aqueous solution, removed out, cleaned and left out in the uncovered position to the atmosphere for duration of time according to the prescribed standards.

5.4.3 Specimen preparation

Before performing the test specimen of standard size and shape must be produced from the material to be tested for the result which is to be compared. It is strongly advised to manufacture the specimen size and shape according to ASTM standards. Figures 5 & 6 shows the tensile test specimens of parent and weld metal coupons. Figure 7 shows the ASTM Standard parent metal and welded coupons before testing. Figure 8 shows the ASTM Standard parent metal and welded coupons after testing. Figure 9 shows specimen prepared for microstructure analysis which is collected from the weldment and parent metal. Figure 10 shows the experimental setup for corrosion tests at KSIT Research center, which contains glass containers for transparency and visibility.

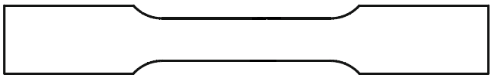

Fig. 5 Parent specimen

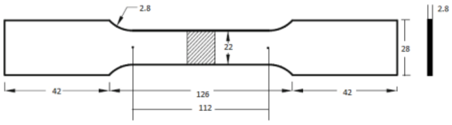

Fig. 6 Welded specimen

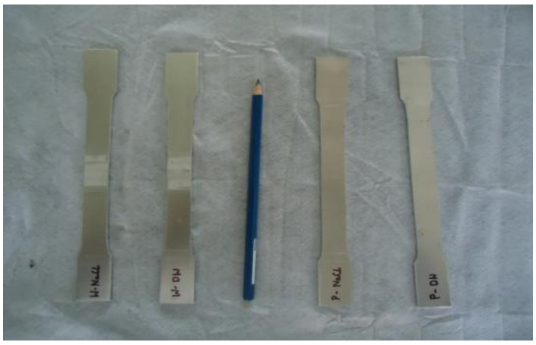

Fig. 7 shows the ASTM Standard coupons before testing.

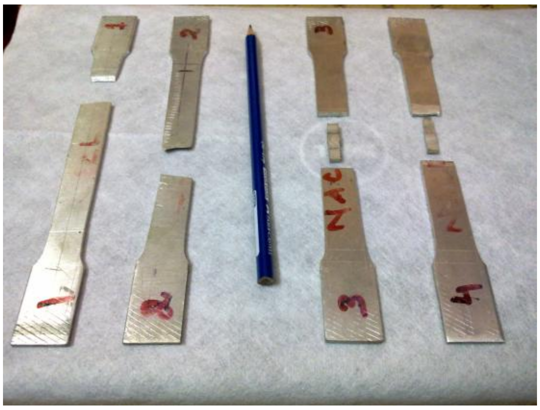

Fig. 8 shows the ASTM Standard coupons after testing.

Fig. 9 Specimen prepared for microstructure analysis.

Fig. 10 Experimental setup for corrosion tests

Figure 10 shows the experimental setup of corrosion tests for both continuous and alternate immersion tests.. Figure 11 indicates the setup for corrosion testing.

Fig. 11 Corrosion tests setup

Table 3 explains the weight loss recordings spread sheet

Time	art1	art2	art3	art4
	NaCl	DW	NaCl	DW
27-04-2016				
09:00	28.9005g	28.6634g	28.9973g	29.1536g
13:00	28.8996g	28.6632g	28.9966g	28.1533g
17:00	28.8995g	28.6631g	28.9965g	29.1533g
28-04-2016				
08:07	28.8996g	28.6631g	28.9966g	29.1533g
12:07	28.8993g	28.6629g	28.9963g	29.1533g
29-04-2016				
08:00	28.8992g	28.6629g	28.9964g	29.1533g
12:00	28.8989g	28.6626g	28.9963g	29.1529g
16:00	28.8988g	28.6625g	28.9963g	29.1527g

Table 3. weight loss recordings spread sheet

VI. RESULTS AND DISCUSSION

Mechanical properties before and after corrosion are evaluated and recorded in tables 4 & 5.

Before corrosion

Table 4 comparison of parent metal and weldments before corrosion

Type	Parent metal	Weldment
Peak load-KN	14.76	11.64
Tensile strength -N/mm^2	324.89	218.25
Load at yield	12.26	11.16

Yield stress- N/mm^2	270.30	209.25
% of elongation	11.77	5.4

After corrosion

It is evident from the tables that that the yield strength of metal is within the range 265-270 Mpa, and 205-210 Mpa of parent and weldment respectively before corrosion and even after corrosion. Similarly, tensile strength of the parent metal is within 320-325 Mpa and of the weldment is 215-220 Mpa.

Table 5 comparison of parent metal and weldments after corrosion

Type	Parent metal		weldments	
Articles	NaCl	DW	NaCl	DW
Peak load -KN	14.64	14.56	9.68	9.88
Tensile strength (N/mm^2)	321.21	32.49	216.98	217.34
Load at yield - KN	12.32	12.12	8.76	9.20
Yield stress (N/mm^2)	270.30	266.78	196.36	202.38
% of elongation	12.44	14.12	5.3	5.1

6.1 Microstructures

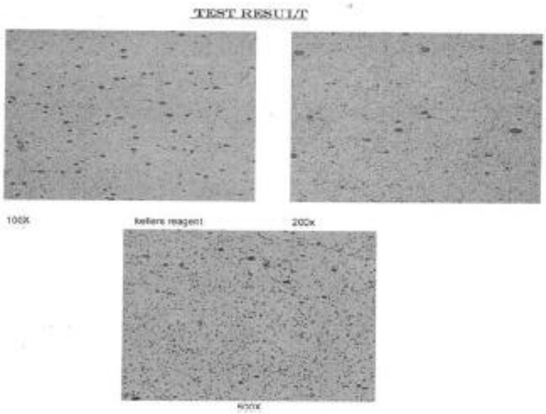

Fig. 12 Micro structure of parent metal subjected to corrosion in 3.5% NaCl solution.

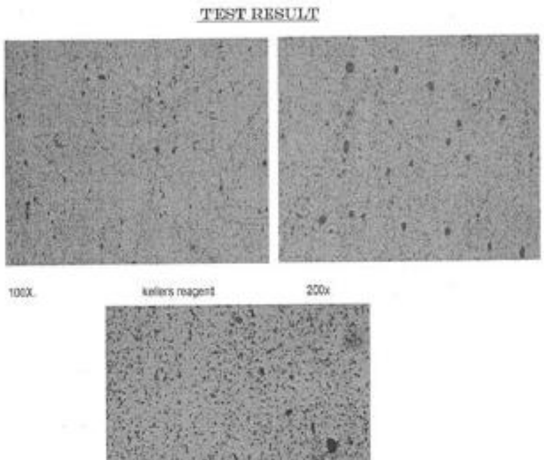

Fig. 13 Micro structure of parent metal subjected to corrosion in demineralised water.

6.2 Microstructures of weldments after testing

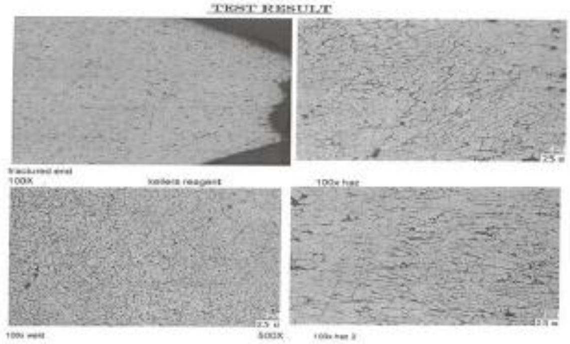

Fig. 14 Microstructure of weldment subjected to corrosion in 3.5%NaCl solution.

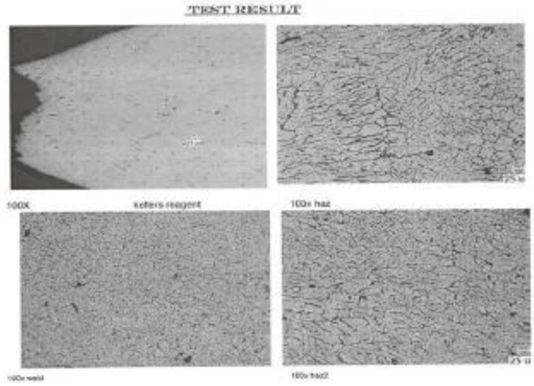

Fig. 15 Microstructure of weldment subjected to corrosion in de-mineralized water.

Microstructure consists of fine precipitates of alloying elements uniformly dispersed in the matrix of aluminium solid solution as shown in figure 11. In the weld region columnar and dendritic structure observed in fig 12.

VII. CONCLUSION

The amount of corrosion in the weldment is almost nil because of the usage of ER 4043 filler in the weldment. This ensures that the welding parameters are optimal on AA6061-T6 aluminium alloy. The microstructure of weld reveals uniform dendritic structure with dendritic arm spacing (DAS) in the order of 20-30 μm. This indicates uniform solidification occurs in the weld. The epitaxial type of nucleation of the weld is clearly appeared. The microstructure is evident in inter-dendritic arms. As the inter-dendritic space is very small and narrow, corrosion does not help in crack propogation.. The NaCl corrosion attack is very uniform. No localized pitting has been observed. This is evident in fig. The spacing between pitting is also uniform. This reinforces uniform corrosion. Localized pitting is hence uniform. Welded portion is stronger than the parent metal. This can be observed in from the microstructure where the pits are deeper and more in number in case of demineralised water than 3.5% salt solution. Failing of the metal is due to dissolution alloying elements. The black spots observed from microscope on the metal surface are compounds called aluminium silicade that ensure defect free welds. Micro-holes are also observed in the weldments before and after corrosion. Clearly it indicates pits are uniform. Due to this ductility is not affected and is within the range of 3 – 5 %. It is observed that the yield strength of metal is within the range 265-270 Mpa, and 205-210 Mpa of parent and weldment respectively before corrosion and even after corrosion. Similarly, tensile strength of the parent metal is within 320-325 Mpa and of the weldment is 215-220 Mpa. Due to the potential difference between the weld zone and the parent metal, corrosion takes place but minimally. This is due to the difference in the alloying elements in the weld and parent metal. The weld is made of aluminium 4043 whose main alloying elements are Al-Si. But the main alloying elements of aluminium 6061 or Al-Mg-Si due to which their exists a difference in potential for corrosion to takes place. The above points inform that the metal can be used for all kinds of marine application and even in the high altitude application where composite materials can cause cracks easily

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