Corrosion Fatigue Performance in Simulated Sea Water of Aluminium 6061-T651 Welded using ER4043 Filler Wire

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Abstract

The fatigue life of Al6061-T651 for various applied stress amplitudes in the unwelded and welded conditions was significantly lower in 3.5% NaCl simulated sea water solution, compared to that in air. The damage ratio increased with a decrease in the stress amplitude in the lower stress range. The reduction in fatigue life in NaCl solution is most likely due to the presence of pits which nucleate on second phase particles, slag inclusions or pores. Failure occurred in the weld metal as a result of the high pitting rate in simulated sea water.

Keywords: 6061-T651 aluminium alloy, pulsed gas metal arc welding, ER4043 filler wire, pitting corrosion, corrosion fatigue properties

2.1 **Introduction**

Aluminium 6061-T651 alloyed with magnesium and silicon displays high strength, excellent formability, satisfactory weldability and good corrosion resistance. This alloy finds application in the ship building and transport industries where welding often forms part of the fabrication process. Al6061-T651 is, however, prone to pitting corrosion in chloride-containing environments [1]. Although the fatigue behaviour of this alloy has been studied in depth, its behaviour when simultaneously subjected to a corrosive environment and constant amplitude fatigue loading in the welded and unwelded conditions has not been characterised.

The good corrosion resistance of Al6061 is due to the formation of a thin, hard and compact film of adherent aluminium oxide on the surface. However, aluminium oxide may dissolve in some chemical solutions, such as strong acids and alkalis leading to a rapid corrosion of aluminium and its alloys. Furthermore, the corrosion resistance could be reduced by the presence of the weldment in the base metal. The area within about 25mm around the weld root exhibits lower corrosion resistance [2].

Fully Automatic Pulsed Gas Metal Arc Welding (FA-GMAW-P) is an ideal and economic welding method for achieving good productivity, reducing the heat input in the weldment and producing welds with good resistance in sea water, as separately confirmed by Czechoweski, Praveen and Lean et al.[3,4,5]. The FA-GMAW dressed welds revealed good mechanical properties as shown in the previous work of Mutombo and Du Toit [6].

This paper reports on the corrosion fatigue behaviour and the corrosion damage ratio (ratio of the fatigue life in simulated sea water to the fatigue life in air) of Al6061-T561, welded using silicon-alloyed ER4043 aluminium filler wire and FA-GMAW-P process.

2.1 **Experimental**

Flat sheets of 2000mm long, 120 mm large and 6.35mm thick of 6061-T651 aluminium alloys (chemical composition, given in the Table 1, is performed with ARL Quantris Optical Emission apparatus supplied by Thermo-Electrical Co.) were joined using FA-GMAW-P with ER4043 (Al-Si) filler alloy [6]. The plates were degreased and welded with a square butt edge preparation, as shown in Figure 1.

Table 1. Chemical composition of Al6061-T651

Element %	*Al*	*Mg*	*Mn*	*Fe*	*Si*	*Cr*	*Cu*	*Zn*	*Ti*	*Others total*
6061-T651	REM	0.96	0.09	0.40	0.80	0.21	0.27	0.00	0.02	<0.01

Table 2. Pulsed gas metal arc welding process parameters

Parameters	*Arc voltage*	*Welding current*	*Wire feed rate*	*Wire diameter*	*Nozzle to plate distance*	*Travel speed*	*Torch angle*	*Gas flow rate*
Unit	*V*	*A*	*m/min*	*Mm*	*mm*	*m/min*	*Degrees*	*l/min*
FA-GMAW	20-23	133-148	6.1-7.6	1.2-1.6	15-20	0.4-0.6	60-80	19-28

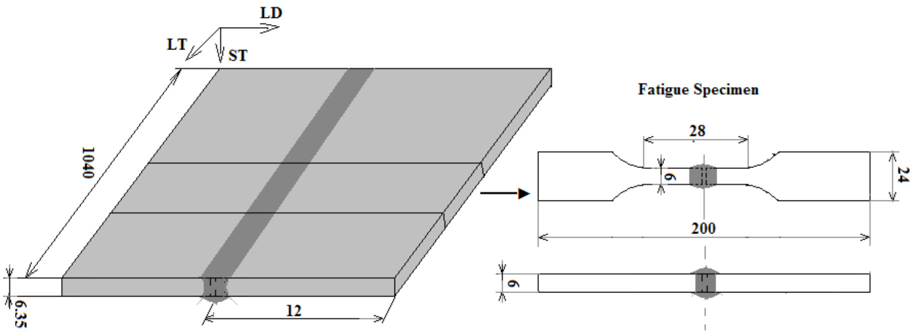

Figure 1. Fatigue Specimen preparation from the 6061-T651 welded plates

The welded and unwelded flat sheets were cut and machined to make the fatigue specimens, as indicated in Figure 1. The cross-section of longitudinal direction (LD)- long transverse (LT) plane and LT-ST (short transverse) plane were prepared according to ASTM standard E3-01 [7] for microstructural analysis. These sections were etched in agreement with ASTM standard E340 [8] and examined using an Optical Microscope and a Scanning Electron Microscopy equipped with Energy Dispersive X-ray Spectroscopy (EDS).

The machined fatigue specimens, schematically shown in Figure 1, were wet-ground flush in the longitudinal direction with 400, 600 and 800 grit papers, to remove all circumferential marks on unwelded and dressed-welded specimens. The fatigue tests were carried out in a symmetric tension-tension cycle (stress ratio R = 0.125) to keep the crack opened. A constant stress frequency of 1 Hz was used for the fatigue tests. The number of cycles to failure was recorded for each specimen, from 3 to 6 experiments that were performed at each stress level depending on the quality of the weld, as recommended by ASTM standard E466 [9]. The fatigue tests were performed in ambient air at a temperature of about 20°C and at relative humidity levels varying between 35.7 and 70.6% RH. An INSTRON testing machine, equipped with calibrated load transducers, data recording system and FASTTRACK software, was used to fatigue specimens to failure under amplitude stress control, as required by the ASTM standard E467 [10]. Welded specimens were visually inspected and those showing large porosities, underfill, undercut, craters and other obvious defects were discarded. The fatigue specimens were then cleaned with ethanol in order to remove any surface oil films, grease and fingerprints.

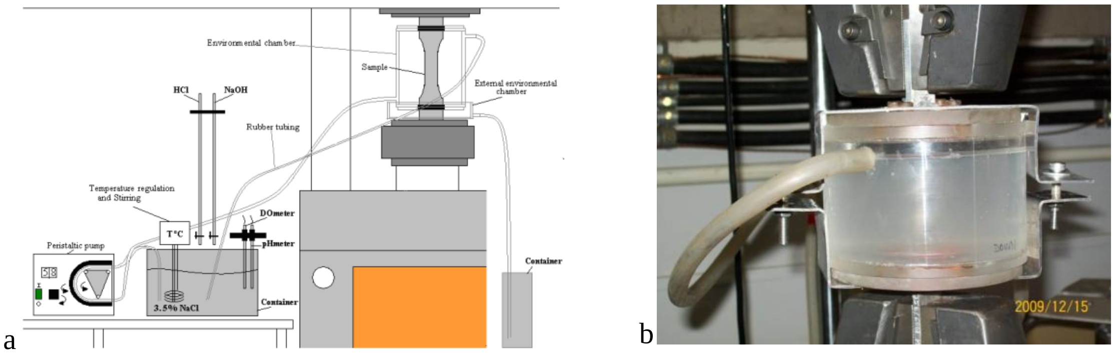

Figure 2. a) Schematic of Corrosion Fatigue set-up in 3.5% NaCl, b) Plexiglas Corrosion Fatigue chamber on the Instron machine

A Corrosive environment of 3.5% NaCl salt water was used with the axial fatigue life testing method to investigate the effect of pitting corrosion on the fatigue life. The corrosion chamber was designed and made in Plexiglas as shown in Figure 2b. The simulated seawater was circulated a constant flow rate from a 25 litres storage by means of a peristaltic pump. The Devolved Oxygen (DO) content, NaCl solution flow rate, pH, temperature, amplitude stress (maximum and minimum stress), and frequency were frequently controlled, figure 2a. The number of cycles to failure was recorded at the end the test. The constant frequency of 1Hz was used to increase the staying time of the specimen in contact with the simulated seawater. The measured DO was varied between 7 and 8 ppm. The corrosion fatigue test was performed at a temperature varying between 19 and 21°C.
The S-N (stress-log N_f) curve was also constructed from number of cycles to failure recorded. Thereafter the corrosion fatigue life or the corrosion fatigue resistance of 6061-T651 aluminium alloy welds in simulated seawater was evaluated.
In order to compare the fatigue resistance in air and in simulated seawater, the damage ratio, which is the ratio of the fatigue life in 3.5% NaCl solution and that of the fatigue life in laboratory air ($N_{f\ NaCl}/N_{f\ Air}$), was calculated and presented as S-$N_{f\ NaCl}/N_{f\ Air}$ curve (i.e. amplitude stress-$N_{f\ NaCl}/N_{f\ Air}$).

2.2 Results and Discussion

Microstructural analysis revealed coarse and elongated grains in 6061-T651 base metal, coarse grains in the HAZ and very fine grains in the weld metal, as shown in Figure 3.

Most of the fatigue failure in unwelded 6061-T651 and welded Al6061-T651 with ER4043 filler wire, with experiments performed in laboratory air, occurred in the HAZ (Figure 5a), whereas that that performed in 3.5% NaCl solution occurred within the weld metal, as indicated in Figure 5b. The heat treated Al6061-T651 in the unwelded condition was about 10 times less resistance in 3.5% NaCl environment than it is in the laboratory air. Its fatigue life is extremely reduced in NaCl solution after welding, using a combination of the FA-GMAW-P process and ER4043 filler metal, (see Figure 4).

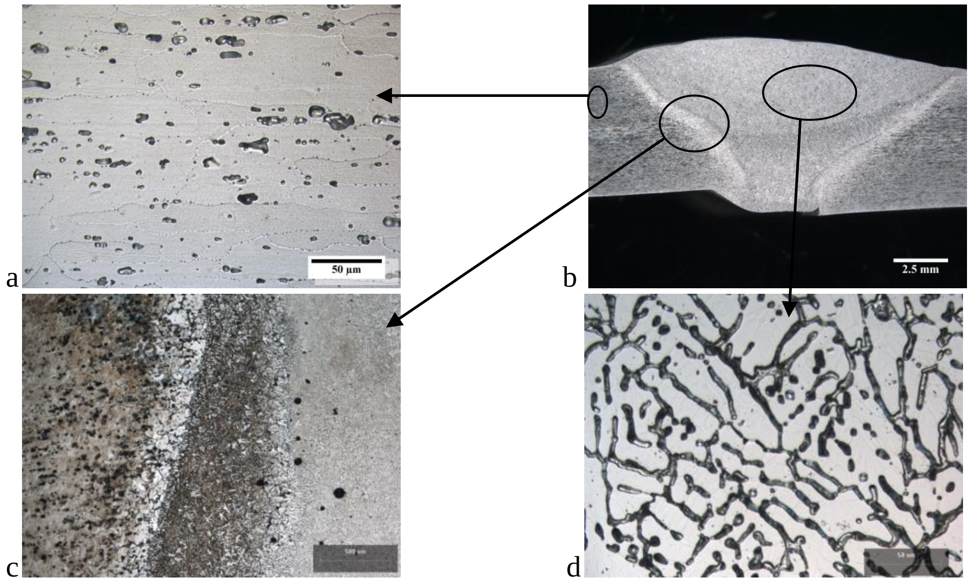

Figure 3. a) Al6061-T651 microstructure, b) FA-GMAW weld, c) HAZ/Weld interface and d) weld metal

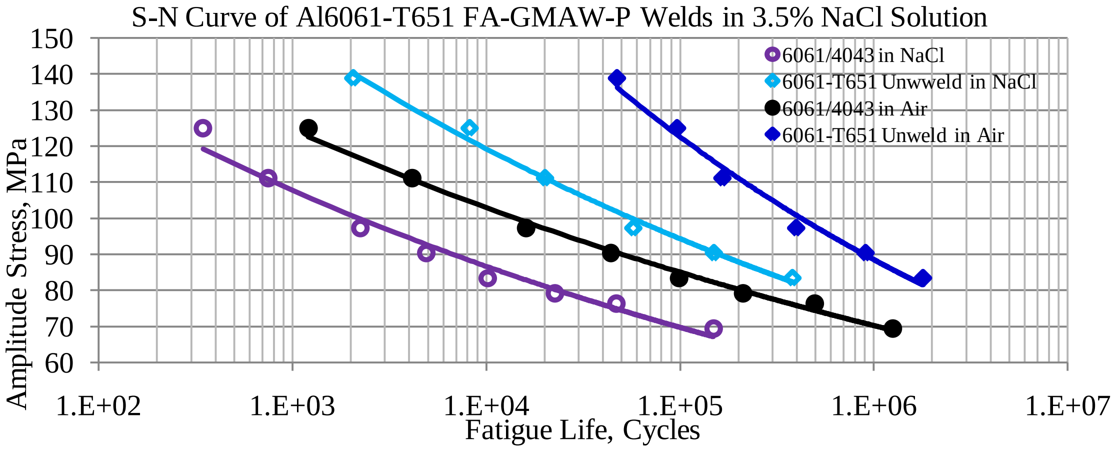

Figure 4. Fatigue life of Al6061-T651 unweld and 606-T651/ER4043 GMAW-P weld

The premature fatigue failure of Al6061-T651 alloy in welded and unwelded conditions is due to early cracks initiation from pits, as indicated in Figure 5a. These pits nucleated from inclusions or around precipitates and intermetallic phases present within 6061-T651 matrix, as shown in Figure 5 c.

The Damage Ratio (DR=cycles $_{\mathrm{NaCl}}$/cycles $_{\mathrm{Air}}$) in Al6061-T651 unwelded alloy increased as the fatigue stress decreased, due corrosion pits negatively affecting the fatigue life, see Al6061-T651 DR curve, in Figure 6. The failure mechanism in Al6061-T651/ER4043 welds is mostly controlled by slip lines formation and their interaction with pores, lack of fusion and precipitates or inclusion at fatigue stress higher than 80MPa, whereas the pitting corrosion becomes part of controlling process at lower, as obviously appearing on the damage ratio cure of Al6061-T651/ER4043, -shown in Figure 6.

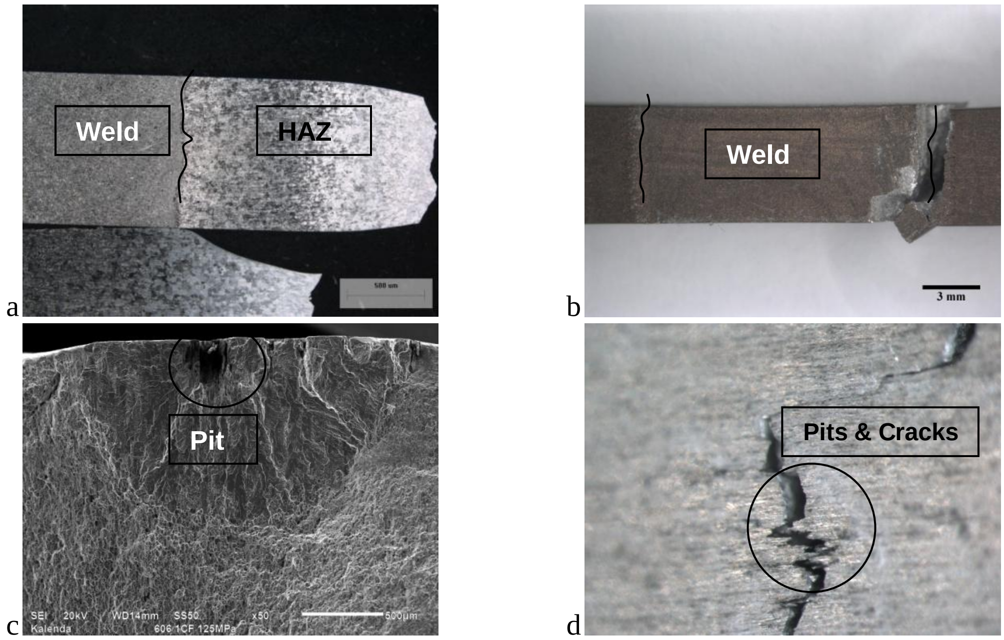

Figure 5. Fracture a) in laboratory air HAZ failed, b) in 3.5% NaCl weld failed, c) crack initiated from pit and d) crack propagating from pits

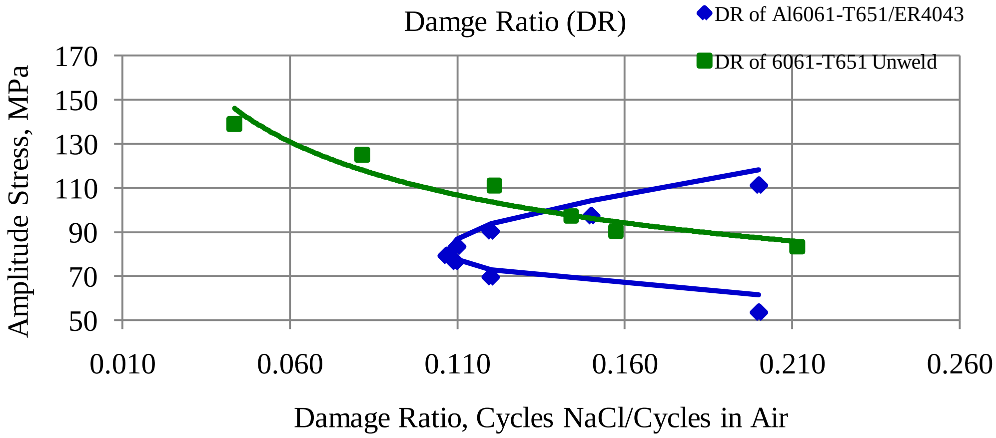

Figure 6. Damage Ratio of unwelded Al6061-T651 and welded Al6061-T651/ER4043 GMAW-P

2.3 Conclusions

The fully automatic gas metal arc welding strongly affects the fatigue behaviour of 6061-T651 aluminium weld. Failure occurred in the heat affected zone when the weld is fatigued in laboratory air. The fatigue life sensibly decreased due presumably to the softening and coarsening effect in the heat-affected-zone, as compare to unwelded aluminium alloys. The silicon-magnesium alloyed aluminium 6061-T651 failed prematurely in the corrosive environment of 3.5% NaCl, especially when it is in the welded condition. The damage ratio increased as the fatigue stress amplitude decreased in the low stress range.

2.4. **References**

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