

Intermetallic Particles-Induced Pitting Corrosion in 6061-T651 Aluminium Alloy

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Keywords: pitting corrosion, 6061-T651 aluminium alloy, intermetallic particles, 3.5% NaCl solution

Abstract. The polished 6061-T651 aluminium alloy was immersed in 3.5% NaCl solution with about 7 ppm dissolved oxygen. Scanning Electron Microscopy equipped with Energy dispersive X-ray Spectroscopy revealed the presence of Al-Si-Fe-containing particles that acted as cathodic sites and promoted the matrix dissolution. The effect of pH and chloride solution is assessed.

Introduction

Artificially aged 6061-T651 aluminium alloyed with magnesium and silicon displays high strength, excellent extrudability, reasonable weldability and good corrosion resistance. This alloy finds widespread application in ship building and in the fabrication of tank containers for transporting various liquids. 6061-T651 aluminium alloy is, however, prone to pitting corrosion in chloride-containing environments. These pits may lead to premature crack initiation, resulting in subsequent failure of high-strength Al6061-T651 alloy structures. Therefore, understanding the mechanism of pitting corrosion in this alloy is of scientific interest and technological benefit.

The aluminium-rich matrix adjacent to $MgSi_2$ intermetallic precipitates in Al-Si-Mg alloys has been shown to be susceptible to preferential corrosion in NaCl solutions [1]. Guillaumin *et al* observed that coarse intermetallic particles containing Al, Si and Mg act as nucleation sites for pit formation [2]. Chen *et al* concluded that microconstituent particles of Al-Cu-Mg and Al-Cu-Mg-Fe induced pitting in 2024-T3 alloy [3].

In this study the role of intermetallic phases and the correlation between chemical composition of constituent particles and pitting corrosion behaviour are investigated.

Experimental Procedure

Specimens of 25mm by 25mm, cut from a sheet of 6mm thickness, were used for the corrosion experiment. The chemical composition of 6061-T651 aluminium alloy is shown in Table 1. Specimens were ground and polished to achieve mirror-like surface. After polishing specimens were ultrasonically cleaned in ethylic alcohol and dried with warm air.

A corrosion environment consisting of 3.5% NaCl (by weight) in distilled water was used to investigate the pitting corrosion of 6061-T651. The dissolved oxygen (DO) content, pH and temperature were monitored. A NaCl solution of about 7pH and 7ppm DO, at 21°C served as the main corrosive environment. For comparison purposes a second solution of deionised (DI) water, at 21°C was also used. All test experiments were conducted in 1 liter solution. The effect of pH was investigated in solution with pH=2 and pH=12. The corroded specimens were thoroughly washed with DI water, acetone and dried with warm air.

Optical microscope (Equipped with Image Analysis Software) and Scanning Electron Microscopy (SEM), equipped with Energy Dispersive X-ray spectrometry (EDS), were used

to investigate the morphology and the chemistry of the 6061 alloy surface and constituent particles.

Results and Discussion

The microstructural and Image analysis revealed the presence of constituent particles of about 2.5 μm ($Stdev=2.23$) in size and 1.2 to 1.5% area fraction. The EDS/SEM analysis mainly identified these particles as Al-Fe-Si rich particles, Figure 1. The presence of Cu, Cr and Mn was also detected, as dispersed in the Al matrix, see EDS spectrum (Fig.2c).

Table 1. Chemical composition (wt %) of 6061-T651 alloy

| <i>Element</i> | <i>Al</i> | <i>Mg</i> | <i>Mn</i> | <i>Fe</i> | <i>Si</i> | <i>Cr</i> | <i>Cu</i> | <i>Others total</i> |
|------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|---------------------|
| 6061-T651 | REM | 0.96 | 0.09 | 0.40 | 0.80 | 0.21 | 0.27 | <0.01 |

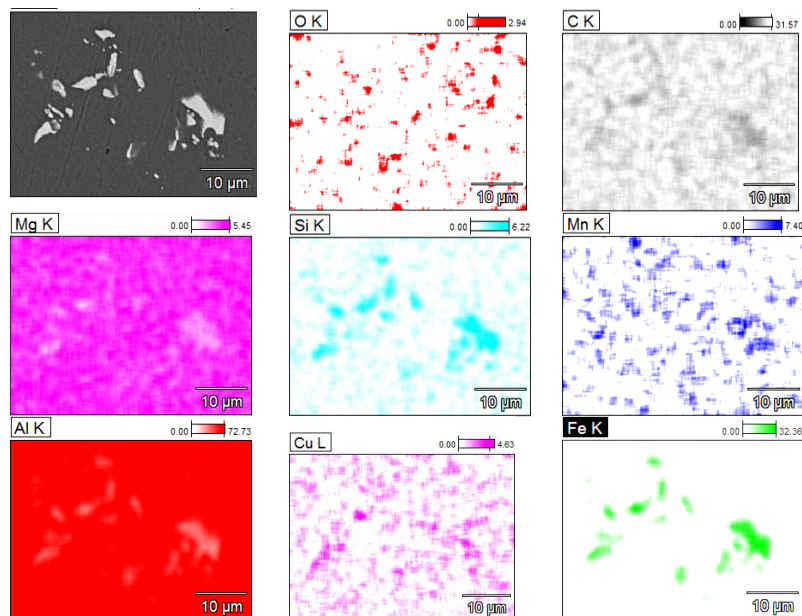


Figure 1. EDS analysis of constituent particles

EDS/SEM analysis of the free corroded specimens (without mechanical disturbance), for specific time in 3.5% NaCl solution, showed the presence of Al-Fe-Si intermetallic particles as detected (Fig.1, Fig.2c and Tables 2, 3 and 4). Al-Fe-Si constituent particles acted as cathodes since the preferential dissolution of aluminium surrounding matrix to produce localized corrosion or pitting is clearly observed on Figure 2b. The corroded surface resulted in high oxygen content and no presence of Cu, Cr and Mn was detected. Mg seemed to not be affected by the 3.5% NaCl corrosive environment, Table 2, 3 and 4.

However the immersion of specimens in the DI water for 24 hours led to non dissolution of the periphery of these intermetallic particles, even though the surface seemed much oxidized thereafter. The presence of dissolved elements such as Cu (Fig. 3c), Cr and Mn were still detected.

The effect of Cu, Mn, Cr and Mg on the corrosion behaviour of 6061-T651 was difficult to be revealed sine these elements are disseminated in the aluminium matrix.

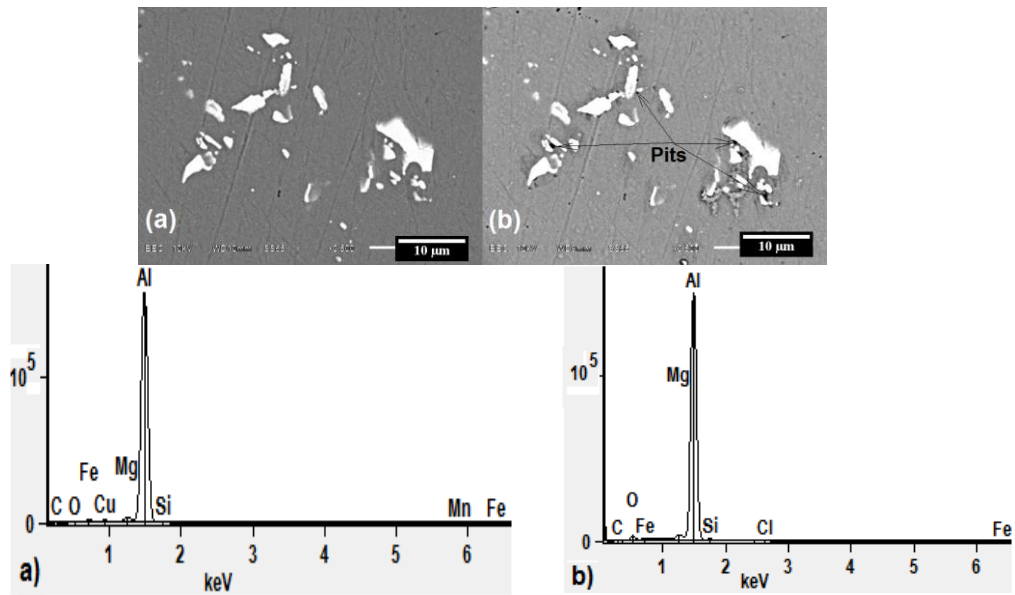


Figure 2. Pitting corrosion of 6061-T651 after 1 hour in 3.5% NaCl solution

Table 2. EDS spot 1 analysis of 6061-T651 corroded in 3.5% NaCl solution

| <i>Element, w%</i> | <i>Spot 1</i> | | | | | | | | | |
|----------------------|---------------|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| | <i>C</i> | <i>O</i> | <i>Mg</i> | <i>Al</i> | <i>Si</i> | <i>Cl</i> | <i>Cr</i> | <i>Mn</i> | <i>Fe</i> | <i>Cu</i> |
| <i>0 Hour</i> | 0.69 | 0.77 | 0.60 | 92.93 | 0.60 | ND | ND | 0.32 | 2.73 | 0.69 |
| <i>1 Hour</i> | 2.42 | 1.09 | 0.56 | 91.84 | 0.56 | ND | ND | ND | 3.05 | 0.57 |
| <i>3 Hours</i> | 3.62 | 2.79 | 0.62 | 89.21 | 0.58 | ND | ND | ND | 2.39 | ND |
| <i>15 Hours</i> | 3.78 | 3.05 | 0.62 | 88.73 | 0.58 | 0.21 | ND | ND | 2.63 | ND |
| <i>Error, w% +/-</i> | 0.14 | 0.03 | 0.03 | 0.19 | 0.05 | 0.21 | - | 0.11 | 0.07 | 0.04 |

Table 3. EDS spot 2 analysis of 6061-T651 corroded in 3.5% NaCl solution

| <i>Element, w%</i> | <i>Spot 2</i> | | | | | | | | | |
|----------------------|---------------|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| | <i>C</i> | <i>O</i> | <i>Mg</i> | <i>Al</i> | <i>Si</i> | <i>Cl</i> | <i>Cr</i> | <i>Mn</i> | <i>Fe</i> | <i>Cu</i> |
| <i>0 Hour</i> | 0.71 | 1.09 | 0.48 | 88.20 | 1.13 | ND | 0.39 | 0.59 | 5.69 | 1.06 |
| <i>1 Hour</i> | 1.99 | 3.62 | 0.44 | 86.54 | 1.19 | ND | 0.27 | ND | 4.48 | 0.75 |
| <i>3 Hours</i> | 3.46 | 3.79 | 0.54 | 85.47 | 1.11 | 0.37 | ND | ND | 5.21 | ND |
| <i>15 Hours</i> | 6.47 | 4.48 | 0.47 | 82.71 | 1.14 | 0.38 | ND | ND | 4.54 | ND |
| <i>Error, w% +/-</i> | 0.15 | 0.05 | 0.03 | 0.18 | 0.05 | 0.02 | 0.06 | 0.11 | 0.16 | 0.04 |

Table 4. EDS spot 5 analysis of 6061-T651 corroded in 3.5% NaCl solution

| <i>Element, w%</i> | <i>Spot 5</i> | | | | | | | | | |
|----------------------|---------------|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| | <i>C</i> | <i>O</i> | <i>Mg</i> | <i>Al</i> | <i>Si</i> | <i>Cl</i> | <i>Cr</i> | <i>Mn</i> | <i>Fe</i> | <i>Cu</i> |
| <i>0 Hour</i> | 0.18 | 1.01 | 0.53 | 92.30 | 0.72 | ND | 0.43 | ND | 3.48 | 0.65 |
| <i>1 Hour</i> | 0.69 | 1.06 | 0.50 | 92.07 | 0.70 | ND | 0.38 | ND | 4.09 | 0.62 |
| <i>3 Hours</i> | 0.53 | 3.33 | 0.64 | 90.04 | 0.70 | 0.19 | 0.21 | ND | 3.99 | ND |
| <i>15 Hours</i> | 5.80 | 3.41 | 0.51 | 85.37 | 0.71 | 0.36 | ND | ND | 3.42 | ND |
| <i>Error, w% +/-</i> | 0.14 | 0.03 | 0.03 | 0.19 | 0.05 | 0.02 | 0.06 | - | 0.11 | 0.04 |

ND: Not Detected

Individual intermetallic particles accelerated coalescence of pits laterally and in depth to form larger pits, as shown in Figure 3b.

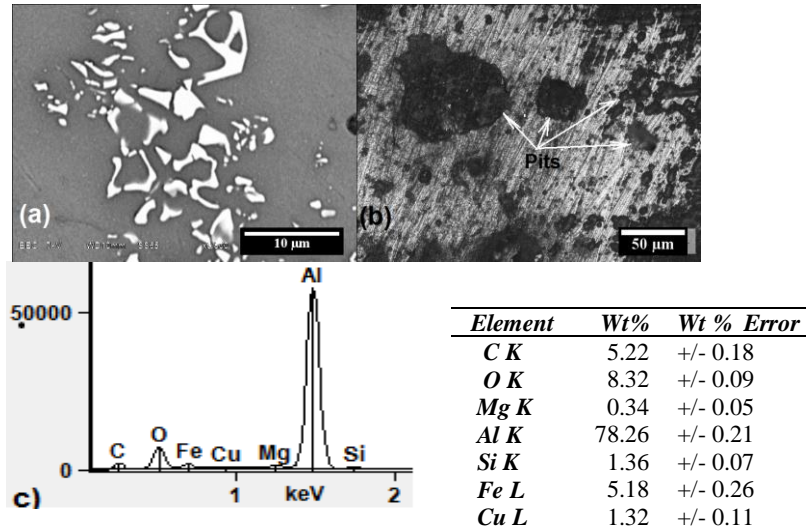


Figure 3. Corrosion of 6061-T651 in deionised water and 3.5% solution

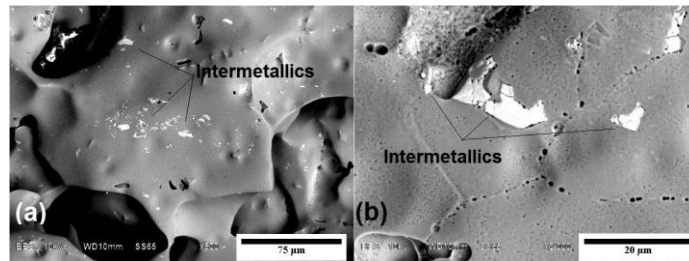


Figure 4. Corrosion in solution of a) pH=2 and b) pH=12

At pH=2 almost no pits have been identified in the aluminium matrix, however the entire surface was attacked showing very large cavities, Figure 4a. On the other hand the alkaline solution (pH=12), led to general corrosion with some localised corrosion on grain boundaries and at periphery of constituent particles, as presented on Figure 4b.

Conclusions

Al-Fe-Si containing rich-particles acted as cathodes and promoted the dissolution of the aluminium surrounding matrix in the aluminium alloy 6061-T651.

The cathodic behaviour of Al-Fe-Si intermetallics depended on the pH of the solution and chloride-containing environment.

Pitting associated with constituent-particles was attenuated in acidic and alkaline solution

Acknowledgments

Author acknowledges the financial support of CSIR

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