Analyzing Resistance of Al-10Si-5Mg Alloy from Stress Corrosion Cracking for Ocean Current Turbine Applications

Andre Amba Matarru 1,a, Muhammad Syahid 2,b, Donny Yoesgiantoro 1,3,c and Syahril Hadi 1,4,d

1 Energy Security Graduate Program, Indonesia Defense University (UNHAN), Indonesia Peace and Security Centre (IPSC), Bogor 16810, Indonesia
2 Departement of Mechanical Engineering, Hasanuddin University, Malino Street, Bontomarannu, Gowa, South Sulawesi 92119, Indonesia
3 The Kirana Tembok (Pioneer of Eco Edu Tourism), Tejakula, Buleleng Regency, Bali 81173, Indonesia
4 Directorate General of New Renewable Energy and Energy Conservation, Ministry of Energy and Mineral Resources of Energy, Pegangsaan Timur Street No.1, Menteng, Jakarta Pusat 10320, Indonesia

E-mail: aandreambamatarru@gmail.com, bsyahid.arsjad@gmail.com, cenergyprogram@gmail.com, dhadi.syahriel21@gmail.com

Abstract. Stress Corrosion Cracking in Marine Applications, especially Ocean Current Turbines must be overcome. Al-10Si-5Mg Alloy which is based on the nature of flexibility and strength, is expected to survive from the SCC. The purpose of this paper is to examine the indications of SCC from immersed specimens in the 3.5% NaCl Solution + Aquades solution, then give varying deflections on the 3 Point Bending Testing. The other tests are harness testing, tensile testing, and macro visualization. The method is experimental for Al-10Si material in addition to a 5% Mg at casting. There are 9 specimens, namely 3 specimens from each of the 3 load values, namely 252 MPa (deflection (y)=2mm), 378 MPa (y=3mm), and 504 MPa (y=4mm). The results provide evidence that when the specimens were submerged with varying stresses, the absence of broken material was obtained even though there were indications of cracking and corrosion. Then the specimen that gets a high stress, becomes more susceptible to fracture due to the predominant cracking effect when compared to low standing specimens (σy=4 mm < σy=3 mm < σy=2 mm). So by the resistance to SCC, the Al-10Si-5Mg alloy can be recommended as an Ocean Current Turbine Blade material.

1. Introduction
The steps taken by the government to anticipate the energy crisis in Indonesia include National Energy Policy, National Energy Management Blueprint 2005 - 2025, National Strategic Policy for Science and Technology Development, and the National Ocean Exploitation Policy which emphasizes energy sustainability through the creation and utilization of renewable energy sources. In Blue Print Energy Management, energy management will be optimized, so that by 2025 the composition of energy is expected to be 33% coal, 30% gas, 20% petroleum and 17% new renewable energy. Indonesia with a total ocean area of almost 8 million km² seeks to increase inventory of non-living resources, one of which is the energy potential of ocean currents [1]. Components that are of concern in the
development of Marine Flow Turbines in the future are made from Aluminium, where the first generation turbines whose blades are made of Polymer (steel-frame fiberglass) are not able to withstand the instability of unstable underwater currents [2].

However, it is undeniable that aluminium alloys are also susceptible to fragmentation by hydrogen, although at the time of reaching the FCC microstructure they explain that the transfer of hydrogen is lower than in High Strength Steel (HSS) and hence, the average growth of cracks is slow. Cracking is usually intergranular. Just like steel, susceptibility increases with increasing alloy strength [3]. So that it is obtained that the indication of the emergence of SCC is something that harms certain alloys.

The design criteria needed include strength, fatigue resistance, corrosion resistance, potential long-term and short-term fabrication costs. Consideration includes the availability of several blade structures as shown in Figure 1 below.

The concept has been evaluated on the basis of price and structural performance for both class 5 and 10 m standards as shown in Table 1 below.

![Figure 1. AlMg blade with bolt-pierced nap, same as Gen4c Verdant blade (a) Fiberglass Composite Blade with axial blade blade (b) Fiberglass Blade Flanked with Flat Side Towering or Broken Bolt (c)](image)

**Table 1. Characteristics of Composite Blade Design**

| Rotor Diameter - Resource | 5m - Tidal | 7m - River | 10m - River | 10m - Tidal |
|---------------------------|------------|------------|-------------|-------------|
| Generator Class           | 56 kW      | 110 kW     | 110 kW      | 500 kW      |
| Peak Water Velocity       | 2.5 m/s    | 2.5 m/s    | 2.0 m/s     | 3.3 m/s     |
| RPM                       | 40 rpm     | 31 rpm     | 22 rpm      | 31 rpm      |
| Root - Thickness/Twist    | Proprietary Verdant Power Design Values |
| Tip - Thickness/Twist     | Proprietary Verdant Power Design Values |

Fiberglass, resin and synthetic foam finishes are selected and the fabrication, bonding and filling fabrication stages have been terminated for resin filling of high and low pressure layers and shear layers. A variety of materials for bonded frame fillings are necessary including Nickel Bronze Aluminium considering balance of strength, durability, and cost [4]. However, it is identified that filling is an important factor in the development of blade manufacturing especially Aluminium that has a density of only 2.7 g/cm³ indicates that only about one third of the steel density is 7.83 g/cm³. In addition, as the Al-Mg alloys, character of Magnesium can be preferentially hardened on grain boundaries as a high anode phase (Mg₅Al₃ or Mg₅Al₈) which results in susceptibility to intergranular cracks and to Stress Corrosion [5].

Stress Corrosion Cracking (SCC) is the combination between Corrosion and Stress which could appear on aggressive maritime environment and generally on the structure that made from steel and aluminium alloy which has enormous structure and mostly applied as the other external components of the power transmission and control systems. During the second exploitation, the metal alloy is known to be intended for an aggressive maritime environment that directs the process of corrosion (ordinary corrosion, pitting, and SCC). On the other hand, rusted construction is the reason for component changes that are faster power transmission components and unexpected impacts cause the potential for dangerous accidents. In maritime applications, SCC is also the most dangerous type of corrosion caused by stress and the electrolyte environment arises simultaneously [6].

Clear rifts arise as a result of hydrogen embrittlement that supports a number of mechanisms and becomes a potential link to the SCC environment. Some environments that support hydrogen give rise to SCC for the susceptibility of alloys, usually in moist air to saline liquids [3]. This is the basic idea of the need for early learning about the treatment of SCC vulnerability arising from 3 determinants,
namely a material component that is vulnerable, an electrolytic environment, and sufficient stress on renewable energy technologies. In this study, the author intends to examine how Analysis of Stress Corrosion Cracking Al-10Si-5Mg Alloys for Maritime Applications especially preventing at Ocean Current Turbine further.

2. Research Methods

2.1. Test material
In this study the material used was Al-10Si in the form of bars with the addition of 5% wt Mg, which was cast with a melting temperature of 700° C which was then poured into metal molds and formed based on the size of ASTM G 39 buckling test specimens with long dimensions 120 mm and a width of 25 mm with a height of 3 mm. And the size of the Al-10Si-5Mg specimen Hardness test with dimensions of 20 mm long, 20 mm wide, with a height of 10 mm as shown in Figure 2 below.

![Figure 2. Bending Test Specimens (a) Hardness Test Specimens (b)](image)

2.2. Corrosion Media
Corrosive Environment in the form of Solution 3.5% NaCl + Aquades (distilled water). The description needed according to ASTM G39 is a description of the temperature and pressure during testing.

2.3. Bending Testing
- Specimens must be made of material that is not affected by the shape (for example plastic) of the corrosive environment or coating the support with a coating material which is usually used in electricity that shown in the Figure 3 below. If necessary, Hydrophobic Fillers can be added to protect against corrosion of cracks at the touch point between support and specimens (Grease or Wax) [7].

![Figure 3. Scheme of Specimen Supporting Configuration](image)

- Deflection Gauges, the presence of deflection in the specimen is determined by a measuring device which is separate or together on the completeness that shown in the Figure 4 below. In the design of the deflection gauge for adjustment of the appropriate individual conditions must weigh the provisions of the 3 Point Bending specimen.
Figure 4. Specimen loading equipment for beam specimens 3 point bending with derivative deflection gauge

Testing is done by giving the specimen loading to deflection. The tools used are Support 3 Point Bending. The maximum deflection tested on specimens until broken without immersion is 4 mm, 5 mm and 7 mm. So that taken as a parameter is 4 mm as the maximum deflection. The maximum load is based on the maximum deflection. The maximum load equation with the formula based on ASTM G 39:

\[
\sigma = \frac{6Et_y}{H^2}
\]

\(E = \text{Aluminum Elastic Modulus}\)
\(t = \text{specimen thickness}\)
\(y = \text{Maximum deflection}\)
\(H = \text{Distance between 2 edge supports}\)

Then if the value of deflection is entered
\[\sigma = 6 \times (70,000,000 \text{ kPa}) \times (3\text{mm})(4\text{mm})/(100\text{mm})^2\]
\[= 252,000 \text{ kPa} = 504 \text{ MPa}\]

So that the variation of loading given is based on multiples of deflection integers, defined:
\(y_1 = 2 \text{ mm} \quad \sigma_1 = 252 \text{ MPa}\)
\(y_2 = 3 \text{ mm} \quad \sigma_2 = 378 \text{ MPa}\)
\(y_3 = 4 \text{ mm} \quad \sigma_3 = 504 \text{ MPa}\)

2.4. Hardness Testing

Hardness testing is done by the Brinell method. Hardness can be defined as the ability of a material to resist plastic deformation. Hardness also has a correlation with strength. Hardness testing is one of the many tests used because it can be carried out on small test objects without difficulty regarding specifications. The most widely used test is to emphasize a certain emphasis and by measuring the size of the stresses formed above it, this method is called the method of suppression hardness.

2.5. Tensile Testing

Tensile Testing was carried out at the Physical Metallurgy Laboratory of the Universitas Kristen Indonesia Paulus. The procedure performed is:

- Removing the test specimens that were previously treated with bending and soaking tests in a mixture of aquades and NaCl of 3.5%.
- Cut specimens similar to the standards in accordance with ASTM B557M as shown in Figure 5 and following the requirements which shown in Table 2.
3. Testing Result

3.1. Results of Bending Testing

Bending Testing after immersion in a corrosive environment. The load given to the test specimens is:

3.1.1 Deflection 4 mm with $\sigma = 504$ MPa

![Figure 6. Dial gauge needle for 4mm deflection](image)

Giving numbers to specimens applies to all three specimens with a thickness of 4 mm, Specimen 1, Specimen 2, and Specimen 3 as shown in the Figure 6 above. The appearance of the Dial Gauge small needle shows the number 4 which means 4 mm, where the long needle in the three specimens has reached number 0 which further clarifies the absolute magnitude to be achieved.

3.1.2 Deflection 3 mm with $\sigma = 378$ MPa

![Figure 7. Dial gauge needle for 3mm deflection](image)
Giving numbers to specimens applies to the three specimens with a defect of 3 mm namely Specimen 4, Specimen 5, and Specimen 6 as shown in the Figure 7 above. The appearance of the Dial Gauge small needle shows the number 3 which means 3 mm, where the long needle on the three specimens has reached the number 0 which further clarifies the absolute magnitude to be achieved.

### 3.1.3 Deflection 2 mm with $\sigma = 252$ MPa

![Figure 8. Dial gauge needle for 2mm deflection](image)

Giving numbers to specimens applies to the three specimens with a defect of 2 mm namely Specimen 7, Specimen 8, and Specimen 9 as shown in the Figure 8 above. The appearance of the Dial Gauge small needle shows the number 2 which means 2 mm, where the long needle on the three specimens has reached number 0 which further clarifies the absolute magnitude to be achieved.

The Figure 9 below is a comparison of cracks in specimens of 4 mm, 3 mm and 2 mm deflection.

![Figure 9. Crack and corrosion results with a 4mm deflection (a), 3mm deflection (b), 2mm deflection (c)](image)
3.2. Hardness Testing Results

The Brinell Hardness value produced from Al-10Si-5Mg is 63.39 kg/mm$^2$ as shown in Figure 10. This value is above the standard number of AA6063-T5 (Al-Mg-Si) alloy which has value 60 kg/mm$^2$ BHN. So it is certain that the value of this hardness enhances toughness to the alloy for its resistance to being loaded.

![Figure 10. Results of untreated Al-10Si-5Mg Hardness Testing.](image)

| No | F (kg) | D (mm) | d (mm) | $\sqrt{D^2-d^2}$ | BHN (kg/mm$^2$) | $\sum$BHN (kg/mm$^2$) |
|----|--------|--------|--------|---------------|----------------|------------------|
| 1  | 60     | 1.588  | 1.1    | 1.15          | 54.36          | 63.39            |
| 2  | 60     | 1.588  | 1      | 1.23          | 67.90          |                  |
| 3  | 60     | 1.588  | 1      | 1.23          | 67.90          |                  |

It can be concluded that specimens that have a larger deflection have less power.

3.3. Tensile Test Results

- Average Stress ($\sigma$) for reflected as 4 mm specimens
  $\sigma = (\sigma_1 + \sigma_2) / 2 = (0.325 + 0.343) / 2 = 0.334$ kgf / mm$^2$
- Average Stress ($\sigma$) for reflected as 3 mm specimens
  $\sigma = (\sigma_4 + \sigma_5 + \sigma_6) / 3 = (0.149 + 4.726 + 2.953) / 3 = 2.609$ kgf / mm$^2$
- Average Stress ($\sigma$) for reflected as 2 mm specimens
  $\sigma = (\sigma_7 + \sigma_8 + \sigma_9) / 3 = (5.895 + 7.838 + 3.180) / 3 = 5.638$ kgf / mm$^2$

It can be concluded that specimens that have a larger deflection have less power.

3.4. Macro Observation

![Figure 11. Photograph of a fracture of a specimen with a deflection of 4 mm (a) deflection of 3 mm (b) deflection of 2 mm (c)](image)

In Figure 11 above, it can be seen the appearance of all fractures of the specimen is brittle fracture which features a surface that is almost even (not concave / convex). The macro structural shows that the spreading evenly of Mg$_2$Si’s precipitation on the matrixes that has formed and gives an effect of maximally strength and hardness properties unto the materials.
4. Conclusion

- The stages of specimens in achieving corrosion are:
  a. Occurrence of the Attached Brown Blob Area
  b. Crack Indication
  c. Color Indication Changes
  d. Crack and Corrosion Indications

- The strength of the aluminum material decreases for specimens which have applied 3 point bending test treatment. The strongest material is the specimen that got the lowest deflection, and vice versa. ($\sigma_y = 4\ mm < \sigma_y = 3\ mm < \sigma_y = 2\ mm$).

- No fracture while the stress had been applied on the appearing corrosive material.

- So with the result of resistance to SCC which does not cause a break in the test material, the Al – 10Si – 5Mg alloy can be recommended as an ocean current turbine blade material.

Acknowledgements

The focus of learning gained in the Energy Security Graduate Program of the Faculty of Defense Management, the Indonesia Defense University is a gratitude for the writer to be guided during the Renewable Energy lesson. This paper is prepared to support the plan to build a marine current energy generator that will be designed by the Government of Indonesia in the success of the target of the application of renewable energy in Indonesia by 2025 by 23% of the energy mix that contained in the Electricity Provision General Plan as known as Rencana Umum Penyediaan Tenaga Listrik (RUPTL) 2019-2028 literature.

The author hopes that there will be an increase in the use of Aluminum material for ocean current turbine blade applications given the large availability in Indonesia and the stability of the moment when turbines spin in producing electricity production that is effective in meeting the power requirements of military and general facilities in the form of an Off Grid System in preventing the failure of the main electricity network to support Indonesia's energy security.

Reference

[1] Ai Yuningsih, A. Masduki 2011 *Potensi Energi Arus Laut Untuk Pembangkit Tenaga Listrik Di Kawasan Pesisir Flores Timur NTT* (Pusat Penelitian dan Pengembangan Geologi Kelautan, Bandung)

[2] Information on http://www.washingtonpost.com/wp-dyn/content/article/2008/09/19/AR2008091903729.html

[3] Dr. R. A. Cottis 2000 *Guides to Good Practice in Corrosion Control: Stress Corrosion Cracking* (National Physical Laboratory, NPL, Serco Group. UK)

[4] Corren, D., Colby, J., & Adonizio, M. A. 2013 *Improved Structure and Fabrication of Large, High-Power KHPS Rotors-Final Scientific/Technical Report* (No. DOE/G018168). Verdant Power, Inc.

[5] Davis, J. R. 2001 Aluminum and aluminum alloy, p351-416. *ASM International*, 351-416.

[6] Darowicki, K., Orlikowski, J., Arutunow, A., & Jurczak, W. 2005 *Novel method of the initiation stage of stress corrosion cracking monitoring with respect to marine constructions.* (Polish Journal of Environmental Studies, 14, 161).

[7] ASTM Standard G 39 – 99 1999 *Standard Practice for Preparation and Use of Bent-Beam Stress-Corrosion Test Specimen* (ASTM International, West Conshohocken, PA)