Fatigue Endurance of Aluminium Casting 7xxx Series as Alternative Material for Organic Rankine Cycle’s Turbine Blade at 180 °C Operation Temperature

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Abstract. Organic rankine cycle (ORC) Turbines are very promising for converting heat in low temperatures from 100 to 220 °C into electrical energy. The use of Fe-25Al-xTi and TiAl alloys as ORC turbine blades encourages the need for development in utilizing lighter but stronger alternative materials. This study analyzed and observed the fatigue resistance of Al-Zn-Mg-Cu alloys as an alternative material by performing chemical composition analysis, hardness test, microstructure test, tensile test, fatigue test, and fractography observation. The results show that there is reduction in mechanical properties and fatigue resistance in artificial aged specimens. This is due to the deployment of precipitate which is a decomposed phase causing a decrease in mechanical properties and fatigue resistance in heat treated specimens.

1. Introduction

The rapid industrial development in Indonesia drives the increasing demand for electrical energy. The limited resources of conventional power plants such as oil and natural gas will not sufficient to power supply needed. On the other hand, the effort to reduce air pollution is conducted by using renewable energy sources as a substitute for conventional energy sources. Therefore, it is necessary the capable technology of utilizing low-temperature renewable energy. The utilization of Organic Rankine Cycle (ORC) which is a modification of the rankine cycle that uses refrigerant as a working fluid to generate electrical energy from low temperature heat energy source 100-200 °C [1], is expected to be an innovation in the utilization of biogas energy and geothermal energy contained in nature [2]. The utilization of the Organic Rankine Cycle (ORC) system is the best way to reduce air pollution levels [3].

Characteristics required in material selection of ORC turbine blades are capable of working in temperatures of 100-200 ° C, good strength and good corrosion resistance. ORC turbine blade material currently used are Fe-25Al-xTi and TiAl alloys [4]. The main problem encountered in the utilization of TiAl and Fe-25Al-xTa are a very specific and costly process. Therefore, TiAl and Fe-25Al-xTa are high enough density. So, it is possible to develop the alternative materials that useful in replacing the utilization of heavy steel and titanium. These alternative materials should have reasonable criteria to be used in the working conditions of the ORC turbine blades, which are strong, good corrosion-resistant, good fatigue resistant and good operation-resistant.

Addition of zinc to aluminum is usually used as a protective layer or sacrificial anode which can increase the homogeneity of aluminum matrix [5]. Al-Zn is well known as an excellent alloy in a corrosive environment. 9% Zn in aluminum alloys increase alloy utility while decreasing toughness and increasing brittleness of alloys, the presence of Zn fills the aluminum atomic lattice so that a solid
solution strengthening mechanism occurs. Zn addition under 3% was reported useless in aluminum alloys [6]. Addition of 2-4% Cu increase machinability and strength of the aluminum alloy matrix. The addition of copper to cast aluminum alloys reported has a great effect on strength and hardness [7]. While the addition of magnesium in the right percentage increases weldability and corrosion resistance to aluminum alloys. Mg in aluminum enhances the mechanical properties of graphite particles which are reinforced in aluminum alloy matrix composite [8].

Fatigue failure of the material occurs due to repeated loading. Structures and Constructions that receives dynamic loads can be damaged at a lower stress than its maximum stress and even below its tensile stress. Fatigue failure is confirmed as a cause of 70-90% of structural element failure in normal operation [9]. Fatigue damage is more dangerous than static damage due to fatigue failure can occur suddenly without any sign or warning. many constructions may be received combined stress that contaminated by corrosive environment causing the component to be threatened its safety.

Aluminum will show changes in structural phenomena if heat treatment is carried out. Artificial aging on aluminum can be done at temperatures between 100 to 200 °C. The main objective of this study is to investigate the phenomenon of Al 7xxx series strength and micro structure changes by heating at 180 °C for 200 hours. This process is analogous to the aluminum work temperature as a turbine material Organic rankine cycle.

2. Experimental Details

2.1. Chemical Composition analysis

The material used in this research is cast aluminum alloy 7xxx series with specific composition of Al-9.05 Zn-4.03 Cu-3.01 Mg. The process of casting was conducted by using gravity casting with metal molds. The temperature used in the casting process was stable at 750 °C. The variables used in 2 (two) conditions, which are as-cast and heat-treated material at 180 °C for 200 hours which in analogy as the operating temperature of the ORC's turbine blade. Many tests that conducted in this research are chemical composition test, hardness test, tensile test, microstructure observation, fatigue test and fractography observation. The result of Chemical composition shown in Table 1.

| Element | Al    | Zn   | Cu   | Mg   | V    | Cr    | Mn   | Fe    |
|---------|-------|------|------|------|------|-------|------|-------|
| Content (%) | 83.25 | 9.05 | 4.03 | 3.01 | 0    | 0.04  | 0.23 | 0.12  |
| Element | Co    | Ni   | Ti   | Si   | Zr   | Sn    | Pb   | Bi    |
| Content (%) | 0     | 0.09 | 0.03 | 0.05 | 0    | 0     | 0.07 | 0.03  |

2.2. Hardness Test

Hardness test was performed in the two conditions of the samples, as-cast and aged material at 180 °C for 200 hours in which each condition was conducted in 36 test points to analyze the uniformity of hardness value in each condition alloy. Sample preparation was done by casting, sample cutting, heat treatment, surface smoothing and polishing. The load that used in this test is 500 gf. Hardness Brinell obtained by using Equation 1 below:

\[ BHN = \frac{2P}{\pi D (D - \sqrt{D^2 - d^2})} \] (1)

2.3. Microstructure Observation

Preparation process was conducted by polishing with TiO₂ and etching process was conducted using a mixture of 12.5 ml 8 ml HNO₃ + HF + 85 ml. The Observations were conducted on both material conditions, as cast and and heat treated at 180 °C for 200 hours.
2.4. Tensile Test
Tensile testing was performed using a universal testing machine with a load of 3000 kgf. The test was performed using JIS Z 2201. The applied voltage was 20.00 kV on two material conditions, as cast and heat-treated material at 180 °C for 200 hours.

2.5. Fatigue Test
Fatigue testing was performed to determine the limit of fatigue resistance by using Torsee's Torsion Repeated and Bending Fatigue Machine. The standard test is based on JIS Z 2273.

2.6. Fractography Observation
Fractographic observations were performed on fracture surface. This observation is useful for analysing fracture mechanisms that occur in 2 material conditions that are as cast and heat-treated material at 180 °C for 200 hours. Tools used in this observation is the SEM FEI inspect S50.

3. Result and Discussions
The results of hardness test on 2 (two) conditions showed that hardness value on as-cast specimen is higher at 64 BHN compared to heat-treated specimen of 42 BHN. The hardness values shown in figure 1 below.

![Figure 1](image)

**Figure 1.** Hardness values on as cast and heat treated aluminium casting alloy

This was happened because an ageing process that occurs in a long time presented the precipitation of second phase as an embrittled phase which are directly affected in the reduction of hardness value [10]. Figure 2 and figure 3 show the phenomenon of precipitation deployment occurring on the aluminium alloy surface. On as cast specimen, the precipitates spread evenly over the grain boundaries. The precipitation becomes barrier against the mechanical force given to the material. While on heat-treated specimens, heat treatment process in 180 °C for 200 hours causes the precipitates spread evenly over the dendrite, since the barrier energy is lost then the resistance to the mechanical force becomes lower and resulting the reduction of hardness toughness.
Similarly with the results of the hardness test, on tensile test also occurs a decline in the value of Ultimate tensile strength from 196.17 MPa to 181 MPa on a heated material. While the yield strength on as cast specimen is 187.77 MPa and 178.4 MPa on heated material. Yield Strength and Ultimate tensile strength value shown in figure 4 and figure 5.

Figure 2. Microstructure observation on as cast specimen

Figure 3. Microstructure observation on heat treated aluminium casting alloys.
Fatigue testing was performed in 5 levels of loading under the yield stress of each condition. The results show that as cast specimens has higher fatigue resistance than heat treated specimens. The longest fatigue cycle in as cast material is 110500 times, whereas in heat treated specimens is only 81050 times. SN diagram of fatigue test shown in figure 6.
The reduction of fatigue value that occur in heat treated specimens caused by the presence of embrittled phases that are present due to the long-term heat treatment process [11].

Figure 7. Fracture analysis on as cast specimen (a) mag. 47x (b) mag. 200x

Figure 8. Fracture analysis on heat treated specimen (a) mag. 41x (b) mag. 500x

Fracture fatigue are shown in figure 7 and figure 8. Both as cast and heat-treated alloy show brittle fracture phenomenon. However, the form of fracture in brittle specimen is very brittle where fractures are in the form of small fractures such as glass crumbs. It shows that as cast specimen toughness is higher when compared to heat treated specimens. The presence of porosity is considered to exacerbate the circumstances that cause the material to fail prematurely.

4. Conclusion
Based on the analysis that has been done, it is known that the process of heating that conducted continuously in a long time resulting the reduction in mechanical properties. the reduction of mechanical properties occurs due to the dissemination of load throughout the grain which makes the material's ability to withstand mechanical loads to decrease. The reduction of the strength value of the material
can be exacerbated by the presence of porosity present as the initial crack that promotes to material fails prematurely.

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