Characterization of Al-7Si-Mg-Cu Turbine Impeller Produced by Investment Casting

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Keywords: investment casting, aluminum alloys, turbine impeller, organic rankine cycle

Abstract. Application of a light-weight material, such as an aluminum alloy, on a turbine impeller can enhance the efficiency of an Organic Rankine Cycle power plant that operates at temperatures below 150 °C. The density of an aluminum alloy only one-third that of steel. However, increased strength of aluminum alloys is needed for turbine impeller qualification. Investment casting was chosen to produce radial inflow turbine impeller due to their complex geometry and precision. It can replace machining process, which is time-consuming and less efficient because of material removal. This study describes the investment casting process used to produce a radial inflow impeller turbine. The study also identifies defects, microstructures and properties of radial inflow turbine impeller. The turbine impeller were produced from Al-7Si-4Mg alloy with 0.38, 3.82, and 6.0 wt. % Cu. Visual examination showed that the turbine impeller was free of macro defects and misruns. Microstructures were characterized by Optical Microscopy and SEM. The structures consisted of α-Al, Si eutectic, AlMgSi, AlMgFeSi (Chinese script) and CuAl2. The higher hardness value of 54HRB was affected by Cu content due to the good mechanical properties of fasa CuAl2.

Introduction

Aluminum alloys are recommended material for turbine impeller used at Organic Rankine Cycle (ORC) power plants that operate at temperatures below 150 °C [1, 2]. An excellent characteristic of an aluminum alloy is its low density only one-third that of steel. Its use can enhance the efficiency of the turbine. In addition, aluminum alloys are resistant to corrosion, which is needed in a turbine. However, increasing strength is required to achieve good performance. An aluminum alloy commonly used in industry is Al-Si-Mg-Cu, which has good castability, a strong mechanical performance and corrosion resistance. Silicon content in aluminum alloys can improve their hardness value without increasing their density because silicon has a lower density than aluminum. However, higher silicon content in aluminum alloys leads to the formation of primary silicon which is brittle but has a high hardness value. Additions of Cu content increase mechanical properties due to the formation of CuAl2, yet flowability does not decrease. Mg content increases the mechanical properties of aluminum alloys after heat treatment due to the formation of Mg2Si [3].

Fabrication of turbine impeller is more complex because the parts are highly precise, the geometry is complex and the tips of the blades are very thin. Process technology to produce turbine impeller includes forging, machining and investment casting. Forging produces good mechanical properties but low precision, so the process must be continued with machining. Fabrication by machining produces high precision for turbine impeller’s complex parts. However, the cost is high due to lengthy process and material removal. Investment casting can produce a highly precise parts characterized by more complex geometry. It is cheaper than machining because material removal is not required [4].

However, the failure rate in production of the impeller by investment casting has been 30-40% [5]. The important features of investment casting that affect the quality of cast products are the ceramic shell, gating system design and solidification process [4, 5]. Some defects commonly appear in products of investment casting: these include misruns, inclusion, macro and micro
porosity and hot cracks. The study of failure rates for investment casting products in a China foundry showed that 30% of defects were caused by inclusion, 20% by porosity, 10% by hot cracks, and 10% by misruns [6].

For this study, we aimed to produce turbine impeller for an ORC power plant by investment casting. Casting parameters and ceramic shell production is described in the experimental section. The turbine impeller was made from Al-7Si-4Mg with varied additions of Cu content. Microstructure and mechanical properties were identified to show the effect of additional Cu content.

**Experimental Method**

The gating system consists of a pouring basin, sprue, two runners, and two ingates; simulation was performed by Z-Cast®. A wax pattern was made using an injection wax machine at a temperature of 90–110°C; tree assembly was based on the design of gating system. Overall height of the trees was 300 mm. Shell molds were processed by dipping wax trees into a colloidal suspension consisting of ethyl silicate (liquid) and zirconia powder. A wet pattern was then poured with zircon sand (particle size approximately 200 µm). Next, the coated pattern was covered with secondary coatings of Mullite with particle sizes ranging between 400 and 600 µm. The secondary coating was applied three times to enhance the strength of the shell mold. The mold was dewaxed in an autoclave at a pressure level of 9 bars and temperature of 200 °C. After that, it was fired at 1050 °C for 1 h to induce sufficient strength for subsequent handling.

An Al-7Si ingot, and Mg and Cu ingots, were used as master alloys. Mg content was 4.3 wt. % and Cu content varied at 0.38, 3.82, and 6.0 wt%. The alloys were melted in a graphite crucible. Degassing was conducted using argon gases to eliminate hydrogen content and slug. The nominal composition of the cast alloys is presented in Table 1. Before pouring, the alloys were tested with a vacuum porosity tester to verify hydrogen content.

<table>
<thead>
<tr>
<th>Alloys</th>
<th>Composition (wt%)</th>
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<tbody>
<tr>
<td></td>
<td>Si</td>
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<tr>
<td>I</td>
<td>7.94</td>
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<tr>
<td>II</td>
<td>7.71</td>
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<tr>
<td>III</td>
<td>7.38</td>
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Pouring temperature was 750 °C and preheating temperature for the ceramic shell mold was 730 °C. The ceramic shell mold was broken after solidification. The cast of the radial inflow turbine impeller was characterized by visual examination to look for macro defects. Optical microscopy and scanning electron microscopy (SEM) were used for microstructural characterization. Specimens for these examinations were cut from the tips of the blades, and were etched by using 0.5% HF. Specimens for hardness testing were cut from the hub of the impeller. Hardness based on the Rockwell B scale was measured by applying a load of 150 kg for 10 s.

**Results and Discussion**

**Visual inspection.** Breaking the ceramic mold after solidification was difficult due to the complex geometry of the turbine, especially between blades. The impeller that made of Al-7Si-4Mg-0.38Cu produced by investment casting is presented in Figure 1a, while the cut of the turbine impeller is shown in Figure 1b. All radial inflow turbine impeller casts were free of macro defects, such as misruns, macro porosity, and surface cracks. Macro defects were not found on the cut of the turbine. Smooth surfaces were obtained for all cast specimens. The successful elimination of defects resulted from a good design of gating system, ceramic shell molds, and casting parameters (i.e., pouring temperature and preheating temperature for shell molds). It should be noted that the degassing process also ensured that the cast was free from porosity.
The design of gating system is one of the important parameters in investment casting. A poor design will lead to misruns and shrinkage. For this study, ceramic shell molding contributed to successful casting. The smooth surface indicated that no reaction occurred between the alloys and the first layer of the ceramic mold. The absence of misruns and shrinkages in the cast showed that the permeability of the molds was adequate to expand the gases within [7].

It is important to note that casting parameters include pouring temperature and mold preheating temperature. Mold preheating temperature is one of the most important casting parameters. A higher preheating temperature not only improves fluidity of liquid metal but it also reduces thermal gradient and cooling rates. However, a higher preheating temperature may lead to a reaction between metal and the mold, thus increasing the propensity for surface porosity [5]. Other disadvantages are coarser grain size and inferior mechanical properties. Therefore, an optimal preheat mold temperature must be found to achieve good properties.

![Diagram of radial inflow turbine impeller](image1)

**Figure 1** (a) Radial inflow turbine impeller that made of Al-7Si-4Mg-0.38Cu produced by investment casting, (b) Cut of turbine impeller.

**Effect of Cu on microstructures.** Figure 2 shows microstructures of the tips of impeller with varied Cu content. Microstructures of the Al-7Si-4Mg-0.38Cu alloy are shown in Figures 2a and 2b. The dendritic structure is fine, as well as the Si eutectic. The structure of Chinese script (AlMgFeSi) formed due to the presence of Mg and Fe. However, The CuAl₂ was not found in Al-7Si-4Mg-0.38Cu alloy due to lower Cu content. The microstructures of the Al-7Si-4Mg-3.82Cu alloy are shown in Figures 2c and 2d. The structure is relatively the same as that of the Al-7Si-4d-0.38Cu alloy (i.e., grain size, Si eutectic, and Chinese script). The CuAl₂ formed in this alloy due to higher Cu content. The microstructures of the Al-7Si-4Mg-6.0Cu alloy are shown in Figures 2e and 2f. It has coarser grain than 0.38Cu and 3.82Cu that may be due to lower rate of solidification. Si eutectic and Chinese scripts were also found. Phases of CuAl₂ formed more than 3.82Cu alloy because of the higher content of Cu. Different amount of in CuAl₂ phase caused significant differences in mechanical properties.

![Microstructure images](image2)

Figure 3 shows the backscattered SEM of as-cast Al-7Si-4Mg-6.0Cu alloys and the corresponding elemental analysis is provide in Table 2. The α-Al matrix can be seen (position 1), and it is clear that the grey phases are Al-Si eutectic (position 2) the white phases are CuAl₂ (position 3) and phases Al₅Cu₂Mg₆Si₆ (position 4), while the black phases are AlFeMgSi or Chinese script (position 5). The element Fe was difficult to detect with EDS because it was present in a smaller quantity (less than 0.5%). However, the content of Fe was evident in the structure of the Chinese script, even though it was present in a small quantity. Phase formations on as-cast 0.38Cu and 3.82Cu containing alloys were similar except for quantities.
Figure 2 Microstructures of tips of turbine impeller of Al-7Si-4Mg with (a, b) 0.38 (c, d) 3.82 and (e, f) 6.0 wt. % Cu produced by investment casting.

Figure 3 Backscattered SEM of a tip of impeller of Al-7Si-4Mg-6.0Cu alloy.

Figure 4 Effect of Cu on the hardness of the Al-7Si-4Mg alloys.
Effects of Cu on hardness value. Figure 4 shows the effect of Cu on hardness of the Al-7Si-4Mg alloys. The addition of Cu significantly increases the hardness value. The highest hardness value was obtained by Al-7Si-4Mg-6Cu of 54.85 HRB. In spite of the alloy contain 6 wt. % Cu has coarser grain than 0.38 and 3.82 wt. % Cu, but the higher Cu content lead to more CuAl2 phase which is hard and though. The presence of phases CuAl2 phase leads to significantly higher hardness. The Si eutectic & AlFeMgSi (Chinese Script) also contributed to the higher value of hardness. Hardness value is also probably caused by Si eutectic and AlFeMgSi (Chinese script). However, the properties of Chinese script is hard but brittle so it tends to be avoided [8].

Conclusion
In this study, characterization of turbine impeller produced by investment casting obtained the following key findings:
1. Visual inspection shows no macro defect of the turbine blade as cast such as misrun, macroporosity, shrinkage and others surface defects. It shows that gating system design, casting parameters and ceramic shell mold work optimally.
2. Microstructures of turbine impeller made of that Al-7Si-4Mg-Cu alloy fabricated by investment casting mainly consisted of α-Al, Si eutectics, CuAl2, Al5Cu2Mg8Si and AlSiFeMg (Chinese script)
3. The higher the Cu content the higher the hardness value. Alloy containing 6 wt. % Cu achieved the hardness of 54.85HRB. Higher Cu content promote CuAl2 phases which is hard and tough.

Acknowledgments
The research was funded by the Riset Madya UI 2012. Thanks to PT. Metinca Prima for facilitating investment casting process. MS is grateful for the provision of scholarship by Hasanuddin University Engineering Faculty Development Project under JBIC Loan.

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