The Influence of Yttrium Addition on The Corrosion Resistance and Tensile Strength of as-Cast Mg-Y Alloys

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Abstract. This study shows the effect of Yttrium addition (2-6 wt%) on the mechanical properties and the corrosion resistance of Mg-Y binary fabricated from sacrificial magnesium anode. The beneficial of Mg anode source was tremendous for magnesium alloy especially for corrosion resistance. Improvement of mechanical properties due to the addition of Yttrium was caused by grain refinement solid solution strengthening. Tensile strength increased with the addition of Yttrium. Mg-Y binary is immersed in the SBF solution to see the corrosion resistance. The hydrogen evolution was increased from 0.32 mL/cm² day, 1 mL/cm² day, and 34.42 mL/cm² day for Mg-2%wt Y, Mg-4%wt Y, and Mg-6%wt Y respectively.

Keywords: Corrosion potential, corrosion rate, grain refinement, magnesium anode source, Mg-Y binary, mechanical properties, solid solution strengthening

1. Introduction
Currently, the biodegradable implant material which are widely used for bone recovery was magnesium-based alloys. This type of implant can reduce stress shielding due to its modulus of elasticity similar to the bone. As its degraded by time, no additional surgical treatment was required after the bone healed [1]. As we know the body needed magnesium in some amount during bone formation [2]. Mostly the constraint of the magnesium was the fast corrosion rate and low mechanical strength which will affect the healing to fail [3]. In this work, Mg-Y alloys was fabricated through casting process. Base material that was used is magnesium anode source. The presence of trace element in magnesium anode source such as Mn give an advantage to increase corrosion resistance [4]. The increase of corrosion resistance is significant with alloying element. The alloy that was used in this research is yttrium. Yttrium can form intermetallic compounds with the impurities that was reduced their bad influences [5]. Yttrium also has a good biocompatibility based on survey on the high rare earth element background regions in China that was the tolerant daily intake of Y around 4.2 mg.day⁻¹ [5]. The mechanical properties increased due to solid solution strengthening mechanism and grain refinement. The microstructure was determining of corrosion behavior.

2. Experimental Methods
In this work, Mg anode source and Mg-Y master alloys was melted in graphite crucible by heat induction furnace until reach liquid phase. The temperature of the liquid phase is between 700°C-750°C. The mixture of HFC-134a, N₂, and CO₂ gas were used for shielded gas during the casting...
process the targeted composition of the alloys was Mg-2Y, Mg-4Y, and Mg-6Y (wt.%). The chemical compositions of the as-cast Mg-Y alloys were determined by AAS methods, and the results are shown in Table 1. After casting, the ingot was cut into test specimen. The specimen was characterized by SEM, EDS, XRD, metallography, immersion test, and electrochemical test.

Table 1. Chemical composition of alloys in wt. %.

| Alloy  | Mg  | Al  | Zn  | Mn  | Fe  | Ni  | Cu  | Si  | Y  |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|----|
|        | balanced | 0.092 | 0.46 | 0.028 | 0.00092 | 0.018 | 0.046 | 2   |
|        | balanced | 0.084 | 0.42 | 0.025 | 0.00084 | 0.017 | 0.042 | 4   |
|        | balanced | 0.076 | 0.38 | 0.023 | 0.00076 | 0.015 | 0.038 | 6   |

2.1 Microstructure and Mechanical Properties

The microstructure of the as-cast alloy was observed using optical metallography. The specimen was cut to 1 cm x 1 cm, etched with 2% oxalic acid before microscope observation. The mechanical testing was undertaken by following ASTM B557 M procedure. The dimension of the dog bone specimen is 45 mm in gauge length and 9 mm in diameter with screw rounded on grip.

2.2 Immersion Test

The immersion test was conducted to measure the hydrogen evolution and the corrosion rates of the alloy. The specimen size was 2 cm x 2 cm in square. Total surface area of the specimen compared to the solution immersion test was not less than 1 cm$^2$:20 mL according to ASTM G31-72. Before test, the surface of the specimen was grinded up to 2000 grit sandpaper. Ringer’s solution was used for test medium with the composition showed in Table 2. The test temperature was set to 37°C±1°C. The hydrogen evolution rate or VH (ml/cm$^2$/day) and the corrosion rate or RH (mmpy) was calculated using the following equation.

\[
RH = 2.279\text{VH}
\]

Time of immersion was prolonged to 4 days. After immersed, the specimen was removed from the hydrogen evolution installation and immersed on chromic acid with composition about 200 gram/l and hold until 30 min to removed corrosion product without removing any amount of metallic Mg. Finally, the specimen was rinsed on distilled water and cleaned ultrasonically in acetone or alcohol after that the specimen dried in air. Before and after immersion test, the specimen was weighed, and the data was recorded. The corrosion rate was calculated using the following equation.

\[
R_i = \frac{k \times \text{mass loss (gram)}}{\text{time (hours)} \times \text{area of exposure (cm}^2) \times \text{density of magnesium alloy \left(\text{g/cm}^3\right)}}
\]

K that used for mmpy is 87600 according to ASTM G31-72.

Table 2. Chemical composition of simulated body fluid used in immersion test.

| Compound                | Amount (mg/l) |
|-------------------------|---------------|
| NaCl                    | 6000          |
| KCl                     | 400           |
| CaCl$_2$·2H$_2$O        | 270           |
| C$_3$H$_7$NaO$_3$       | 3120          |
2.3 Electrochemical test
The electrochemical test was used for measuring the corrosion potential and current of the alloy in Ringer’s solution medium. The specimen size is plate with the exposed area closed to 0.05 cm² approximate to O ring seal. Before test, the specimen surface was ground up to 2000 grit. The temperature of the test was set to 37°C±1°C which is simulated normal human temperature. The data was recorded and analyzed by VersaStat® automatic laboratory corrosion measurement system using standard three-electrode configuration, with a saturated calomel as a reference, a graphite electrode as the counter and the sample as the working electrode.

3. Results and discussion

3.1 Microstructure and mechanical properties
The microstructure revealed that grain refinement increases due to the addition of Yttrium as shown in Figure 1. As the yttrium content increased the grain size was degreased. Grain refinement could make the mechanical properties increase related to Hall-Petch equation. The result was confirmed by tensile test result (showed in Table 3) which show increasing tensile strength as the Yttrium content increased. Beside of that the hardness data also confirmed that was increased mechanical properties due to increasing of Yttrium content. This could indicate the strengthening mechanisms to this alloy was due to Yttrium addition. Alloy 1 was not tested because when machined the specimen failed to form because alloy 1 was most brittle than the others. The force that applied for each alloy to form dog bone specimen was same and indicate that Alloy 1 was most brittle and weaker than the others. There was need strengthening mechanism to increase mechanical properties especially for toughness. Mechanism of non-basal slip was studied for increasement of mechanical properties especially for its properties. The non-basal slip system was pyramidal slip that accommodate Mg-Y binary to increase the ductility [6]. The tensile properties were increased as the Y content was increased but there is a reduction in ductility from the addition of 4% weight Yttrium to 6% weight Yttrium due to reduction of grain size [5].

![Figure 1. Microstructure of Mg-Y alloy.](image)

| Alloy  | Hardness (HV) | Yield Strength (MPa) | Ultimate Tensile Strength (MPa) | Elongation at Break (%) |
|-------|---------------|----------------------|-------------------------------|-------------------------|
| Mg2Y  | 38            | -                    | -                             | -                       |
| Mg4Y  | 48            | 125,7                | 146,19                        | 1,57                    |
| Mg6Y  | 60            | 133,6                | 164,26                        | 1,55                    |

Table 3. Mechanical properties of Mg-Y alloys.
3.2 Immersion Test

The immersion test results were depicted in Figure 2. Calculated corrosion rates as the function of hydrogen evolution measurements were 0.74 mmpy, 2.29 mmpy, and 78.44 mmpy for Mg-2%wt Y, Mg-4%wt Y, and Mg-6%wt Y respectively. The higher corrosion rates in Y addition above 2%, was likely caused by higher secondary phase in the alloy which lead to micro galvanic corrosion especially for Mg-6%wt Y [7]. As additional of yttrium, the amount of secondary phase will be increase [8]. Based on cast processing the phase distribution of primarily phase and secondary phase should be random and not uniform. This type of microstructure can accelerate of corrosion rate of the magnesium [7].

The corrosion rate according to mass loss measurement were 1.2 mmpy, 5.5 mmpy, and 104.7 mmpy for Mg-2%wt Y, Mg-4%wt Y, and Mg-6%wt Y respectively. Both of two calculated, the optimum composition for corrosion rate of Mg-Y binary according to this research is Mg-2%wt Y and this study related to common research [5].

![Figure 2. Hydrogen evolution rates measurement on Mg-Y alloys.](image)

3.3 Electrochemical Test

Based on electrochemical test, the data were current density and potential corrosion for each alloy. Tafel extrapolation were used from origin. Current density that could calculated from this origin were 0.96 A/m², 0.61 A/m², and 0.26 A/m² for Mg-2%wt Y, Mg-4%wt Y, and Mg-6%wt Y. I corrosion equals to corrosion rate [3]. So, the corrosion rate decreased gradually with increasing Y content. The corrosion data that resulted based on Electrochemical test and immersion test was contradiction. The differences data caused by differences of modus corrosion between Immersion test and electrochemical test. Time of exposure in medium corrosion from each test was different significant. Formation passive layer depends on time of exposure in medium corrosion. Passive layer gives a tremendous effect on corrosion rate [9]. Passive layer that formed based on electrochemical test and immersion test was different. Passive layer that formed on electrochemical test was uniform and solid while passive layer for immersion test was porous.
Figure 3. Electrochemical measurement results of magnesium alloy with different yttrium addition.

4. Conclusion
The tensile strength and ductility increase due to increasement of Y content. Mg2Y was best corrosion resistance from the others based on immersion test. Mg6Y was best corrosion resistance from the others based on electrochemical test. The immersion test was best to revealing corrosion rate for those alloys because in electrochemical test, there would be some error in calculation current density due to transitive area that was exposed in electrolyte.

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