# High Strength Magnesium-Yttrium based Alloys Exhibiting Controlled Degradation for Musculoskeletal Medical Implant Application

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**Statement of Purpose:** Degradable metals hold great promise as materials which exhibit higher mechanical properties than degradable polymers while corroding over time to alleviate complications such as stress-shielding effects and infection inherent to permanent inert metallic biomaterials. Specifically, degradable Mg alloys have emerged as a promising alternative for orthopedic and craniofacial applications due to positive bone remodeling behavior and good biocompatibility of Mg. Increasing strength and controlling the rapid corrosion of Mg are ongoing goals for optimizing Mg alloys for musculoskeletal applications. In order to address these goals, novel Mg-Y based alloys were developed with the addition of varying concentrations of Y as well as other alloying elements to impart different properties. Heat treatment was conducted to reduce the second phase volume fraction by dissolution into the α-Mg matrix to reduce risk of microgalvanic corrosion. Hot extrusion was employed to reduce the grain size, thereby improving mechanical properties through the Hall-Petch relation wherein grain boundaries act as pinning sites to impede the propagation of dislocations. Corrosion and *in vitro* cytotoxicity analyses have also been conducted.

**Methods:** Pure magnesium and other high purity alloying elements and master alloys were melted in an electrical resistance furnace at temperatures between 700-750°C. After stirring and holding the temperature to achieve high solubility, the molten metal was poured into a mild steel mold. The as-cast alloys (termed alloys A, B, C, D, with alloys A-C containing increasing Y content and alloy D containing Zn) were then solution treated and hot extruded. Alloy samples were polished and the microstructure was observed under optical and scanning electron microscopy. Vickers microhardness was measured by applying a load of 100 g for 10 s and measuring the indentation using optical microscopy. Tensile mechanical testing was also conducted following ASTM E-08 at an extension rate of 1.3 mm/min. Immersion corrosion testing was performed in Hank's Balanced Salt Solution at 37 °C for one week with average corrosion rate calculated in conformation with ASTM G31-72. To investigate alloy toxicity, MC3T3 pre-osteoblast cells were cultured directly on the alloys at a density of $4 \times 10^4$ cells/ml. The viability of seeded cells was evaluated after 1 day using the live/dead assay with cells imaged by fluorescence microscopy. Cytotoxicity on MC3T3 cells cultured for 1 and 3 days in extract media collected for 3 days from immersed alloy samples was determined using the MTT assay.

**Results:** Hot extrusion brought about significant grain refinement as validated by optical microscopy. Microhardness significantly improved by addition of Zn and increasing the Y content in Mg-Y alloys. Strength was also significantly improved by addition of Zn (Fig. 1) due to formation of long period stacking order (LPSO) phases at grain boundaries, as confirmed by microstructural analysis.

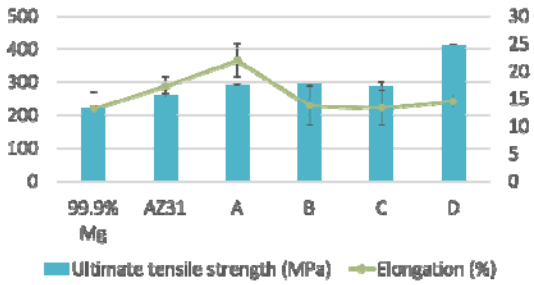


**Figure 1**. Tensile mechanical properties of Mg alloys studied compared to pure Mg and commercial AZ31 alloy.

Reduction in elongation was observed with increasing Y content. Corrosion rate was reduced by increasing the Y content, likely due to the formation of $Y_2O_3$ which has a high thermodynamic stability. The direct live/dead assay (Fig. 2) displayed high cell density of attached live MC3T3 cells on extruded alloys after 1 day of culture, even when compared to tissue culture plastic.

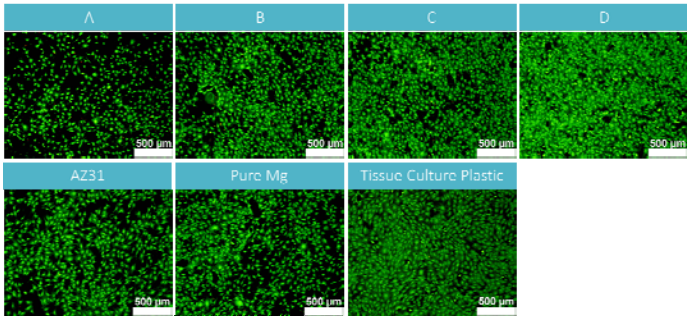


**Figure 2**. Fluorescence microscopy images of MC3T3 after performing the live/dead assay following 1 day of culture on the alloys.

The MTT assay displayed low toxicity of the alloy extract, with at least 60% cell viability observed with no extract dilution.

**Conclusions:** Extrusion resulted in alloys with high mechanical properties with strength superior to commercial Mg alloy and AZ31. Corrosion was also well controlled through the processing methods described, and cell viability studies shown here demonstrated low toxicity of the alloys when in direct contact with cells and when their degradation products were exposed to cells. Further biocompatibility and biomechanics test studies will be conducted in relevant animal models that will be described in the near future.