Development of Biodegradable Magnesium-Yttrium Based Alloys for Craniofacial and Orthopedic Applications

Da-Tren Chou[1], Daeho Hong[1], Partha Saha[1], Prashant N. Kumta[1,2,3]

[1] Dept. of Bioengineering, [2] Chemical and Petroleum Engineering, [3] Mechanical Engineering and Materials Science, University of Pittsburgh, 414 Benedum Hall 3700 O'Hara St, Pittsburgh, PA 15213, United States. E-mail: dac105@pitt.edu

Statement of Purpose: Metallic biomaterials currently used for orthopedic and craniofacial devices have been selected for their excellent mechanical properties and corrosion resistance. However, these permanent metals risk causing stress-shielding effects, infection, and other complications which have led to a rise in interest of biodegradable metals. Magnesium (Mg) alloys have emerged as the most promising candidate due to their high strength to weight ratio, similar mechanical properties to bone, good biocompatibility, and degradability in aqueous environments. However, the chloride concentration in the implant environment may result in rapid corrosion of Mg and release of hydrogen gas, leading to premature mechanical failure and possible toxicity. In order to satisfy the requirements for orthopedic and craniofacial biomaterials, novel Mg-Y based alloys were developed with different processing conditions. Heat treatment was applied to reduce the volume fraction of secondary phases by dissolving them into the α-Mg matrix to reduce risk of microgalvanic corrosion. Severe plastic deformation using equal channel angular pressing (ECAP) was employed to reduce the material's grain size, thereby improving mechanical properties through the Hall-Petch relation wherein grain boundaries act as pinning points to impede the propagation of dislocations.

Methods: Pure Mg and high purity elemental ingots/shots/granules were melted in an induction furnace and re-melted (740-780^{o}C) in a resistance furnace. After stirring, the molten metal was poured into a mild steel mold preheated to 500 °C. The as-cast Mg-Y based alloys (WX41) were further solution treated at 400°C for various durations and then water quenched. Immersion corrosion measurements were performed using physiological saline (0.9% NaCl solution) at 37 °C with average corrosion rate after 10 and 14 day immersion calculated in conformation with ASTM G31-72. MC3T3 cells were cultured directly on Mg alloy specimens at a density of 4×10^4 cells/mL. Viability of seeded cells cultured for 1 day was evaluated using the live/dead viability/cytotoxicity kit. Cells on the scaffolds were imaged using fluorescence microscopy. To investigate feasibility of ECAP, preliminary ECAP was conducted on an as-cast Mg-Y alloy preheated to 550 °C. Vickers microhardness was measured by applying a load of 100 g for 10 s.

Results: After immersion in physiological saline, the Mg-Y based WX41 alloy heat treated for 10, 20, 40, and 70 h demonstrated reduced corrosion rate over the as-cast form and pure Mg, with similar corrosion to the slow corroding commercial alloy AZ31 (Fig. 1), demonstrating a reduction in galvanic corrosion by reduction of secondary phases as confirmed by microstructure observation. The direct live/dead assay (Fig. 2) showed higher density of attached live cells on the WX41 alloy after heat treatment for 40 h compared to the WX41 prepared in other conditions, AZ31, and pure Mg. ECAP was applied to a Mg-Y alloy which resulted in slight grain refinement and a severely deformed microstructure with many shear bands and twinning. An increase in hardness from 39.3HV to 60.5HV after 2 passes of ECAP was caused by work hardening due to formation of subgrain bands and an increase in dislocation density. High cell attachment was observed in the ECAP sample compared to the as-cast alloy. The effect of ECAP on mechanical properties, corrosion, and osteoblast attachment, proliferation, and differentiation will be investigated in further detail.

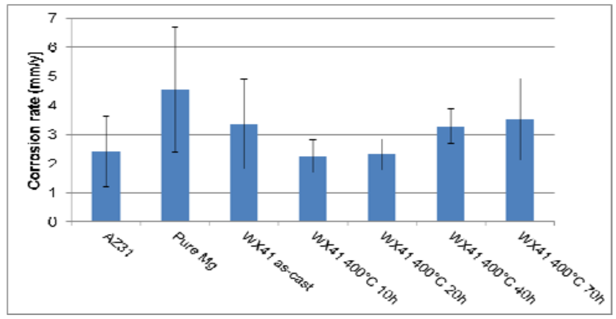

Figure 1. Immersion corrosion rate of as-cast and heat treated WX41 alloy, AZ31, and pure Mg.

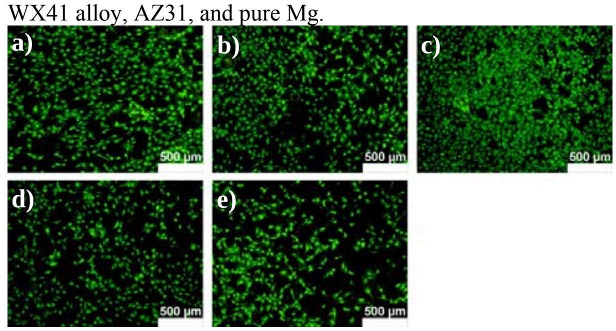

Figure 2. Fluorescent images of live (green) and dead (red) cells attached to a) WX41 as-cast, b) WX41 heated at 400 °C for 20 h, c) WX41 heated at 400 °C for 40 h, d) AZ31, e) pure Mg.

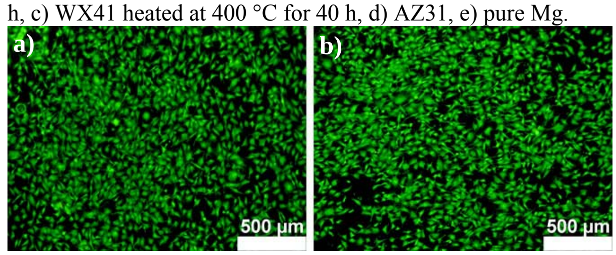

Figure 3. Fluorescent images of live (green) and dead (red) cells attached to a) Mg-Y alloy as-cast and b) Mg-Y alloy after 2 ECAP passes.

Conclusions: Biocompatible, slow corroding Mg-Y based alloys were developed for biodegradable orthopedic and craniofacial devices. Heat treatment retarded the alloy degradation rate by reducing volume fraction of secondary phases, while equal channel angular pressing improved the hardness. In the future, Mg-Y alloys will be subjected to ECAP followed by heat treatment and changes in its properties will be assessed.