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Research Article

Magnesium Modeling using SolidWorks

Hawkins KM, Jones SJ, Gibbs D and McCullough MB*

Department of Chemical, Biological, and Bioengineering, North Carolina A&T State University, USA

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Abstract

Increased cost and complexity associated with orthopaedic surgeries has led to advancements in degradable materials. Degradable metals like magnesium have shown great promise as magnesium based alloys provide the strength of metals but the degradability of polymers. As the development of degradable magnesium alloys expands there is a significant need for simplified computational models that can account for the numerous mechanical changes associated with degradation. The current study examined initial *in silico* models of Magnesium samples to gain insight on how degradation impacts mechanical performance over time. Models of magnesium rods were created and analyzed using the finite element analysis functionality in a commercially available software package. SolidWorks is widely known for its design capabilities and generation of 3D solid models; however its analyses capabilities would be useful for such a smart material, like magnesium. Therefore, this work explores the analysis capabilities of SolidWorks, for degradable magnesium in a skeletal environment.

Keywords: Computational modeling; SolidWorks; Magnesium; Finite element analysis

Abbreviations: Mg: Magnesium; FEA: Finite Element Analysis

Introduction

Degradable metals and their alloys are becoming more popular in medical devices. This degradability eliminates the need for removal surgeries and reduces interference with physiological processes. More specifically, degradable magnesium (Mg) based alloys appear to be well suited for orthopaedic device applications due to controllable corrosion rates and lower moduli comparable to natural bone [1]. There have been many

proposed uses for magnesium alloys in orthopaedics including bone screws, sutures, and suture anchors [1-3]. In spite of the promise of these alloys, concerns remain regarding the material's mechanical integrity after implantation. The nature of many orthopaedic procedures requires devices that provide a precise level mechanical support for the healing of bone and/or other tissues. If the implanted device provides too little support the tissues fail to heal, if the device provides too much support, tissues will fail to heal from stress shielding. It is therefore important to understand the mechanical properties of magnesium alloys at implantation and as the material degrades.

*Correspondence: McCullough MB, Department of Chemical, Biological, and Bioengineering, North Carolina A&T State University, Greensboro, NC 27411, USA, Tel: +1 336-285-3660; Fax: +1 336-334-7904; E-mail: mattbm@ncat.edu

Corrosion and degradation, are complicated, creating additional challenges in understanding the mechanical

behaviors of Mg based alloys. Among these challenges are identifying and simulating the various types of corrosion (i.e. stress and pitting) experienced in situ. Other factors to consider include alloy composition, stresses encountered, and the surrounding solution or environment.

Orthopaedic devices like screws and plates are complex in geometry and difficult to prototype for experimental testing. Therefore, researchers use computational methods and more specifically Finite Element Analysis (FEA) for analysis of device designs and configurations [4]. To the best of the author's knowledge, most of the current studies utilizing FEA to study magnesium degradation have been applied to arterial stents. Wu et al. 2010 used FEA to optimize stent designs in order to minimize the principal strain experienced by a cardiovascular stent and in turn, slow degradation [4]. Gastaldi et al. [5] proposed a corrosion model based on continuum damage mechanics (CDM) to simulate Mg corrosion experienced by stents. Even with these successful simulations, significant difficulty in modeling Mg degradation exists. Of these difficulties three were summarized as follows: 1) the elements exposed to a corrosive environment must be gradually weakened and removed when the damage is severe enough, 2) after the said elements are deleted new contact must be assigned to the remaining surface elements and, 3) a changing equilibrium must be displayed between the stent and arterial vessel as the constant compressive load of the vessel is applied to the gradually weakened and damaged stent [6]. By

adapting the CDM approach proposed by Gastaldi et al. [5], a refined model of stent degradation was later validated with experimental results and found accurate [6]. The purpose of this study was to use the finite element functionality within SolidWorks to model of Mg degradation and determine changes the mechanical integrity, of Mg samples, over time.

Methods

In summary, a 15 mm long, 5.2 mm diameter rod was modeled in a version of 2012, Dassault Systèmes Corporation; Waltham, Massachusetts, USA using the extrusion command. These specific dimensions for the cylinder were used because they are close to those used for Anterior Cruciate Ligament (ACL) interference screws, an orthopaedic device that would benefit from degradable technology, but requires significant mechanical strength. To simulate degradation of magnesium, a volume loss rate of 46.1 mils/year used [7]. This rate represented a subcutaneous insertion of AZ91D into mice for 2 months. Only uniform exterior surface degradation was assumed for this model. The degradation volumes were calculated for every two weeks and separate models were created, decreasing the surface area accordingly over the course of one year. Twenty-seven total models were generated representing decreasing volume. The initial and final magnesium rod geometry after one year can be seen in Figure 1.

The finite element simulations were run using

Figure 1: SolidWorks CAD models of the initial magnesium rods (left) and after one year of simulated, uniform degradation (right).

Figure 2: Maximum displacement verses time (left) and maximum stress verses time (right) plots of the finite element data.

SimulationXpress Analysis Wizard, a finite element analysis program within SolidWorks. The cylinders were given the built in Mg alloy material properties and modeled as linear elastic with a Young's modulus of 45 GPa. Three-dimensional tetrahedral elements were automatically used to mesh all rods. Because each rod was considered a solid component, tetrahedral elements were selected by the software. A convergence test was performed to optimize the number of elements in the model. Three built in density levels, low, medium, and high were used. Changes in maximum stress and displacement were compared at these density levels. The numbers of nodes and elements sufficient for this study were in approximately 10,000 and 6,700, respectively.

All degrees of freedom were eliminate on the circular face, found at one end of the rod. A 454 N tensile load was applied to the opposite face. This load simulated a critical load experienced by an ACL interference screw in the knee. The maximum displacement and stress experienced by each rod at that specific time point were observed and plotted in Microsoft Excel.

Results

The maximum stresses and displacements for each model are show, against time. As seen in Figure 2 (left), changes in displacement were relatively minimal, until the 12th week. As expected the maximum stresses within the rod increased, beginning at week one and continued to rise over the course of the analysis (Figure

2 (right)). This signified that the load bearing capacity of the rod decreased as it degraded. The rise in maximum stress appears to be exponential as maximum stress nearly doubled by the 52nd week.

Discussion

The purpose of this study was to use the finite element functionality within SolidWorks to model of Mg degradation and determine changes the mechanical integrity, of Mg samples, over time. This was accomplished by modeling samples of homogeneous Mg sample with a simple shape (*i.e.* cylinder), then axially loading the samples. As expected, maximum stress in each cylinder increased over time, due to the reduced cross sectional area. It was noted that none of the stresses appeared to surpass the material yield, leading to the presumption that the rods were not expected to fail from the tensile load within the first 52 weeks. These findings show promise for magnesium alloys in the body if they are able to remain structurally sound up until this point, the amount of time regarded as desirable for the alloys to remain structurally intact.

There are limitations of the study. One is the assumption of uniform corrosion in each cylinder. Corrosion is a complicated and often unpredictable process. There are numerous types of corrosion reported in the literature. Corrosion behavior depends heavily on the specific alloy and solutions used [7,8]. Stress corrosion is one specific form of corrosion that was not considered in this study. In skeletal environments, stress corrosion is

frequently observed and can potentially lead to quick failure at generally safe loads [5]. Future studies will consider the potential for Mg to pick up particulates, which add to the volume over time [8]. These and other changes in geometry affect device behavior and will need to be considered using contact analysis. In addition, combining mechanical simulations like the ones described here, with simulations of chemical reactions from different environments will prove useful in the development of numerous medical devices, based on Mg alloys.

Conclusions

The current study highlighted the ability to model Mg degradation in a 3D CAD based software package. This work provides a greater understanding of degradable device behavior in the body. The study found that the stresses and displacements in the magnesium rod under the same load, increased exponentially as the rod degraded. This work will help predict performance of degradable materials in different devices by offering an alternative framework to how computational models are formulated.

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