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Research paper

Surface integrity and process mechanics of laser shock peening of novel biodegradable magnesium–calcium (Mg–Ca) alloy

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ABSTRACT

Current permanent metallic biomaterials of orthopedic implants, such as titanium, stainless steel, and cobalt–chromium alloys, have excellent corrosive properties and superior strengths. However, their strengths are often too high resulting in a stress shielding effect that is detrimental to the bone healing process. Without proper healing, costly and painful revision surgeries may be required. The close Young's modulus between magnesium-based implants and cancellous bones has the potential to minimize stress shielding while providing both biocompatibility and adequate mechanical properties. The problem with Mg implants is how to control corrosion rates so that the degradation of Mg implants matches that of bone growth. Laser shock peening (LSP) is an innovative surface treatment method to impart compressive residual stress to a novel Mg–Ca implant. The high compressive residual stress has great potential to slow corrosion rates. Therefore, LSP was initiated in this study to investigate surface topography and integrity produced by sequential peening a Mg–Ca alloy. Also, a 3D semi-infinite simulation was developed to predict the topography and residual stress fields produced by sequential peening. The dynamic mechanical behavior of the biomaterial was modeled using a user material subroutine from the internal state variable plasticity model. The temporal and spatial peening pressure was modeled using a user load subroutine. The simulated dent agrees with the measured dent topography in terms of profile and depth. Sequential peening was found to increase the tensile pile up region which is critical to orthopedic applications. The predicted residual stress profiles are also presented.

1. Introduction

Biodegradable implants are a relatively new and emerging form of treatment for common bone ailments. Biodegradable implants are useful to the healing process due to the ability to gradually dissolve and absorb into the human body after implantation. The development of biodegradable implants has had a beneficial effect on in-vivo treatment of patients with various bone ailments.

Currently, biodegradable implants are mainly made of polymers, such as poly-L-Lactic acid. However, these polymer based implants usually have an unsatisfactory mechanical

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strength. An alternative to biodegradable polymer implants is permanent metallic implants composed of steel or titanium alloys. Permanent metal implants have superior strength compared to polymers. As a consequence, metal implants are often too stiff resulting in a stress shielding effect that can be damaging to the healing process (Benli et al., 2008; Completo et al., 2008; Au et al., 2007; Shi et al., 2007; Isaksson and Lerner, 2003; Nagels et al., 2003; Gefen, 2002). Stress shielding occurs when bone is shielded by an implant from carrying load. As a result, the bone tends to weaken over time resulting in more damage. To minimize the effects of stress shielding on the human body while still retaining strength, a soft lightweight metal is required. Therefore, Mg alloys are proposed as an ideal biodegradable implant material due to its biocompatibility and superior strength to weight ratio compared to that of other biomaterials.

Magnesium is an element essential to the human body. Intake of a certain amount of magnesium (300–400 mg/day) is normally required for regular metabolic activities (Seiler, 1987). The direct corrosion product of magnesium, Mg^{2+}, is easily absorbed or consumed by the human body (Song, 2007). However, the rapidly generated by-products of magnesium corrosion such as hydrogen gas and hydroxides are not physiologically favorable. Hydrogen evolution and alkalinization resulting from corrosion of Mg are the most critical obstacles in using magnesium as an implant material.

A straightforward strategy to overcome these difficulties is to control the corrosion rate of a biodegradable magnesium implant. Alloying is one of the possible solutions to control the corrosion rate of Mg in the human body. A concern with the alloying approach is biocompatibility of the alloying element(s). Alloying elements must not generate toxic, carcinogenic, or mutagenic products.

In this study, calcium (Ca) was alloyed with Mg to form a Mg–Ca alloy. It is well known that Ca is a major component in human bone and is also essential in chemical signaling with cells (Ilich and Kerstetter, 2000). Ca has a low density (1.55 g/cm^3) such that when alloyed with Mg, the density is similar to that of bone. The Ca in Mg–Ca alloys produces hydroxyapatite (HA) as a corrosion product on the surface of the implant. HA is a favorable biocompatible mineral which stimulates bone cells to attack the implant surface to form proper bonding (Aksakal and Hanyaloglu, 2008). The proper bond between implant surface and surrounding bone allows for fractured segments to realign in correct anatomical position which is critical to recovery.

Laser shock peening (LSP), used in conjunction with alloying, is a promising surface treatment technique to improve the surface integrity by imparting compressive residual stresses that are beneficial for controlling corrosion of Mg–Ca implants. LSP has been initiated to fabricate an array of dents on component surfaces (Warren et al., 2005; Warren and Guo, 2007; Caslaru et al., 2008; Sealy and Guo, 2008). Previous finite element analyses (FEA) of LSP investigate individual peening of a metal substrate. FEA of single peens neglects the effect of neighboring dents on topography, hardness and residual stress. The topography, hardness and residual stress are critical for the corrosion and fatigue performance of a biomedical implant. The purpose of this study is to determine the effects of sequential peening of Mg–Ca alloy on surface topography as well as predict the residual stress profile. Sequential peening experiments and simulations were performed and compared to single peening experiments and simulations.

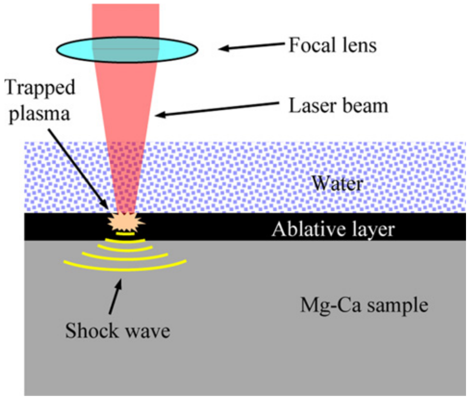

Fig. 1 – Schematic of micro dent fabrication using LSP.

2. Micro dent fabrication

LSP is a mechanical process where pressure waves caused by expanding plasma plastically deform the surface of a material. The plastic deformation from LSP induces deep compressive residual stress well below the surface. The residual stress can penetrate as deep as 1 mm below the surface (Clauer, 1996). As a result, compressive residual stress can inhibit the corrosion rate of a Mg–Ca implant (Abbas et al., 2005; Mondal et al., 2008). Furthermore, the compressive residual stress greatly improves against fatigue crack formation and propagation induced by cyclic loading (Dane et al., 1998; Manna and Cowie, 1996). LSP also produces surface dents which act as a geometric benefit. Surface dents provide a porous structure that is favorable for cell adhesion and growth to an implant surface.

LSP uses a thin layer of ablative material that is opaque to the laser as shown in Fig. 1. The opaque ablative material, typically black spray paint or tape, is a sacrificial layer (Fairand and Clauer, 1976). The sacrificial layer minimizes undesirable thermal effects on the surface caused by the laser. The laser vaporizes the ablative layer to form high pressure plasma (Fan, 2005). The plasma, confined by a thin layer of water film, expands rapidly resulting in a recoiling pressure wave on the order of GPa (Masse and Barreau, 1995; Montross, 1999; Berthe et al., 1997; Fabbro et al., 1990; Fairand et al., 1972). The resulting pressure in confined ablation mode is much larger than the dynamic yield strength. Once the pressure exceeds the dynamic yield stress, plastic deformation occurs and forms a dent. The pressure wave is the mechanical process that plastically deforms the surface.

In the following study, Mg–Ca samples were sectioned 15 mm thick from a 38.1 mm diameter round stock. In order to remove the effects of surface residual stress induced by machining, each sample was turned and later polished to a mirror finish. The Mg–Ca samples were polished using a Lecloth^{TM} pad. In order to prevent and remove any micron