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Mechanical characterization and modeling of graded porous stainless steel specimens for possible bone implant applications

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ABSTRACT

A detailed experimental and numerical investigation was performed on graded porous stainless steel preforms for bone implant applications in order to understand the variation of mechanical properties along the graded direction. A simple powder metallurgy methodology was employed to fabricate preforms whose surfaces were later densified with a specially designed densification tool. Homogeneous preforms without densification were tested under uni-axial compression for their stress–strain response. The stress–strain responses of the preforms having various porosity levels were used in numerical modeling in an attempt to understand the porosity gradient generated during the densification process. Micro-indentation experiments were also conducted to determine the variation of Young's modulus values along the densified layer of preforms. Numerical results indicated that the equivalent plastic strain correlated well with the porosity gradient. In addition, it was found that the diameter of the ball used as a densification tool could significantly influence the porosity gradient of the preform.

1. Introduction

Powder metallurgy (PM) has become an attractive method for production of bone implants because PM techniques allow for the introduction of porosity into the implant structure. Porosity is important for two main reasons. First, it can be controlled to lower the modulus of elasticity of the bulk material to match natural bone. Second, it allows for cell growth and fluid transfer into the implant. The porosity is often homogeneous in the structure, and this presents drawbacks. The yield strength of a homogeneous PM structure is low in comparison to that of natural bone. Furthermore, the surface porosity of the structure creates surface defects that can rapidly wear and develop into fatigue cracks. These cracks are accelerated by the corrosive environment of the body, decreasing the service life of the implant (Amel-Farzad, Peivandi, & Yusof-Sani, 2007; Becker & Bolton, 1997; Teoh, 2000). These problems can be solved by replacing the homogeneously porous structure with one having a porosity gradient. In fact, natural bone has a three-zone structure. First is the cortical bone, which is the dense outer surface of the bone, second is a highly porous cancellous bone at the core, and third is a zone connecting both through a porosity gradient (Adam & Askin, 2009). Bender, El Wakil, and Chalivendra (2011) have previously described a methodology for the production of a PM specimen with a porosity gradient that mimics the structure of natural bone. The current work aims to elaborate on the effects of specific process parameters on the porosity gradient and mechanical properties of graded structures produced according to Bender et al. (2011). The final outcome was the ability to control the morphology of the cross section of the preforms by controlling the process parameters.

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Graded PM structures have been shown to perform nearly as well as wrought materials. Jandeska et al. (2004) investigated the rolling fatigue life of PM structures, whose surface has been subjected to densification, for use as gears. The fatigue life of PM parts with a densified layer of 0.38 and 0.75 mm were comparable to the fatigue life of the wrought steel currently used for gear applications. The study showed that at the lower stress level of 1900 MPa, the PM structure having densified surface, was equivalent or better then the wrought steel. However, the fatigue life of the wrought steel exceeded that of the PM parts densified surfaces at the higher stress of 2500 MPa. Hanejko and Rawlings (2011) also came to the conclusion that surface densification of PM parts could be used to obtain properties very similar to those of wrought steels. Furthermore the pitting resistance of surface PM structures densified surfaces was tested by Bengtsson, Dizdar, and Svensson (2000) by indenting the roller with a Vickers indentation tip and then performing a roll fatigue test. Results show that the pitting resistance of the PM parts with densified surfaces was equivalent to that of wrought steel.

2. Experimental and numerical methods

2.1. Fabrication of the graded steel preforms

Type 302 Stainless steel powder, purchased from Pellets LLC, was used to produce the graded implant structure. The powder was sieved through a 325 sieve. Loose sintering technique was employed to consolidate the powder into porous preforms. The sintered PM specimens had a homogenous porosity; therefore, a secondary operation was necessary to produce parts with graded porosity. This was achieved using a custom tool as reported previously (Bender et al., 2011). It consisted of a hardened alloy steel ball that protrudes from one end of the tool while the other end was designed to fit in the tool post of a lathe. The ball is used to indent the porous specimen causing the pores of the PM compact to collapse. The surface densification process reduces the porosity at the outer surface while maintaining a porous core. This is a result of the Hertzian contact between the ball of the tool and the porous material causing a non-uniform strain distribution below the surface.

PM samples with an initial density of 70% of the fully dense material were subjected to surface densification to depths of 1, 1.5, and 2.5 mm, in order to observe the effect of the densification depth on the resulting porosity gradient. Next, the initial density was varied from 65% to 72% to characterize the effect of initial density on the porosity gradient. Image analysis using MATLAB as described by Bender et al. (2011) was performed to develop a relationship between density as a percentage of the full theoretical density and depth below the indented surface on all the samples.

2.2. Mechanical characterization

2.2.1. Micro-indentation

In order to characterize the mechanical properties of the graded structure an in-house built micro-indenter was used. When selecting an indentation tip, it was necessary to ensure that the size of the indentation would be large in comparison to the pore size and, at the same time, small with respect to the scale of the porosity gradient. A diamond Vickers tip was chosen because it is small enough to capture the effects of the porosity gradient, yet large enough to encompass the effect of the porosity as part of the metallic structure. A Vickers indentation tip is a square pyramidal shape with angles of 136°. The Young's modulus of elasticity of the material was determined along the porosity gradient by performing micro indentation and applying the theoretical approach given by Oliver and Pharr (1992). The basic assumptions of their model are: (a) deformation upon unloading is purely elastic, (b) the compliance of the sample and the indenter tip are combined as springs in series, (c) the unloading curve is not linear and follows a power law, and (d) the equations describing the elastic unloading of a flat, semi-infinite half space are the same as those for an indented surface. All above assumptions are applicable to the present study. In addition to above, the specimen thickness is several times higher than the indentation depth, which is around 30 times in the current study. Specific to porous test specimens, the average pore diameter is 10 μm and the indenter tip diameter is 250 μm, hence the micro-indentation is performed on a region of several small pores. Th Oliver and Pharr model (Oliver & Pharr, 1992) used usually for homogenous continuous material and it can be well employed to samples with pores that are very small compared to indenter tip.

The reduced modulus, E_r as given in Eq. (1), can be calculated using parameters taken from the load deflection curve of the indentation:

$$E_r = \frac{1}{2}\left(\frac{\pi}{A_c}\right)^{\frac{1}{2}}\frac{1}{C}, \tag{1}$$

where C is the compliance of the system calculated by

$$C = dh/dP, \tag{2}$$

where h is the indentation depth and P is the indentation load. A_c is the contact area. For a Vickers indentation tip, the contact area can be evaluated by

$$A_c = 24.5(h_c)^2, \tag{3}$$