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Design optimization of cementless hip prosthesis coating through functionally graded material

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ABSTRACT

Many metals and its alloys that have been used in biomedical applications which carry the most applied load from the natural bone to the artificial joint. Consequently, this leads to causing stress shielding and bone osteoporotic. Therefore the optimization of the artificial hip materials is one of the challenging opportunities in prosthetic design. It is found from literature that there are contradictions due to the use of hydroxyapatite (HAP) as a coating material. In this study a finite element analysis and optimization method have been carried out in order to find a new design of the hip stem coating using functionally graded material (FGM). The using of FGM coating leads to diminishing stress shielding at the medial proximal region of the femur. In addition, it reduces the interface shear stress between the coating and bone that affects the long term stability of the hip implant. In this study the gradation of the Young's modulus of the coating material changed through the vertical direction. Then the optimal design is compared with HAP coating and with homogenous uncoated titanium stem. The optimal design, in the case of a coating material which consists of HAP at the upper layer of the coating graded to collagen at the lower layer, is increase the maximum von Mises stress in bone at the medial proximal region of the femur by 65% and 19% compared to homogeneous titanium stem and titanium coated with HAP, respectively. The maximum lateral shear stress is reduced by 23% and 12%. However, the maximum medial shear stress is reduced by 39% and 14% compared to homogeneous titanium stem and titanium coated with HAP, respectively.

1. Introduction

Interfaces are the first contact between the natural human body and the artificial implants. Artificial implants must fulfill structural and mechanical demands. Therefore, the most materials used to satisfy these requirements may be titanium and titanium alloys, which are the best biomaterial used for oral applications due to its lightweight compared with other metallic materials [1]. Recently, the functionalities of titanium and titanium alloys have been getting much attention. Surface treatment or coating is a successful way in the scientific community to develop the implant biocompatibility and bioactivity. Recently, many researchers used a HAP coating on Ti which has shown very good osteoconductivity. HAP has a structure and chemical composition similar to the natural bone [2]. However, using HAP coating on uncemented joint replacement implants showed some controversial, due to its relatively slow rate of osseointegration which limits its applications [3].

The mechanical properties of HAP coatings have been affected after immersion in collagen. The results were investigated by Ou et al. [4] showed that the elastic modulus of the HAP, the disk and the coatings, was 3.6 GPa. However, the composition had an elastic modulus of 7.5 GPa, after immersion in collagen solution. They concluded that the strengthening phenomena of collagen were more clear for homogenous and small grain HAP coatings. Collagen I was used by Hu et al. [5] as an additive to the dilute electrolyte used for deposition of HAP coating. The modified HAP coating has a crystal structure similar to that of the natural bone.

Zhang et al. [6] evaluated the residual stresses and interfacial shear strength of fluoridated HAP coatings on Ti substrates. The results showed that, the residual stress reduced by increasing the fluorine in the HAP coating, and the interfacial shear strength was also increased. With increasing fluorine concentration in HAP coating; adhesion strength increases and the interfacial failure mode between coating and substrate changes from brittle to ductile [7]. Shear strength testing showed that silicon-substituted

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HAP coating exhibited higher shear strength than HAP coating alone on Ti substrates [2].

Three samples of coatings were tested in a simulated body fluid under a corrosion test [8]. The first coating is TiO_2 layer. The second coating consists of two layers; the first layer is TiO_2 and the second layer contains 50% TiO_2 and 50% HAP. The third coating consists of three layers; TiO_2, 50% TiO_2 and 50% HAP, and HAP. It was found that the first coating had the best corrosion resistance followed by the second and the third coatings. However, the second coating had a corrosion resistance with the best ability to bone bonding.

Svehla et al. [9] examined the effect of coating thickness on the shear strength and bone ingrowth in a sheep model. The results showed that 100 μm thick HAP layer has a better fixation and ingrowth and less resorption compared with other coating thicknesses. They did not recommend the using of thicker HAP coating for Ti substrates. The effect of HAP coating thickness on osseointegration for dental implants in dogs was evaluated by Zhang et al. [7]. The results showed that HAP coating has a great effect on early osseointegration. However, the thickness of the coating has no obvious effect on osseointegration.

It is found from literature that few researches have been found on developing a functionally graded coating on Ti substrates. The application of the functionally graded coating on the artificial human joints has not been studied well. However, the effect of coating thickness is not obvious and clear through many dental and bone implants researches. Therefore, the aim of this work is to find an optimal FGM coating for cementless hip joint implant with a suitable coating thickness. The objective of this optimization study is to reduce the stress shielding occurred in the femur bone after Ti stem implantation and diminishes the shear stress at the coating/bone interfaces.

2. Properties of FGM femoral stem implant coating

This study considers the coating of the cementless hip stem as a FGM. The material properties of the coating graded in the vertical direction from E_1 at the lower layer of the coating, to E_2 at the upper layer of the coating as shown in Fig. 1. The volume fractions of the FGM coating composites calculated according to the following relations [10,11]:

$$V_2 = (y/h)^m \quad (1)$$

$$V_1 = 1 - V_2 \quad (2)$$

where y is the vertical position of the stem coating, h is the total coating height, and m is a composition variation of the FGM coating. When $m < 1$, the FGM coating is rich in the material at the upper layer of the coating. However, when $m > 1$ this means that the FGM coating will be rich in the material at the lower layer of the coating. Note that $0 < m \leqslant 10$.

The equivalent elastic modulus at different regions of the coating calculated from the following equation [10,12]:

$$E = \frac{E_0(1-p)}{1 + p(5+8\upsilon)(37-8\upsilon)/\{8(1+\upsilon)(23+8\upsilon)\}} \quad (3)$$

where

$$E_0 = E_2\left[\frac{E_2 + (E_1 - E_2)V_1^{2/3}}{E_2 + (E_1 - E_2)(V_1^{2/3} - V_1)}\right] \quad (4)$$

$$v = v_1 V_1 + v_2 V_2 \quad (5)$$

where v_1 and v_2 are the Poisson's ratio of the two-phase FGM, respectively.

p is the porosity of the FGM coating calculated from the following equations:

$$p = A(y/h)^n[1 - (y/h)^z] \quad (6)$$

where A represents the porosity in the mixture calculated using the following equation:

$$\frac{((n+z)/n)^n}{1 - (n/(n+z))^z} \geq A \geq 0 \quad (7)$$

where m, n, z are arbitrary constants.

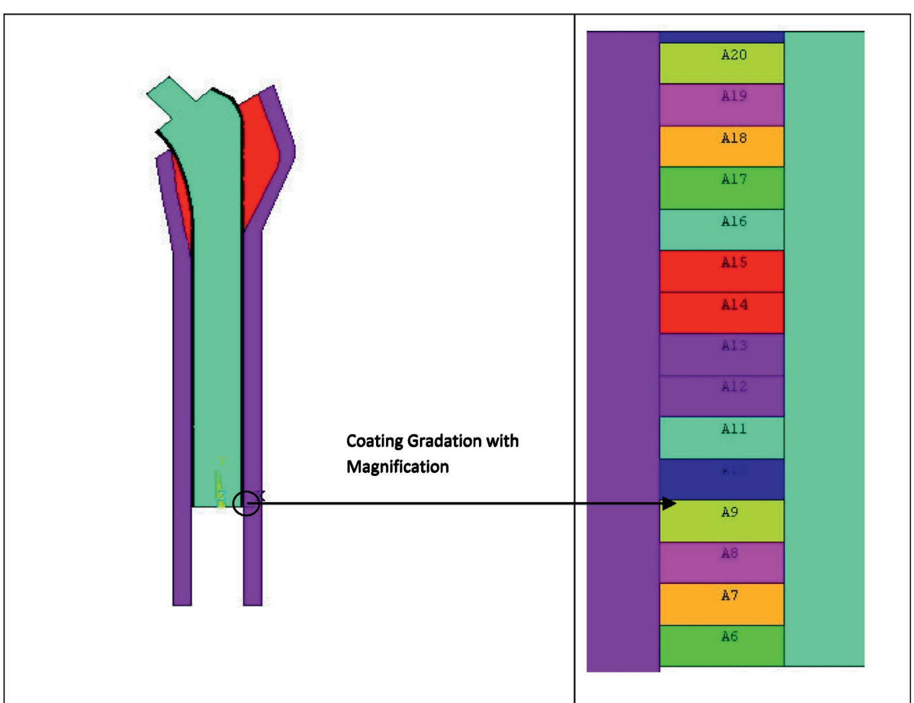

Fig. 1. Homogenous stem with FGM coating in vertical direction.