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An investigation into the flexural characteristics of functionally graded cobalt chrome femoral stems manufactured using selective laser melting

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ABSTRACT

In order to reduce the stress shielding of the femur following Total Hip Arthroplasty (THA), stiffness matching strategies between the host bone and femoral stem still need to be investigated. Additive Layer Manufacturing (ALM) technologies such as Selective Laser Melting (SLM) can produce components from a single alloy with varying mechanical properties, and hence, functionally graded parts. This work considers the flexural characteristics of laser melted cobalt chrome femoral stems, by using a combination of mechanical testing and finite element analysis. A functionally graded design methodology was considered in order to reduce the weight and stiffness of the femoral stems. Three separate functionally graded designs were investigated by incorporating square pore cellular structures of varying density. The results confirmed that selective laser melting can repeatedly manufacture a functionally graded femoral stem that is 48% lighter and 60% more flexible than a traditional fully dense stem. However, there are concerns associated with the repeatability of the manufacturing process for producing stems with cellular structures that incorporate strut sizes, which are equal to or less than 0.5 mm.

1. Introduction

Femoral stems are orthopaedic implants that are inserted into the medullar of the femur during Total Hip Arthroplasty (THA). Historically, femoral stems have been manufactured from biocompatible alloys such as Ti–6Al–4V and cobalt chromium molybdenum (CoCrMo), by using traditional manufacturing methods such as casting, forging and machining. However, these manufacturing processes produce implants with a constant elastic modulus and are much stiffer than the bone that they are replacing. Consequently, this mismatch in stiffness can reduce the load that is transferred to periprosthetic bone and promote a phenomenon known as stress shielding. This phenomenon can promote the loosening of femoral stems through a reduction in periprosthetic bone density [1], and can therefore have a detrimental effect on the longevity of the prosthesis. It is thought that in order to reduce stress shielding, stiffness matching strategies between the stem and the bone need to be investigated [2].

The application of alternative materials for femoral stems has been considered. A novel femoral stem with a cobalt chrome core surrounded by a flexible composite layer was analysed physically and numerically, with prototypes being manufactured [3]. It was concluded that a stiffness configuration with this construction could reduce stress shielding without compromising the stability of the prosthesis. More recently, a carbon fibre and polyetheretherketone composite femoral stem that could be manufactured using injection moulding was proposed [4]. Again this configuration was found to reduce stress shielding. However, the bone-implant interface stability would be compromised. These studies infer that composite femoral stems offer more flexibility when compared to their bulk metallic counterparts. However, the use of titanium and cobalt chrome alloys for femoral stems is still considered to be the gold standard for THA, due to their reliability and relative ease of manufacture when compared to their composite counterparts.

Additive Layer Manufacturing (ALM) processes such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM) fabricate parts on a layer-by-layer basis, by using a laser or electron beam to selectively melt and fuse together metallic powder until the required geometry has been formed. ALM technologies have introduced a capability to produce lightweight components with optimised mechanical properties and functionality [5]. This offers the potential to manufacture functionally graded components from a single alloy where the mechanical properties of components are altered by introducing porosity into designs. Porous cellular

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structures that are based upon the unit cell approach have been conceptually utilised to reduce the stiffness and weight of orthopaedic implants [6].

Research investigating the mechanical behaviour of cellular structures manufactured using ALM techniques is ever growing. It is evident from the review that the literature has been more biased towards investigating the effective mechanical properties and failure modes of titanium alloy open cellular structures. Uniaxial compression and three point bend tests have been used to investigate the properties of open cellular structures with hexagonal pores, where it was evident that the build angle and the orientation of the part have an effect on the mechanical properties [7]. Similar methods have been used to determine the mechanical behaviour of rhombic dodecahedron open cellular structures [8]. These structures were then incorporated into the design of a femoral stem, where a reduction in stiffness to the order of two was observed when compared to a traditional fully dense titanium alloy stem. The behaviour of square pore cellular structures manufactured using EBM have also been investigated whilst subjected to uniaxial compression and shear [9]. Here the strength was heavily dependent upon the strut size, and it was suggested that there was no obvious weakness in the connecting layers of the structures when they were subjected to shearing forces. Li et al. [10] when performing compression fatigue testing on titanium alloy cellular structures observed that the fatigue strength increased with an increasing relative density, and that cyclic ratcheting of the struts within the cellular structure was the dominant failure mechanism. Brenne et al. [11] found that the fatigue strength and energy absorption of titanium alloy structures manufactured using SLM was improved when the components were heat-treated, and areas of high strain local to the applied load were also observed within the struts. The authors subsequently suggested that these areas could be reinforced to create an equal load distribution within the structure.

In THA, femoral stems are either monoblock (single piece), manufactured from a cobalt chrome alloy or modular in design. Modular stems often consist of a titanium alloy stem that is mechanically connected to a CoCrMo femoral head using what is referred to as a taper junction. Modular stems offer the surgeon flexibility and the patient some degree of customisation. As the elastic modulus of Ti–6Al–4V is approximately half that of CoCrMo, it is used preferentially for reducing stress shielding in the host bone. However, metal on metal wear debris can be released from the taper junction in modular designs. This wear debris has been linked to adverse soft tissue reactions in the human body and is especially prevalent with large diameter metal on metal hip replacements [12]. Therefore, it would be beneficial if alternative designs of monoblock CoCrMo femoral stems were considered.

Rivera et al. [13] investigated the mechanical properties of an open cellular CoCrMo structure with a pore size of 0.5 mm, which would facilitate bone in growth into an acetabular cup. A cellular structure was proposed which had similar mechanical properties to commercially available products that are manufactured using alternative alloys. In addition to this, recent work has considered square pore CoCrMo cellular structures manufactured using SLM, offering compressive properties similar to human bone [14]. Three of the structures investigated have been utilised in this work to design and manufacture functionally graded CoCrMo femoral stems. It is hypothesised that this design and manufacturing approach will provide lightweight femoral stems that exhibit improved stiffness characteristics when compared to traditional CoCrMo prostheses. It is proposed that functionally graded femoral stems manufactured using SLM could have the potential to improve the load transfer to periprosthetic bone and improve the longevity of femoral stems.

2. Methods

2.1. Femoral stem design and manufacture

A femoral stem was designed to suit the anatomy of the proximal left femur of the male cadaver from the Visible Human Project [15]. The stem geometry was designed to incorporate features that are included in current proven designs [16]. A curved geometry was used in the proximal-medial portion of the stem, in order to achieve cortical fixation in the high diaphysis region local to the lesser trochanter of the femur. In this instance, the flexural behaviour of the stem portion of the prosthesis was of interest. Therefore, for economic purposes, the femoral neck and head region of the stem were removed from the design and manufacture of the test samples.

Four different stiffness configurations for a femoral stem were investigated. Three designs were based upon a functionally graded approach (PC1, PC2 and PC3), where the stems had a 1 mm thick fully dense CoCrMo outer skin that encased a porous core comprised of a square pore cellular structure. A fully dense CoCrMo stem (FDS) was manufactured to act as a benchmark for comparison.

Using Solidworks 2012, the fully dense stem was modelled as a single body whereas the functionally graded stems were modelled as two continuum bodies. In this instance, the two separate bodies were created to represent the outer skin and core of the stem. The unit cells that were representative of the cellular structures were also designed within the software. The CAD files were converted into an STL file format and imported into Materialise Magics 17.0 software. The structures module within Magics 17.0 was used to generate the internal cellular structure for each of the functionally graded stems, by duplicating the appropriate unit cell geometry. The two bodies were then booleaned together to form one part. The slice files for each component that contained the two dimensional geometry of each layer were generated for manufacture. Ten stems were manufactured, one fully dense stem and three samples for each of the functionally graded configurations. Typical solid models for the femoral stems are shown in Fig. 1 and the properties of the cellular structures for each stem are summarised in Table 1 [14].

The stems were manufactured from a medical grade CoCrMo alloy powder (EOS Cobalt Chrome MP1) on a EOSINT M270 Xtended Direct Metal Laser Melting machine. The powder was sieved to a particle size no greater than 63 μm and the stems were produced

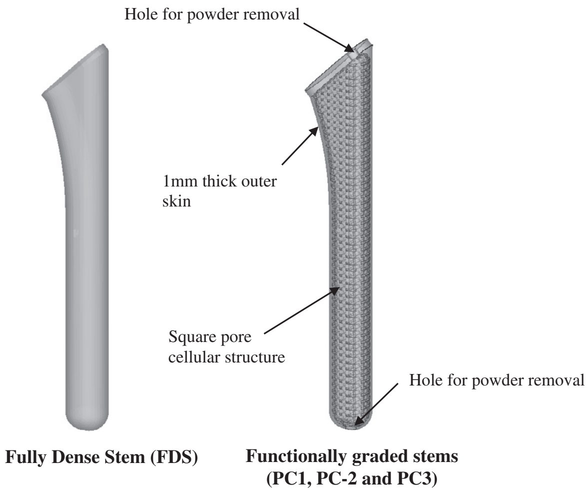

Fig. 1. CAD models of a fully dense and functionally graded stem.