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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.

Keywords: Femoral stem; laser melting; functionally graded; orthopaedic implants.

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 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 ingrowth 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 in 20 μm layers using a laser with a 100 μm spot size. A laser power of 200 W was employed, with a laser step over distance of 0.08 mm and a laser scan speed of 800 mm/s. The material processing was performed in a nitrogen-based atmosphere with less than 0.1% oxygen present in the build chamber. Upon completion of the build, the excess powder located within the components was removed. The stems were stress relieved in an argon atmosphere

at a temperature of 1050°C for two hours and were left to cool in the furnace. The components were removed from the build plate using an ONA PRIMA S 250 Electro Discharge Machining (EDM) facility. Each stem was weighed on calibrated digital scales that offered an accuracy of ± 0.1 g. Comparisons were noted between the functionally graded and fully dense stems.

2.2 Mechanical testing

Cantilever bend tests were performed using a Zwick Roell 1474 materials testing machine having a maximum load capacity of 100 kN. The physical tests were performed to investigate the flexural properties of each stiffness configuration. BS EN ISO 7438:2005 [17] was referred to design a bespoke test set up that was manufactured in order to eliminate any deformation that could occur within the fixture when loaded, as shown in Fig. 2. The most distal 20 mm of the femoral stem was clamped and fully constrained in the test fixture and the load was consistently applied at a distance of 140 mm from the distal tip of the stem. The components were loaded to failure by using a crosshead displacement speed of 2 mm/min. The real time force versus displacement data was recorded from the test machine in order to calculate the stiffness for each stem. Three samples for each of the functionally graded femoral stems were tested and the results from one fully dense stem were used as a benchmark for comparison.

2.3 Finite element modelling

Three-dimensional finite element models were created in ANSYS 13.0, by importing the femoral stem geometries that were produced in Solidworks. The models were meshed using

four node tetrahedral elements and mesh sensitivity was studied until further mesh refinement changed the maximum von Mises stress in the stem by 5% or less. The boundary conditions were applied in order to replicate the physical test conditions as shown in Fig. 3. The most distal 20 mm of the stem was fully constrained and the vertical load was applied through a nodal displacement at a distance of 140 mm from the distal tip of the stem. The cellular structures were modelled as single continuum bodies, which were assigned material properties with respect to the structure being modelled in each instance. The fully dense CoCrMo alloy and cellular structures were both modelled with nonlinear material properties by using a bilinear isotropic hardening stress-strain relationship. The material properties for the fully dense CoCrMo and cellular structures were defined from [18] and [14] respectively and are summarised in Table 2. A Poissons ratio of 0.3 was assumed throughout for all materials. The stiffness values for each femoral stem design were calculated from the force displacement relationships that were computed by the finite element software.

2.4 Microstructural characterisation

Horizontal (parallel to the build plate) and transverse samples (vertical to the build plate) were cut away from a femoral stem by using EDM, for metallographic analysis. The samples were mounted in resin, ground and polished to a mirror condition. Oxalic acid was used to reveal the materials microstructure. An Olympus LEXT (OLS 3000) optical laser scanning confocal microscope was used to characterise the materials microstructure and analyse porosity in its as built, stress relieved condition.

3. Results

3.1 Femoral stem manufacture

The components in their as built condition can be observed in Fig. 4. Upon completion of the build, the components were inspected and there were no visible cracks or defects present on the outer surfaces of the stems. As expected with SLM a somewhat rough surface finish was created due to the stair step effect that occurs when manufacturing curved geometries. Each individual stem was weighed and the values are shown in Table 3. The functionally graded stems provided a 39% to 58% reduction in weight when compared to the fully dense stem.

3.2 Mechanical testing

The mean stiffness values for each design were calculated from the real time force versus displacement data and are summarised in Table 3. Additionally, the typical force-displacement curve for each stiffness configuration can be compared from Fig. 5. From the results, a reduction in stiffness of between 54.7% and 64.4% was achieved when the functionally graded approach was considered. Fig. 6 compares the force-displacement relationship for each of the functionally graded stiffness configurations, where it is evident that the PC1 and especially the PC2 designs have similar trends and repeatability in terms of the mechanical behaviour. However, in contrast to this, the PC3 design did not show reasonable repeatability and tended to fail with more unpredictable mechanisms. For instance, the sample PC3-2 fractured approximately half way down the length of the stem, whereas all of the PC1 and PC2 test samples fractured at the expected point of cantilever support. In addition to this, the sample PC3-3 fractured at a force that was 52% lower than the average force of the other two samples.

3.3 Finite element modelling

Stiffness values for each femoral stem were calculated from the force-displacement curves that were generated from the finite element software, and have been summarised for comparison in Table 4. The numerical analysis overestimated the stiffness of the functionally graded stems by between 9.4% and 27.3% dependent upon the stiffness configuration. Fig. 6 compares the numerically derived force-displacement relationship with the physical test for each functionally graded stem. It is considered that a reasonable agreement can be observed between the two methodologies, perhaps with the exception of the PC3 design.

3.4 Microstructural characterisation

From Fig. 7a, it can be observed that the acid etching revealed a microstructure with a morphology that is typical of laser melted CoCrMo [19]. Isolated pores were observed in both the horizontal and transverse samples. The maximum pore size in both orientations was similar, with an average pore size of between 30 μm and 50 μm being observed throughout.

4. Discussion

This work has investigated the flexural behaviour of laser melted CoCrMo femoral stems using an alternative functionally graded design methodology. From reviewing the literature, this is the first study to investigate the stiffness characteristics of such stems when subjected to cantilever bending. It was hypothesised that the design and manufacturing approach employed in this work could provide lightweight femoral stems that exhibit improved stiffness characteristics when compared to a fully dense stem.

The results from this work have confirmed the hypothesis in that laser melted functionally graded femoral stems are lighter and less stiff when compared to a traditional fully dense CoCrMo prosthesis. However, from the mechanical testing it can be interpreted that the PC3 design would not be reliable in this instance. This provides an indication that SLM potentially has repeatability issues with manufacturing femoral stems incorporating a cellular structure with a strut size of 0.5 mm. It has previously been observed that the strength of square pore cellular structures are dependant upon the strut size [9, 14]. From observing the physical test data of the PC3 design it can be assumed that internal structural defects were inherent with the manufacturing process. Therefore, it is considered that techniques such as micro-computed tomography would be useful for the inspection of such functionally graded implants.

Based upon the results from this work, the PC2 design would be the recommended stiffness configuration. This design showed the greatest agreement and repeatability when comparing the force-displacement curves. Thus, indicating that this stem is the most reliable design in relation to manufacturability and mechanical behaviour. The yield strengths of the fully dense CoCrMo and the cellular structure with a 1 mm strut size are in the region of 600 MPa [18] and 175 MPa [14] respectively. Considering this and interpreting the physical test data, the structural integrity of the PC2 stem would not be compromised if it were subjected to static loads that were representative of *in vivo* loading conditions. However, it should be noted that this recommendation is based upon a sample size of three specimens only. The sample size restriction was due to the limited build envelope size on the EOSINT M270 Xtended Direct Metal Laser Melting machine.

A cantilever bend test set up was used in this work to compare the flexural behaviour of the different femoral stem designs. This methodology was employed to investigate the stiffness of the stems when loaded in what corresponds to the frontal plane of the human anatomy. Stress shielding of the proximal- medial femur can occur following THA [20]. Therefore, investigating the stiffness of the prostheses in what corresponds to the frontal plane of the anatomy provides a suitable indicator of the stems ability to reduce stress shielding in this area.

The femoral stem geometry utilised in this work was designed to suit the anatomy of a proximal femur [15]. It is considered that alternative stem geometries could provide different stiffness values to what have been presented in this work. However, it is thought that similar stiffness reduction ratios would be observed when comparing functionally graded and fully dense stems that offered different geometries.

This work presents an original study that has investigated the structural stiffness of laser melted, functionally graded CoCrMo femoral stems when subjected to monotonic loading conditions. However, it is recommended that any future testing should be more replicative of *in vivo* loading conditions, and should consider the effect of cyclic loading. This would determine the fatigue life of such femoral stems, which is an important factor that governs the clinical use of orthopaedic implants. Previous studies have investigated the fatigue behaviour of titanium alloy open cellular structures [10, 11]. However, there does not appear to be any published literature that has physically investigated the fatigue characteristics of the stiffness configurations that are used in this work.

The finite element models of the functionally graded stems were simplified by modelling the volume representing the cellular structure as a continuum part, with a single value being assigned for the elastic modulus. Previous, published studies that have modelled cellular structures with their designed geometry have highlighted that the stiffness can be overestimated by up to a factor of four when compared to physical test data [8, 9, 14]. It is considered that a reasonable agreement was achieved between the physical testing and numerical analysis in this work with the exception of the PC3 design. If the stiffness value for the sample PC3-3 was removed from the data set then a closer comparison would have been achieved between the physical test and numerical analysis. Therefore, the results show that the flexural behaviour of the functionally graded stems used in this work can be modelled with reasonable accuracy, without having to model the geometry of the cellular structures explicitly. This methodology can contribute towards reducing the size of finite element models and hence computational expense.

This work has investigated the flexural behaviour of laser melted CoCrMo femoral stems by using an alternative functionally graded design methodology. From the results, the PC2 femoral stem has been proposed as the optimal stiffness configuration. It is thought that this functionally graded stem could potentially be utilised for either cemented or cementless THA. For cemented fixation, the outer stem surface could be polished smooth. Whereas, for cementless fixation, a porous beaded topography could be designed onto the surface of the implant and then be manufactured using SLM, as shown in Fig 8. This work has highlighted the use of SLM to produce more flexible and lightweight CoCrMo femoral stems that could potentially assist in reducing stress shielding and therefore contribute towards improving the longevity of CoCrMo femoral stems.

5. Conclusions

Within the discussed limitations of this study, the main findings of this work can be summarised as follows:

- SLM is capable of repeatedly manufacturing a functionally graded CoCrMo femoral stem that is 48% lighter and 60% more flexible than a traditional fully dense stem.
- SLM could not repeatedly manufacture femoral stems that incorporated a cellular structure with a strut size of 0.5 mm. Technologies such as micro computed tomography scanning would be needed to investigate the reasons associated with this failure.
- Cellular structures were modelled as continuum parts with a physically determined compressive elastic modulus in the finite element models. Good correlation was achieved between the numerical analysis and physical test data. Indicating that this simplified approach is suitable for modelling the behaviour of femoral stems when subjected to bending.

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

**Functionally graded stems
(PC1, PC-2 and PC3)**

Fig. 2. Cantilever bending test set up.

Fig. 3. The finite element model and applied boundary conditions.

Fig. 4. Components on the build plate in their as built, none stress relieved condition.

Fig. 5. Typical force-displacement relationship for each femoral stem design.

Fig. 6. Force-displacement relationships for each of the functionally graded specimens.

(a) PC1 design (b) PC2 design (c) PC3 design.

(a)

(b)

(c)

Fig. 7. Micrographs of the CoCrMo femoral stem samples. (a) Sample with transverse orientation (b) Sample with horizontal orientation.

Fig. 8. CAD model showing the cemented and cementless design concept.

Table 1. Characteristics and mechanical properties of the cellular structures utilised in the functionally graded designs.

Femoral stem	Strut size (mm)	Pore size (mm)	Effective elastic modulus (GPa)	Effective compressive yield strength (MPa)
PC1	1.50	1.88	17.98	295.72
PC2	1.00	1.80	13.64	175.15
PC3	0.50	1.57	4.79	65.43

Table 2. Material properties assumed for the bilinear stress strain relationship used in the finite element modelling.

Material	Elastic modulus (GPa)	Yield strength (MPa)	Tangent modulus (GPa)
Fully dense CoCrMo	200.00	600.00	29.41
PC1 cellular structure	17.98	295.72	4.10
PC2 cellular structure	13.64	175.15	1.66
PC3 cellular structure	4.79	65.43	0.05

Table 3. The individual and mean values for stem weight and stiffness derived from the cantilever bend testing.

Femoral stem	Weight (g)	Mean weight (g)	Stiffness (N/mm)	Mean stiffness (N/mm)
FDS	230.00	230.00	869.94	869.94
PC1-1	141.00		397.18	
PC1-2	140.00	140.30	365.28	394.45
PC1-3	140.00		420.89	
PC2-1	119.00		348.75	
PC2-2	118.00	119.00	367.94	351.37
PC2-3	120.00		337.43	
PC3-1	98.00		313.72	
PC3-2	96.00	96.60	365.28	309.32
PC3-3	96.00		248.95	

Table 4. Comparison of the stiffness values obtained using numerical analysis and physical testing.

Femoral stem	Mean stiffness from physical test (N/mm)	Stiffness from numerical analysis (N/mm)	% Difference
FDS	869.94	911.14	4.7
PC1	394.45	431.43	9.4
PC2	351.57	419.25	19.2
PC3	309.32	394.27	27.3