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Finite Element Analysis in Additive Manufactured Customised Bone Scaffold

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Abstract

Bio Additive Manufacturing (BAM), an interdisciplinary field of Additive Manufacturing (AM) and Tissue Engineering (TE), aims to manufacture the customised bone scaffold for bone replacement. One of the current challenges in bone tissue engineering is to create customised scaffolds with suitable mechanical properties, high porosity, full interconnectivity and suitable pore size. In this paper, the patient's CT scan data in DICOM format is exported into MIMICS software to convert the 2D images into 3D IGES data. The customised bone scaffolds with pore size of 0.8mm and inter pore distance ranging from 0.6 mm to 1 mm are developed in modeling software and porosities of customised bone scaffolds are determined. The customised bone porous scaffold and ASTM standard compressive specimens were fabricated through AM technique. Finite element analysis (FEA) was carried out to study the mechanical properties o

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Introduction

Additive Manufacturing processes produce end-use components from CAD models by additive material layer by layer, and the final components are often produced in a single step without the requirement for any additional processing. [1].Earlier Additive Manufacturing techniques were used for "Rapid Prototyping" in the domain of product design and development for concept modelling, pattern building, assembly verification and functional testing. In the recent times, Additive Manufacturing techniques are being used for the production of actual end-use products for various sectors. One of the interesting sector with significant potential impact is the medical field, where implants, scaffolds and prosthesis are being manufactured using Additive Manufacturing Technique[2]. Traditional methods of scaffold fabrication include fiber bonding, solvent casting and particulate leaching [3], membrane lamination, gas foaming, cryogenic induced phase separation [4,5] and so on. However, all of these techniques are mainly based on manual work and lack of corresponding designing process, so extra procedure was needed to obtain suitable shape and the microstructure. These traditional techniques also have many disadvantages such as long fabrication periods, poor repeatability and insufficient connectivity of

pores[6]. To overcome the limitations of these conventional techniques, automated computer controlled fabrication techniques, such as Additive Manufacturing (AM), are being explored.

Many of the researchers [7,8] present the patient specific implant fabrication and its property evaluation. This paper presents the fabrication of the customised bone porous scaffold and its compressive property evaluation using FEM.
In this paper, Patient data derived from CT (Computerised Tomography) scan was used in Materialise MIMICS (Materialise Interactive Medical Image Control System) software to convert two dimensional data in DICOM (Digital Imaging and Communications in Medicine) format into three dimensional data in IGES (Interactive Graphic Exchange Specification) format. The customised bone porous scaffold with pore size of 0.8 mm diameter and inter pore distance ranging from 0.6 mm to 1 mm in steps of 0.1 mm were created using Dassault Systems SOLIDWORKS 2011 modeling soft-

ware. The customised bone porous scaffold and ASTM standard compressive specimens were fabricated through SLS technique. Finite element analysis (FEA) was carried out to study the mechanical properties of the polyamide scaffolds.

Materials and Methods

Modeling of customised bone porous structures

The patient's DICOM images from Computed Tomography (CT) scan are used in Materialise Interactive Medical Image Control System (MIMICS) software to get three dimensional details of the bone. The med CAD module in MIMICS is used to export the 3D model data from the imaging system to the CAD system in IGES file format. This IGES format is imported into Dassault Systems SOLIDWORKS 2011 software to generate the solid model. The total length of the tibia bone was 376 mm. Fig.1 shows the region selected for study and considered as defective bone.

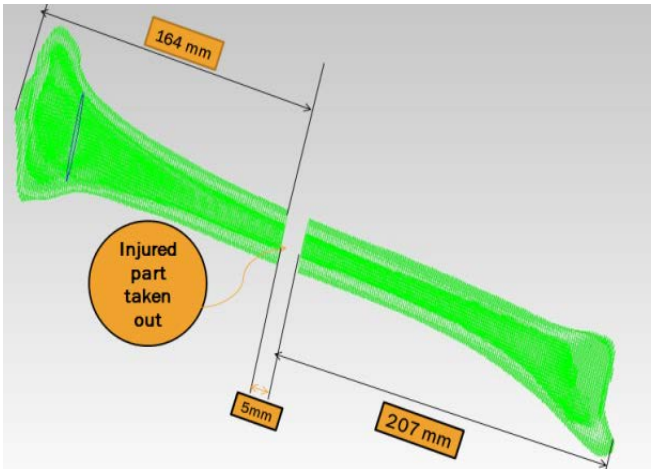

Figure 1*.Region considered as defective bone*

This region has been taken at a distance of 164 mm from the knee. The height of this region was taken as 5 mm and modeled as 4 layers each of 1.25 mm thickness. In the present work, five customised bone porous scaffolds with pore size of 0.8 mm diameter [9] and inter pore distance ranging from 0.6 mm to 1 mm in steps of 0.1 mm were created using Dassault Systems SOLIDWORKS 2011 software. Table 1 presents the 3D CAD model developed for the five customised bone scaffolds.

Fabrication

SLS is a laser-based solid free form technique in which an object is built layer–by-layer using powdered materials, radiant heaters, and a computer controlled laser [10].The CAD data for the customised bone porous scaffolds were exported from Dassault Systems SOLIDWORKS software in .stl (stereolithography) file format and processed via the SLS application software. During the SLS process, a powder bed is formed in the build chamber and a laser scans across the powder bed in a series of lines parallel to the x-axis , moving slightly in the y direction after each line. As it scans, the laser liquefies and fuses powder material in a selected region of the part chamber determined by a cross –section in a 3D CAD model of the part being produced. After each cross-section is finished, a layer of powder is spread over the newly sintered layer, and the sintering process begins again. In this way, the part is built up layer by layer. After SLS processing was completed, the scaffolds were allowed to cool inside the machine process chamber and were then removed from the part bed. After the scaffolds were fabricated, loose powder was removed from the pores via sandblasting. The five customized. bone porous scaffolds were fabricated using 3Dfast Srl on a Formiga P100 system (EOS GmbH) in polyamide EOSINT P/PA2200.

Compression Test

The compressive cubic test specimens conforming to the ASTM D695: ISO 604. The five compressive cubic test specimens with size 25.4 mm x 25.4 mm x 25.4 mm were fabricated using 3Dfast Srl on a Formiga P100 system (EOS GmbH) in polyamide EOSINT P/PA2200 as shown in Fig. 2.

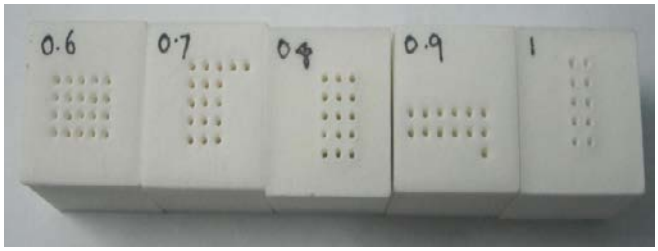

Figure. 2 SLS processed Polyamide compressive specimens with inter pore distance 0.6, 0.7, 0.8, 0.9,1 mm respectively.

Compressive specimens were mechanically tested using a TINNUS OLESAN Universal Testing Machine. The specimen was placed between compressive steel plates parallel to the surface. The specimen was then compressed to 50 % strain between the two steel plates at a rate of 1 mm/min

FE model and load conditions

The compressive specimen was made of Polyamide PA2200 material, simulated as a linear, elastic and isotropic material. For compressive analysis, all the nodes at the bottom surface were arrested, and compressive load of 2000 N was applied at the top surface as the pressure load in the Z - direction. Finite element analysis was carried out on five compressive specimens in ANSYS 13 software.

Results and Discussion

Customised bone porous scaffold fabrication

The customised bone porous scaffolds made of polyamide PA2200 with pore size of 0.8 mm diameter and inter pore distance ranging from 0.6 mm to 1 mm in steps of 0.1 mm were fabricated by using Selective Laser Sintering Technique. All the fabricated customised bone porous scaffolds possessed well defined pores (illustrated in Fig. 3.a.) and its structural configuration was also observed to be consistent with the CAD data. (illustrated in Fig.3.b.)

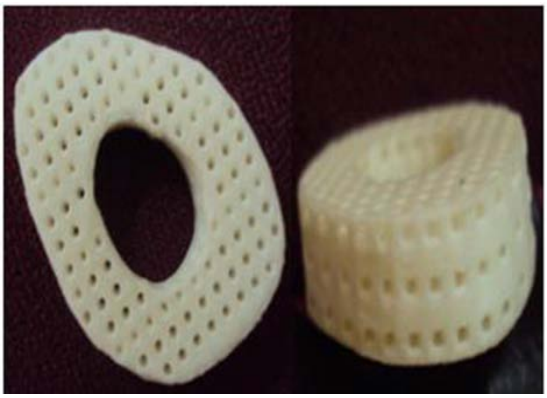

Figure 3a.. *Fabricated scaffold (Pore size 0.8 mm, inter pore distance 1 mm)*

Determination of porosity

The conventional technique used to measure the porosity is mercury intrusion porosimetry, which is better suited for characterising the average channel size between particulates, rather than the pore size distribution and interconnectivity in high volume fraction void open-cell foams [11]. In the present work, the pore size distribution in the porous structure could be easily controlled and measured as the customised bone porous structures was modeled using computer aided solid modeling package.

Figure 3b. *Scaffold CAD model*

The porosity was calculated using the formula given in Equation 1

$$\emptyset = (1 - \frac{V_1}{V_2}) \times 100 \quad (1)$$

Where

V_1 = Volume of porous scaffold with pores mm^3.

V_2 = Volume of porous scaffold without pores mm^3.

Φ = Porosity in %

Table 1. *3D CAD model of customised bone scaffold*

Pore size (mm)	0.6	0.7	0.8	0.9	1
0.8					

Using the equation 1, the theoretical porosities were determined based upon the volumes computed from the solid model package and provided in Table 2. The porosity was also determined experimentally by determining the mass of the fabricated customised polyamide scaffold with pores and the customised polyamide scaffold without pores. Knowing the density of polyamide, the volumes of customised polyamide scaffold with pores (V_1) and the volumes of customised polyamide scaffold without pores (V_2) were determined. Using the equation 1, the experimental porosities were determined for the five customised bone porous structures under study. The relationship between experimental and theo-

retical porosity is shown in Figure3.

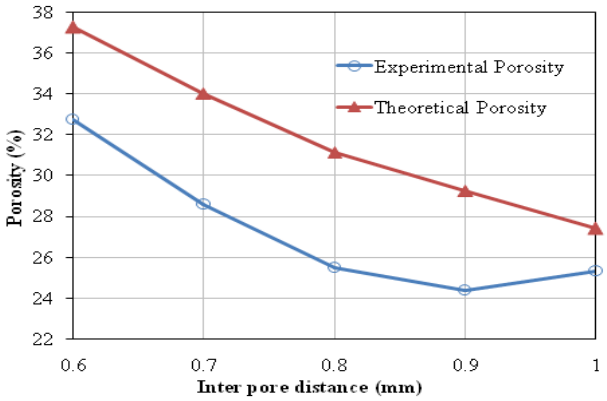

Figure. 3. *Relationship between Experimental Porosity and Theoretical Porosity*

The level of porosity, pore size distribution, pore morphology and the degree of pore interconnectivity in bone grafts significantly influence the extent of bone ingrowth [12]. The average experimental porosity of the customised bone porous structures is 27.3 % against the theoretical porosity of 31.8 %, showing the reduction of 14 % compared to theoretical porosity. This can be attributed to the limitations of the Additive Manufacturing Process employed where clogging of pores leads in increase in volume of customised bone porous structures and decrease in experimental porosity.

Mechanical Properties of Polyamide samples

In tissue engineering applications, porous implants must have sufficient mechanical strength to retain their initial structures after implantation, particularly in the reconstruction of hard, load – bearing tissues, such as bones and cartilages. The bio stability of many implants depends on factors such as strength, elasticity, absorption at the material interface and chemical degradation. Therefore, the investigation of compressive properties is of primary importance in determining the suitability of the designed porous scaffold.

In this study, the response of ASTM standard cubic test specimens under compression loading was determined. The stress – strain relations obtained from the compressive cubic test specimens are shown in Fig. 4.

Three definite regions could be observed from the stress strain curve for all the five samples namely, a linear elastic region, a region where rate of increase of stress with strain reduces steadily and a region where the stress increases steeply. The deformation of the cubic polyamide sample was elastic and, hence, recoverable, while those in the subsequent two regions were non-recoverable. The compressive stiffness and compressive strength for the polyamide specimens are shown in Table 2.

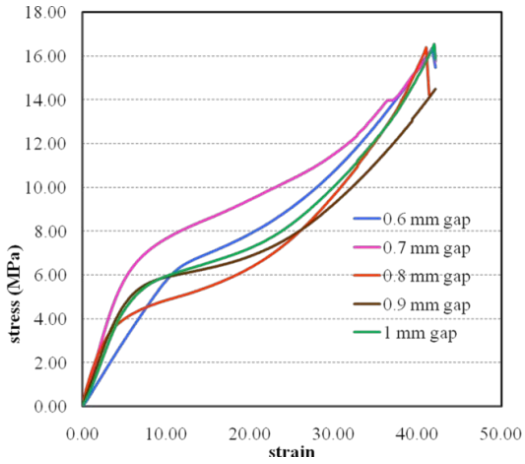

Figure. 4. *Stress strain curve for the compressive cubic test specimens*

Table 2. *Details of Compressive stiffness and compressive strength*

S.No	Inter pore distance(mm)	Compressive Stiffness (MPa)	Compressive Strength (MPa)
1	0.6	58.59	5.76
2	0.7	108	7.25
3	0.8	111	4.63
4	0.9	108	5.91
5	1	92.16	5.66

Finite Element Analysis of Compression Testing Samples

Finite Element Analysis was carried out using ANSYS 13 software, to compare the stress fields developed under uniaxial compression. It was found from the compression testing that the behaviour of the material is linear at 2000 N. In finite element simulation the same compressive load was applied, and the finite element analysis was carried out using ANSYS 13, for the five compression testing samples. The details of the experimental stress and numerical stress are presented in Table 3. Further, it may be noted that the experimental results of polyamide cubic specimens closely matches with the numerical results with a maximum variation of 11 %.

Table 3. *Details of Compressive stress*

S.No	**Inter pore Distance (mm)**	**Experimental Compressive Stress (MPa)**	**Numerical Compressive Stress (MPa)**
1	0.6	3.9	3.6
2	0.7	4.8	4.25
3	0.8	4.01	3.7
4	0.9	4.3	3.8
5	1	3.98	3.6

Conclusion

The customised bone porous scaffolds made of polyamide with pore size of 0.8 mm diameter and inter pore distance ranging from 0.6 mm to 1 mm in steps of 0.1 mm were designed and fabricated using Additive Manufacturing Techniques and differences in porosities were evaluated. The use of this Additive Manufacturing techniques promises new cost-effective and rapid solutions to customized made– to–order bone porous scaffold production. Mechanical properties of porous polyamide samples were determined. Finite element analysis of polyamide specimen was completed and thereby compared the properties with the properties of human bone. Thus SLS process has been able to produce the customised bone porous polyamide scaffold with properties similar to human trabecular bone and maxillofacial cancellous bone.

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