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Additive manufacturing of a novel bone scaffold and its porosity evaluation

Arul Kishore A[1], Rashia Begum S[2], Arumaikkannu G3
[1](Department of Mechanical Engineering, Anna University Chennai, India)
[2](Department of Mechanical Engineering, Anna University Chennai, India)
[3](Department of Manufacturing Engineering, Anna University Chennai, India)

ABSTRACT : *Additive manufacturing (AM) is one the advanced process for building up a component layer by layer, with one layer of material was bonded to the previously laid layer using a 3D design data. In the field of medical science AM is very much useful in the development of Bone Scaffolds. The bone scaffold needs the good level of porosity for the cultivation of cells. In this work, an algorithm for a novel structure was introduced for the scaffolds with the cylindrical shells arranged in a circular pattern which have the theme of flexible porosity. Scaffold models were developed using CATIA V5 for four different porosities. The novel structures made of Poly Amide (PA 2200) material were fabricated using a commercially available Selective Laser Sintering machine (SLS). The differences in scaffold theoretical and experimental porosities were investigated and the percentage of error was discussed.*

Keywords – *Additive manufacturing, bone scaffolds, polyamide, porosity, selective laser sintering*

1. INTRODUCTION

Additive manufacturing (AM) is a process wherein parts are created by the addition of material layer by layer, while traditional manufacturing is a subtractive process staring from a stock material. These processes create near-net-shaped 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. AM typically uses (stereolithography) .stl data of the part to be fabricated as input data. The CAD model of the part is sliced into 2D layers, and each contoured layer’s data is transferred onto the machine. Parts are built through a directed sintering of the powder using a high energy laser power. 2D data, which is a simpler representation of a complex shape designed using CAD can be easily fabricated.

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 and prosthesis are being manufactured using Additive Manufacturing Technique.

In Tissue Engineering, Customized 3D scaffolds are essential to lead cell proliferation and to maintain native phenotypes in regenerating biologic tissues or organs [1].Tissue engineering typically involves the use of three-dimensional customized scaffolds to guide cell attachment, differentiation, proliferation, and subsequent tissue regeneration. The various researches suggest that the choice of scaffold material and its internal porous architecture significantly affect regenerate tissue type, structure, and function [2, 3]. The shape and inner microstructure are the two critical properties of customized scaffold for repairing defective bone.

Traditional methods of scaffold fabrication include fiber bonding, solvent casting and particulate leaching [4], membrane lamination, gas foaming, cryogenic induced phase separation [5, 6] 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 [7]. To overcome the limitations of these conventional techniques, automated computer controlled fabrication techniques, such as Additive Manufacturing, are being explored. From the literature, it was found that the novel structure for artificial bone was developed from a new computer aided technique and fabricated using conventional method [11]. To make use of the advantage of AM technique, we developed CAD model of the bone scaffolds and it was used directly to a SLS machine for the fabrication of bone scaffold.

In this work, one dimensional porous novel structure with six different input parameters was introduced. A special macro program was generated for the creation of CAD model of novel structure by using the input parameters as variables. Four CAD models were developed by using one input parameter as a variable and the other five parameters as constant. The volume of the generated CAD model was determined in the macros and they are processed to find the theoretical porosity. The CAD model of novel structure was used to fabricate the bone scaffold using SLS technique. The experimental porosity of novel bone scaffold was determined and it is compared with the theoretical porosity. The percentage of error between the experimental and theoretical porosities was investigated with the aim of adopting the optimized porous structure for the bone scaffold.

II. DESIGN OF NOVEL STRUCTURE

The novel structure was introduced for the bone scaffolds which would be able to withstand the good level of porosity and good compressive properties. The scaffolds are modelled as one dimensional porous structure to have good strength and also to have good void space for cell culture. The construction of the novel structures are made flexible with the porosity by changing the input parameters of the scaffolds [8, 9].

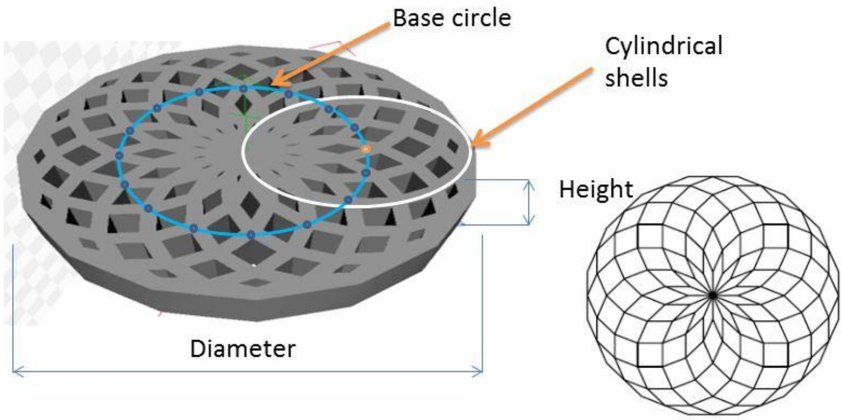


Figure.1 CAD model of the bone scaffold by using CATIA V5 Macros

The geometry was generated with one dimensional porous architecture which has the good mechanical and micro structural properties of bone scaffolds produced by SLS [10]. The CAD model for the novel scaffold is generated by created with cylindrical shells which have been arranged in a circular pattern. The Fig.1 shows the architecture of the bone scaffolds model with cylindrical shells.

2.1 Novelty in the model

1. The architecture of this novel model can be used for the development of bone scaffolds with the different characteristics of needs.
2. Also the modelling concepts of the novel structure can be used widely for different applications like automobile wheels, filters, architectures, dies, etc., apart from the bone scaffolds.
3. The creation of the novel model was automated by developing macros program. The user can define the input parameters for the development of novel model.

2.2 Algorithm

The scaffold model was generated by arranging the cylindrical shells on the circumference of a base circle. The center of each cylindrical shells was located on the equally divided circumferential points which was divided equally

Input:
The radius of the model – R
Number of circles – n
Thickness for the circles – T
Height of the model – H

1. Get the value of R
2. Locate the center of the base circle as origin
3. Start the loop (N*= 1 to n)
4. Assign circumferential points (X, Y)
   X = R x cos (N* x360/n)
. Y = R x sin (N* x360/n)
5. Draw two circles with radius R and (R-T) in the circumferential points
6. Extrude the two concentric circles with the height H
7. End the loop

2.3 Automation and Icon creation

The CAD models were created by using the VB script written for the scaffold model [11, 12]. The algorithm was used in the VB script and new macros program was generated. After forming the script a special icon is created as shown in Fig.2. in the CATIA V5 window for the CAD model generation. This helps to execute the VB Script written to model the structure.

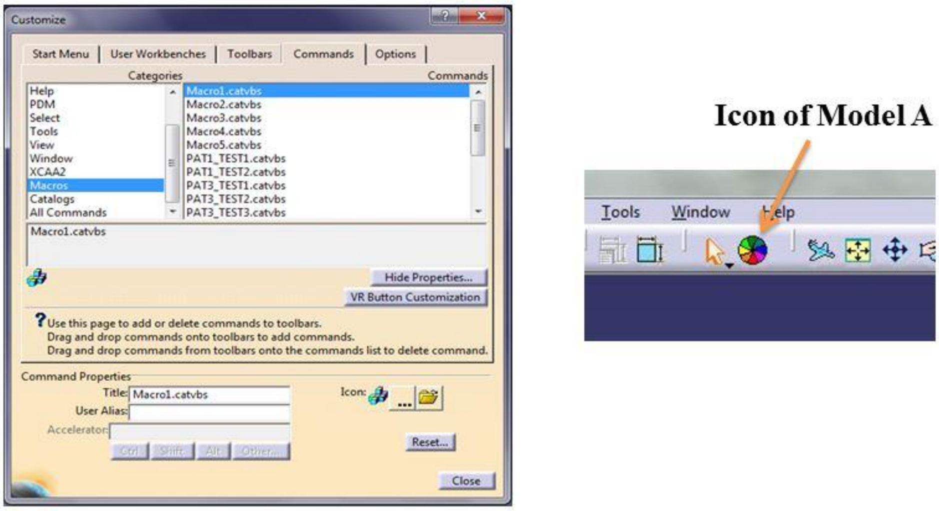


Figure.2 Icon creation for CAD model generation.

III. FABRICATION

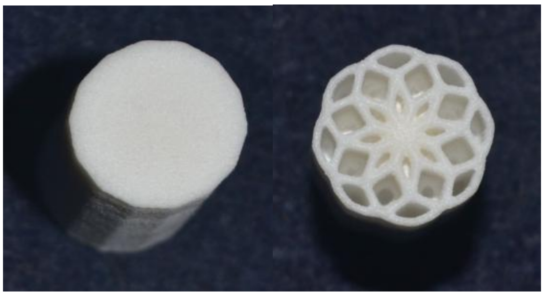
The scaffold characteristics and properties such as porosity, surface area to volume ratio, pore size, pore interconnectivity, structural strength, shape (or overall geometry) and biocompatibilities are often considered to be critical factors in their design and fabrication [13]. Selective laser sintering (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 [14].

The CAD data for the scaffold were exported from CATIA V5 software in stereolithography (.stl) 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 segmentally 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 bone scaffold was fabricated using 3Dfast Srl on a Formiga P100 system (EOS GmbH) in polyamide EOSINT P/PA2200, whereas PA2200 (Poly Amide) is a bio compatible material.

IV. RESULTS AND DISCUSSION

Fabrication and Porosity Relationship

The bone scaffold made of polyamide PA2200 with number of cylindrical shells ranging from 8 to 14 in steps of two were fabricated by using Selective Laser Sintering Technique with length oriented parallel to build direction [15, 16]. The three input parameters namely the radius of the scaffold as 6.35mm, thickness of the cylindrical shell as 0.5mm and height of the scaffold as 25.4mm is kept constant. The fabricated Polyamide scaffolds possessed well defined pores (illustrated in Fig. 3) and their structural configurations were also observed to be consistent with the CAD data.



(a) Scaffold without pores (b) Scaffold with pores

Figure.3 Fabricated Polyamide scaffolds

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 [17]. 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 [18]. In the present work, the volume of the bone scaffold could be easily controlled and measured as the scaffold with the varying number of cylindrical shells was modeled using computer aided solid modeling package. Theoretical porosity was obtained based upon the volumes computed from the solid model package and provided in Table I. The porosity was calculated using the formula given in equation 2.

$$P = (1- (V_S/V_B)) x100 \qquad (2)$$

Where, V_S = Volume of scaffold with pores mm3, V_B = Volume of scaffold without pores mm3 and φ = Porosity in %

The porosity was also determined experimentally by determining the mass of the fabricated scaffold with pores and the scaffold without pores. Knowing the density of polyamide, the volumes of scaffold with pores (Vs) and the volumes of scaffold without pores (V_B) were determined (illustrated in Fig. 3). Using the equation 2, the experimental porosities were determined for the four scaffolds and it have been presented in Table 1.

No. of cylindrical shells	Theoretical porosity (%)	Experimental porosity (%)	Error (%)
8	**50**	**35.43**	**29.15**
10	**39.5**	**25**	**36.71**
12	**33.22**	**18**	**45.82**
14	**27.5**	**14**	**49.1**

The average experimental porosity of the bone scaffold against the theoretical porosity was investigated showing the reduction of error percentage as 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 scaffold and decrease in experimental porosity.

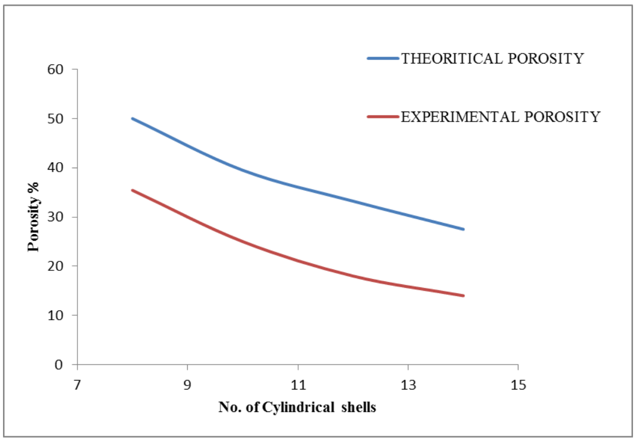


Figure.4 Relationship between porosity and number of cylindrical shells

It was observed that the porosity values increases with decrease in number of cylindrical shells as shown in Fig 4. The error was measured between experimental porosity and theoretical porosity. The percentage of error was also reduced with decrease in number of cylindrical shells as shown in Fig 5

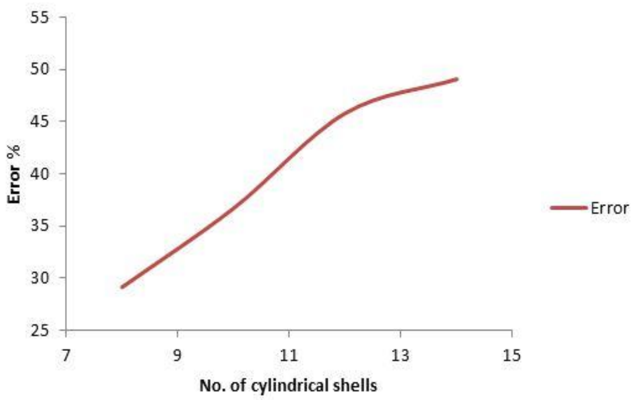


Figure.5 Variation of error percentage with the number of cylindrical shells

V. CONCLUSION

In the present work novel bone scaffold have been successfully modeled using special macros written VB script in CATIA V5 software. The theoretical porosities of novel scaffold were determined from macros. The novel bone scaffolds were fabricated using SLS technique and its experimental porosities were determined. The percentage of error between the theoretical and experimental porosity was reduced with decrease in number of cylindrical shells and increase in porosity

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