International Journal on Recent and Innovation Trends in Computing and Communication
Volume: 3 Issue: 1

ISSN: 2321-8169
27 - 32

Development and Analysis of Different Density Auxetic Cellular Structures

M. Usman Aslam[1, 2], Saied M. Darwish[1, 2]

[1]Industrial Engineering Department, King Saud University
[2]Advance Manufacturing Institute, King Saud University

***Abstract*—**Auxetic structures exhibit negative Poisson's ratios in one or more directions. When stretched, they will become fatter or thinner when compressed, in contrast to conventional materials (like rubber, glass, metals, etc.) in the direction normal to the applied loading direction. The present work intends to develop different density auxetic cellular structures, analyze their different mechanical properties and highlights the von-misses stresses develop during compression and tension of these auxetic cellular structures.

Index Terms*—Auxetic cellular structures, Additive manufacturing, Mechanical Properties, Von-misses Stress.*

*****

I. INTRODUCTION

Auxetic cellular structures have appealed considerable interest in recent years due to their unique mechanical properties resulting from a negative Poisson’s ratio ν. A new field of endeavor is to study materials exhibiting negative Poisson’s ratio (NPR) [1]. These types of materials get fatter when they are stretched, or become thinner when compressed, in comparison with the conventional materials (like rubber, glass,etc.). This is known as the Poisson effect. Poisson’s ratio ν (nu) is a measure of this effect [2]. The value of the Poisson’s ratio controls the elastic behavior of a material same like the Young’s modulus E. A negative value of ν leads to higher indentation resistance, shear resistance, and fracture toughness to name only a few affected properties.

Materials in form of 3D cellular solid [3] are found in many natural structural elements like bone, cork, and wood. Currently, man-made cellular solids such as foams and honeycombs had increasingly used in different Engineering applications, that requires customized stiffness, light weight and impact resistance. Numerous research efforts have been made to analyze the mechanical response of periodic and non-periodic cellular solids in 2D and 3D under different loading conditions.

Additive manufacturing [4] represents a new method of part fabrication. Additive Manufacturing (AM) techniques such as fused deposition modeling (FDM) is commonly used for prototyping, and production applications.FDM works on an "additive" principle by laying down material in layers; a plastic filament or metal wire is unwound from a coil and supplies material to produce a part [5]. FDM builds concept models, functional prototypes and end user parts in standardize, engineering level and high performance thermoplastics. It’s only the professional 3D printing technology that uses production level thermoplastics, so parts are unmatched in thermal, mechanical and chemical strength [6].

The purpose of the present work is to develop, analyze and fabricate different density auxetic cellular structures.

II. AUXETIC STRUCTURE PROPERTIES

Considerable amount of work has been done to evaluate the properties of auxetic structures. Most of the work was either numerical or experimental. With the decrease in Poisson's ratio values (more negative), the in-plane effective elastic modulus of auxetic structures decrease through the elastic analysis based on their analytical model [7]. In another simulation based analysis, [8] suggested that with the decrease of Poisson's ratio, the in-plane modulus of the 2D re-entrant honeycomb structure increases. The out-of-plane modulus [9] showed the opposite trend, which was also observed during the experiments.

Numerous research efforts described that the auxetic foam structures possess superior mechanical properties as compared to the regular foams. Indentation tests were performed with copper auxetic foams, and the results suggested that the indentation resistivity of the auxetic foam increases significantly with the relative density [10]. Auxetic foam exhibited about 300% higher compressive strength as compared to the regular foams [11].

Some work was also done specifically on the 2D extruded re-entrant honeycomb structure. Finite element analysis used with the extruded 2D re-entrant honeycomb structures and concluded that, unlike the regular structures, the thickness versus strut length ratio has a significant effect on the shear modulus of the auxetic structure [8].

III. DEVELOPMENT OF AUXETIC CELLULAR STRUCTURES

There are many kind of cellular structures are available which are different in their shapes like honeycomb, diamond, triangular, rectangular, hexagonal etc. Reticulated mesh structures are developed from Materialise/Magics [12] software. The mesh array structure generator utilized a singleunit cell or lattice-structure unit referred to as a dode element which varies in element dimensions, strut diameters remained fix and the thickness of the unit cell is changed as shown in Fig. 1.In the present work we have developed three structural models by using thin, medium and thick dode elements. The change in thickness produces density or correspondingporosity variations in the models.

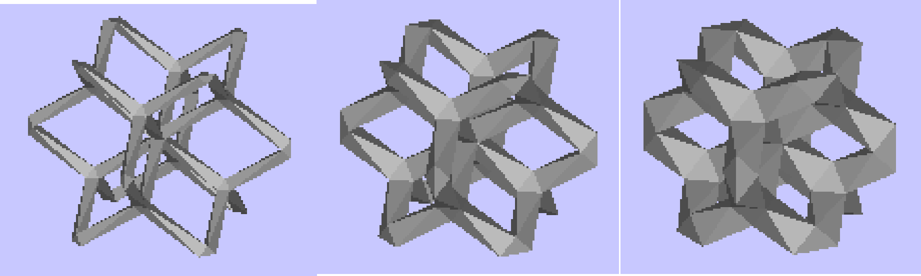


Fig.1.Dode thin, medium and thick unit cells [12].

Firstly we developed a solid cylinder sample as shown in Fig. 2. After that by using these dode thin, medium and thick unit cells we have developed three cylindrical model samples as shown in the Fig. 3.

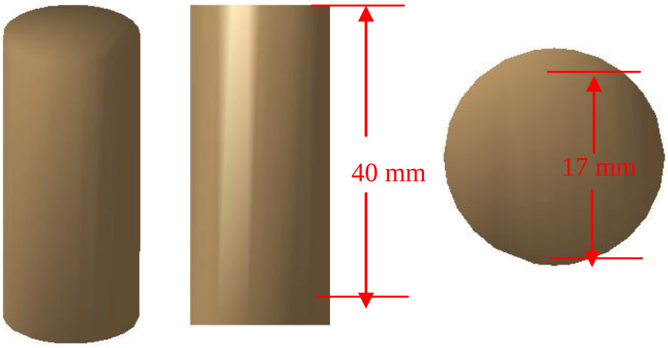
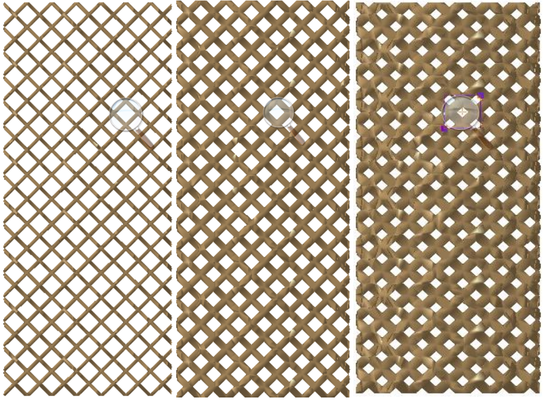


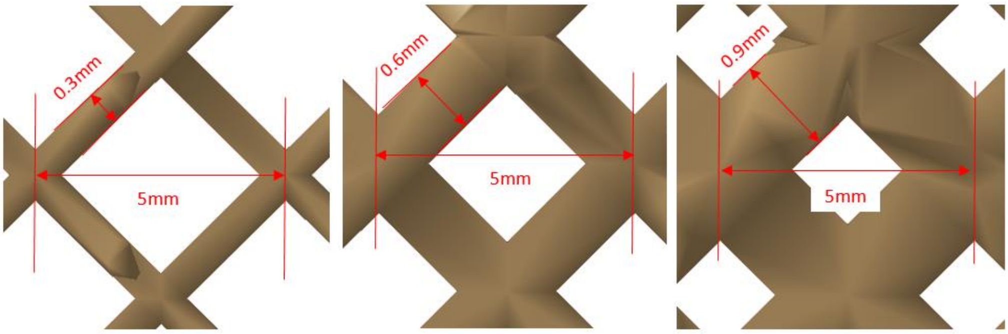
Fig.2.Solid cylindrical sample.



(a) (b) (c)

Fig.3.Auxetic cellular structure models (a) Model 1: dode thin, (b) Model 2: dode medium, and (c) Model 3: dode thick.

Figure 3 shows three different open-cell structure models having different porosities designed using Materialise/Magics [12] software. For these three models, the specimen size was fixed as shown in figure 4. However, relative densities of structures were calculated based on change in thickness of unit cell from 0.3 mm to 0.9mm to give porosity values ranging from 76% to 92% as shown in Fig. 4.



(a) (b) (c)

Fig.4.(a) Model 1: dode thin, (b) Model 2: dode medium, and (c) Model 3: dode thick.

The cellular structures porosity was calculated as [3]:

$$Porosity\ (\%) = \frac{V_{(Bulk\ )} - V_{(Cellular\ \ )}}{V_{(Bulk\ )}} * 100 \tag{1}$$

Where, $V_{(Bulk)}$ is the cylinder volume (9.221E+3 mm^3), while $V_{(Cellular)}$ is cellular structure volume. Cellular structure volume was directly calculated based on geometry by Catia software.

IV. FINITE ELEMENT ANALYSIS

Finite element analysis (FEA) is one of the most effective techniques for the prediction of the mechanical behavior of structures [3, 13]. The designed 3D-models were imported into a FE analysis software package ANSYS®.The results of the analysis allow for calculation of effective elastic modulus and poisson's ratioin tension for model 1, 2, and 3. A linear elastic model with Isotropic properties is employed for all models. Ti-6Al-4V alloy was assigned as the structures material with a modulus of elasticity 113.8 GPa and poisson's ratio of 0.24. Ti-6Al-4V is widely used as abiocompatible material for biomedical implants and can beprocessed in additive manufacturing techniques such aselectron beam melting (EBM) or selective laser melting(SLM). Ti-6Al-4V has been selected in this research becausewe focus on using the proposed structures in biomedical applications [3].

A. Prediction of Effective Elastic Modulus and Poisson's Ratio for Model 1, 2 and 3

A tension displacement of 0.043 corresponding to strain of 0.2% was imposed evenly on the top surfaces of model 1, 2 and 3 to simulate tension testing. The effective stiffness calculation approach is similar to the approach used by Osama and Parthasarathy et al. [3, 14].

The directional effective stiffness *E(zz)* was calculated by using Hook's equation:

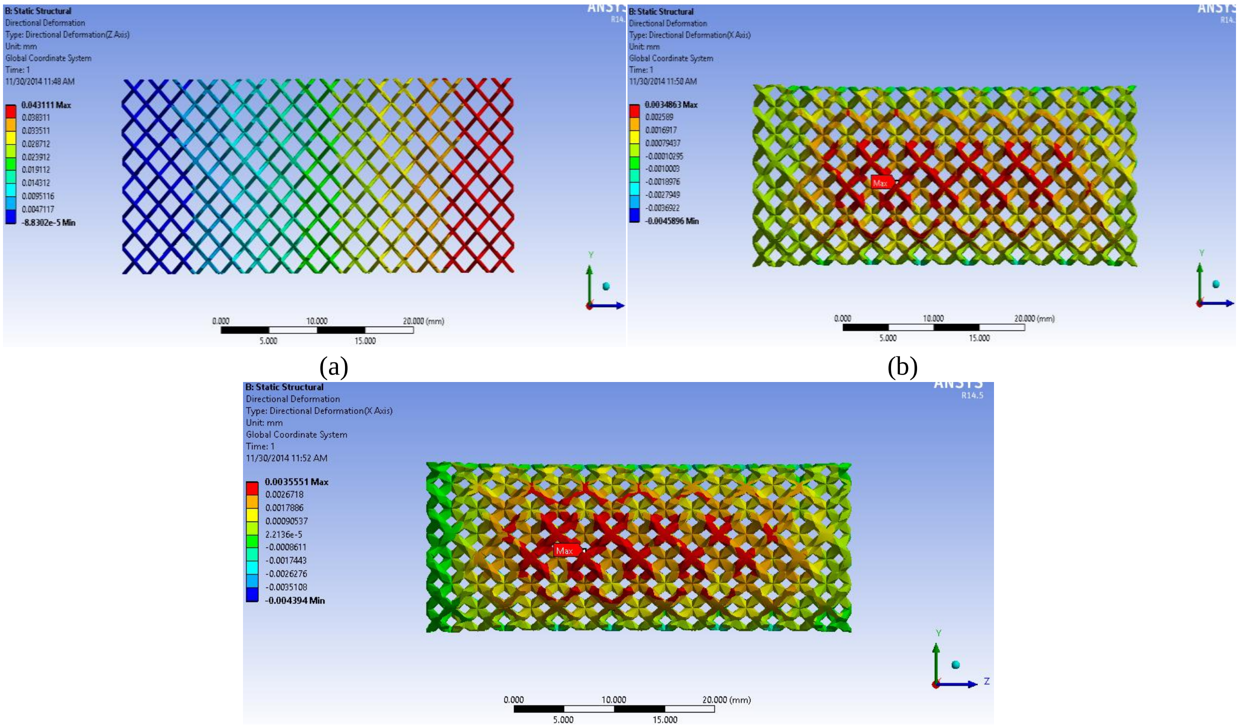
$$E(zz) = \frac{Forc\,e\ Reaction}{0.002 * Area} \tag{2}$$

Where force reaction is the force at fixed surface and area is the surface area (236.58 mm^2) corresponding to the tension. Poisson's ratio is the negative ratio of transverse to axial strains. The poisson's ratios were calculated using the equation [3, 14]:

$$\nu(yz) = -\frac{\xi(y)}{\xi(z)} \tag{3}$$

Where,$\xi(y)$ is the resulting strain normal to the acting force and $\xi(z)$ is the strain in applied displacement z-direction.

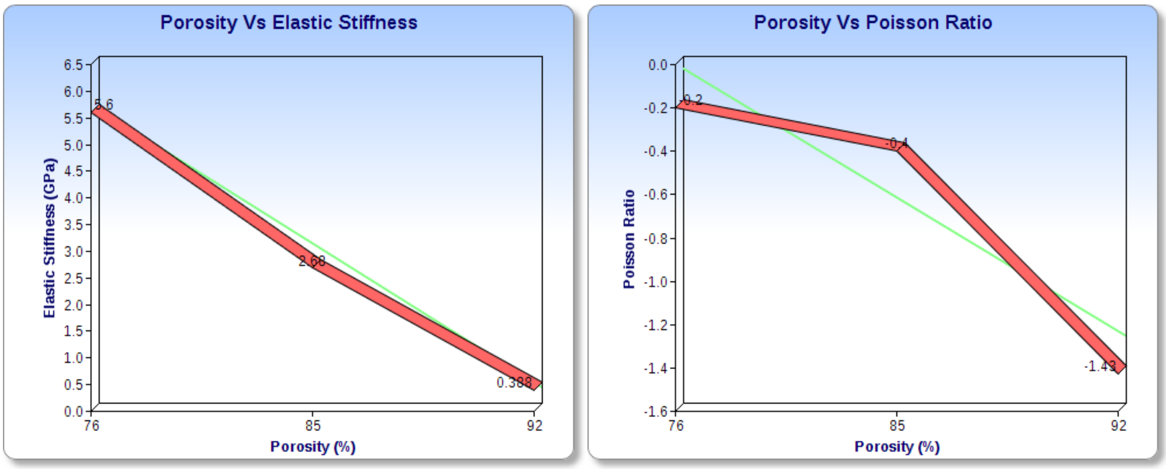
Figure 5 shows the deformation in transverse y-direction for model 1, 2 and 3. Different color shows the different deformation levels where red indicates the highest deformation. The predicted effective modulus as a function of structure porosity and poisson's ratio result for different structure porosities are shown in figure 6.



(a) (b)

(c)

Fig.5.(a) Deformation of model 1 (b) Deformation of model 2, and (c) Deformation of model 3.

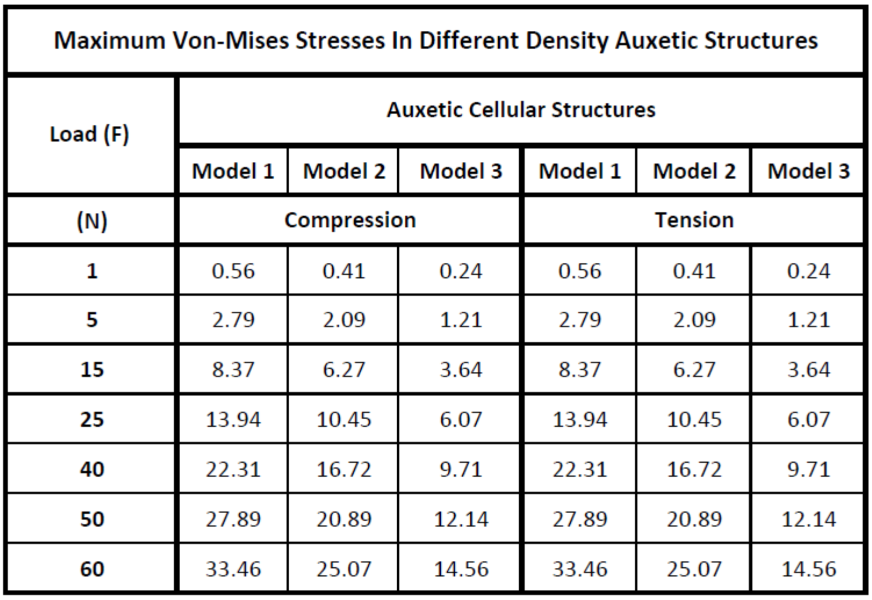


(a) (b)

Fig.6.(a) Effect of porosity on effective stiffness (b) Effect of porosity on poisson’s ratio.

V. VON-MISSES STRESSES IN DIFFERENT DENSITY AUXETIC STRUCTURES

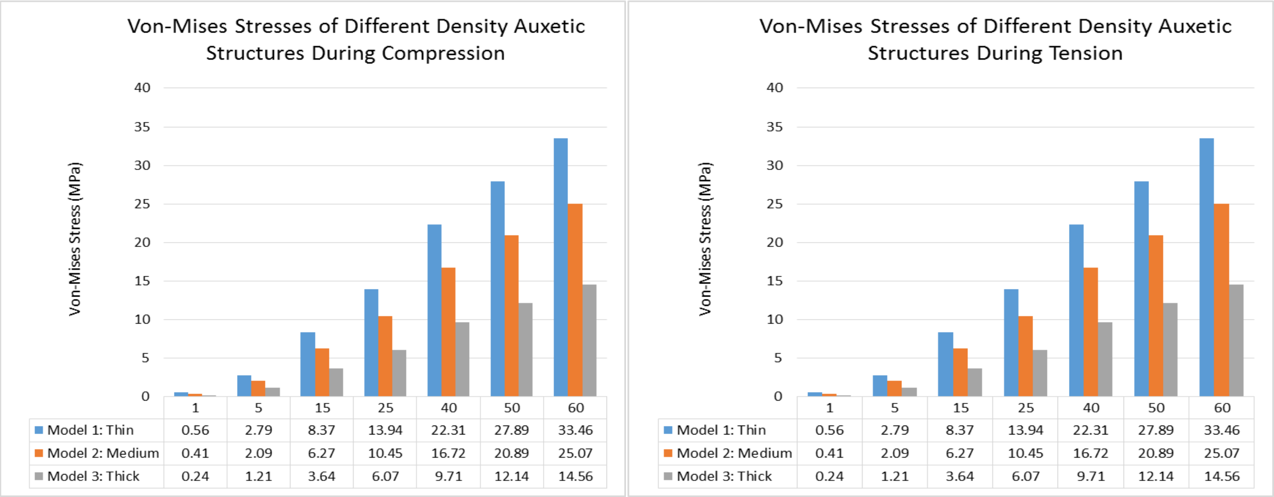
By using FE analysis software package ANSYS® the maximum von-misses stresses of different density auxetic structures are calculated. For model 1, 2 and 3 both compression and tension test were performed at different values of force as shown in Fig. 7. The graphical representation of results for model 1, 2 and 3 are shown in Fig. 8.



Maximum Von-Mises Stresses In Different Density Auxetic Structures

Load (F)	Auxetic Cellular Structures					
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
(N)	Compression			Tension		
1	0.56	0.41	0.24	0.56	0.41	0.24
5	2.79	2.09	1.21	2.79	2.09	1.21
15	8.37	6.27	3.64	8.37	6.27	3.64
25	13.94	10.45	6.07	13.94	10.45	6.07
40	22.31	16.72	9.71	22.31	16.72	9.71
50	27.89	20.89	12.14	27.89	20.89	12.14
60	33.46	25.07	14.56	33.46	25.07	14.56

Fig.7.Maximum von-misses stresses during compression and tension.



	1	5	15	25	40	50	60
■ Model 1: Thin	0.56	2.79	8.37	13.94	22.31	27.89	33.46
■ Model 2: Medium	0.41	2.09	6.27	10.45	16.72	20.89	25.07
■ Model 3: Thick	0.24	1.21	3.64	6.07	9.71	12.14	14.56

	1	5	15	25	40	50	60
■ Model 1: Thin	0.56	2.79	8.37	13.94	22.31	27.89	33.46
■ Model 2: Medium	0.41	2.09	6.27	10.45	16.72	20.89	25.07
■ Model 3: Thick	0.24	1.21	3.64	6.07	9.71	12.14	14.56

Fig.8.Graphical representation of results.

VI. FABRICATION OF AUXETIC CEELULAR STRUCTURES BY USING ADDITIVE MANUFACTURING

Additive manufacturing or 3D printing is a process of making a 3D solid objects of any shape from a computerized model. 3D printing is achieved using an additive process, where sequential layers of material are laid down in different shapes [15]. 3D printing is also considered unique from traditional machining techniques, which mostly consist the removal of material.

Fused deposition modeling (FDM)begins with software which process an STL file (stereo lithography file format) and mathematically slice and orient the model for the building process [16]. A fused deposition modeling machine melts a plastic filament and extrudes it through a nozzle. The molten material is laid down on the building platform, where it cools and solidifies. By laying down layer on layer the part fabrication proceed.

FDM requires supporting structure which anchors the parts on the building platform and supports hanging structures. Through the use of a second nozzle, the supporting structure can be built in a different material. Many parts can be produced at the same time as long as they are all anchored on the platform [17].

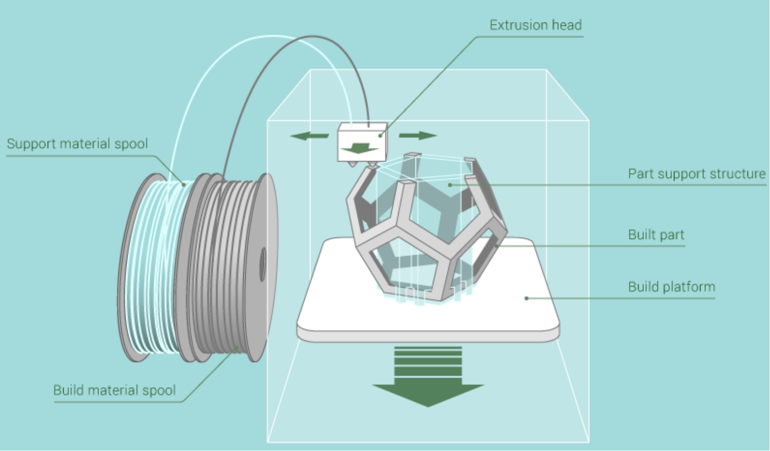
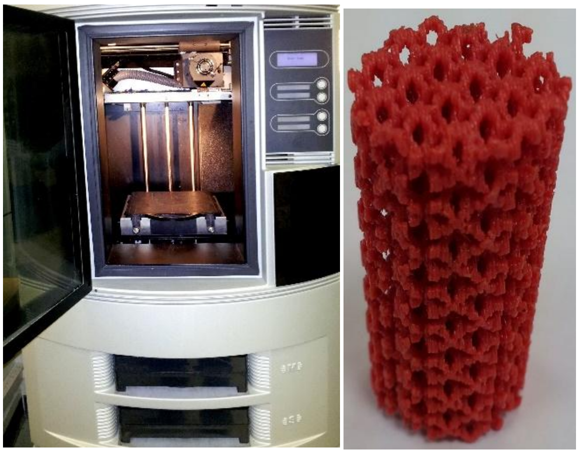


Fig.9.Part fabrication by FDM process [17].

Fabrication of complex functionally graded cellularstructure with controlled gradation in all spatial directions isa challenge task. However, the advances in computer aideddesign (CAD) and Additive manufacturing (AM) techniquesoffer a fast and low cost solution of production problems [3].Figure 10 shows 3D sample fabricated by 3-dimensional printer (Dimension Elite) from a polymer material (acrylonitrile-butadiene-styrene).



(a) (b)

Fig.10.(a) 3-D printer Dimension Elite, (b) 3D sample fabrication by FDM process.

VII. CONCLUSION AND FUTURE PROSPECTS

The aim of this research was to understand the unusual behavior of auxetic cellular structures under different loading condition by finite element modeling. It was observed that structure relative density have a significant effect on structure mechanical properties. As illustrated in figure 8, in agreement with Ashby and Gibson [18], Parthasarathy [19], and Osama [3] for model 1, 2 and 3, effective elastic modulus increases with decrease of porosity. Effective elastic modulus was in the range of 0.3 to 5.6 GPa, which are interesting results for bone substitution applications [20]. Also the increase in structures porosity leads to an increase in negative poisson’s ratio of model 1, 2 and 3. Figure 10 shows that model 3 produces less von-misses stresses as compared to model 2 and 1. Medical Implants with auxetic cellular structures have better bone ingrowths and higher stability in the functioning body. Additive Manufacturing (AM) technology easily combines auxetic structures and solid parts in the same technological process and also can produce custom made objects. My future work is to propose a novel design of tibial component of total knee replacement using auxetic cellular structures.

ACKNOWLEDGMENT

The financial support provided by the Princess Fatimah Alnijris's research chair for AMT, King Saud University, Riyadh, Kingdom of Saudi Arabia.

REFERENCES

[1] J. Schwerdtfeger, P. Heinl, R. F. Singer, and C. Korner, “Auxetic cellular structures through selective electron-beam melting”, Phys. Status Solidi B, vol. 247, no. 2, pp. 269–272, 2010 / DOI 10.1002/pssb.200945513.
[2] “Poisson’s Ratio”, [Online]: Available, http://en.wikipedia.org/wiki/Poisson%27s_ratio
[3] Osama A. M. Abdelaal, Saied M. H. Darwish, “Analysis, Fabrication and a Biomedical Application of Auxetic Cellular Structures”, International Journal of Engineering and Innovative Technology (IJEIT), vol. 2, no. 3, September 2012.
[4] Dr. Andrey Koptyug, Dr. Lars-Erik Rännar, Dr. Mikael Bäckström, “Additive manufacturing technology applications targeting practical surgery”, International Journal of Life Science and Medical Research, vol. 3, no. 1, pp. 15-24, 2013.
[5] Chee Kai Chua; Kah Fai Leong, Chu Sing Lim, “Rapid Prototyping: Principles and Applications in Manufacturing”, World Scientific Publishing Co., Inc. River Edge, NJ, USA, 2003.
[6] http://www.stratasys.com/3d-printers/technologies/fdm-technology#sthash.39tSMQhM.dpuf
[7] Jinhee Lee, J. B. Choi, and K. Choi, “Application of homogenization FEM analysis to regular and re-entrant honeycomb structures”, Journal of Materials Science, vol. 31, pp. 4105-4110, 1996.
[8] F. Scarpa, P. Panayiotou, and G. Tomlinson, “Numerical and experimental uniaxial loading on in-plane auxetic honeycombs”, Journal of Strain Analysis, vol. 35, pp. 383-388, 2000.
[9] F. C. Smith, F. Scarpa, and G. Burriesci, “Simultaneous optimization of the electromagnetic and mechanical properties of honeycomb materials”, Proceedings of SPIE, the International Society for Optical Engineering, vol. 4701, pp. 582-591, 2002.
[10] R. S. Lakes, “Design considerations for materials with negative Poisson's ratios”, Journal of Mechanical Design, vol. 115, pp. 696-700, 1993.
[11] E. A. Friis, R. S. Lakes, and J. B. Park, “Negative Poisson's ratio polymeric and metallic foams”, Journal of Materials Science, vol. 23, pp. 4406-4414, 1988.
[12] http://www.materialise.com
[13] N. Michailidis, F. Stergioudi, H. Omar and D. N. Tsipas, “Investigation of the mechanical behavior of open-cell Ni foams by experimental and FEM procedures”, Advanced Engineering Materials, vol. 10, No. 12, pp. 1122-1126, 2008.
[14] J. Parthasarathy, B. Starly and S. Raman, “A design for the additive manufacture of functionally graded porous structures with tailored mechanical properties for biomedical applications”, Journal of Manufacturing Processes, vol. 13, pp.160-170, March 2011.
[15] "3D Printer Technology – Animation of layering". Create It Real. Retrieved 2012-01-31.
[16] http://www.engr.mun.ca/~kmay/CleanStation/MSDSP400SCWaterWorks_US.pdf
[17] https://www.additively.com/en/learn-about/fused-deposition-modeling#read-more
[18] L.J. Gibson and M.F. Ashby, “Cellular Solids: Structure and Properties”, Cambridge University Press, Cambridge, U.K, ED-2, 1997.
[19] J. Parthasarathy et al., “Mechanical evaluation of porous titanium (Ti6Al4V) structures with electron beam melting (EBM)”, Journal of the Mechanical Behavior of Biomedical Materials, vol. 3, No. 3, pp. 249-259, 2010.
[20] E. Sallica-Leva et al., “Microstructure and mechanical behavior of porous Ti6Al4V parts obtained by selective laser melting”, Journal of the Mechanical Behavior of Biomedical Materials, vol. 26, pp. 98-108, 2013.