Solid Freeform Fabrication 2016: Proceedings of the 27th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference

# Design for Additively Manufactured Lightweight Structure: A Perspective

L. Yang[1], O. L. A. Harrysson[2], D. Cormier[3], H. West[2], S. Zhang[1], H. Gong[4], B. Stucker[5]
[1]Department of Industrial Engineering, University of Louisville, Louisville, KY 40292
[2]Department of Industrial & Systems Engineering, North Carolina State University, Raleigh, NC 27695
[3]Department of Industrial & Systems Engineering, Rochester Institute of Technology, Rochester, NY 14623
[4]Department of Manufacturing Engineering, Georgia Southern University, Statesboro, GA 30458
[5]3DSIM, 1794 Olympic Pkwy, Park City, UT 84098

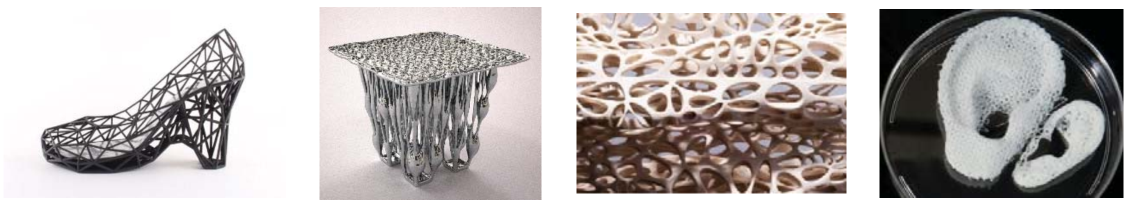
**Abstract**

The design of lightweight structures realized via additive manufacturing has been drawing considerable amount of attentions in academia and industries for a wide range of applications. However, various challenges remain for AM lightweight structures to be reliably used for these applications. For example, despite extensive advancement with geometric design, there still lacks adequate understanding with the process-material property relationship of AM lightweight structures. In addition, a more integrated design approach must also be adopted in order to take non-uniform material design into consideration. In our works, a design approach based on unit cell cellular structure was taken in the attempt to establish a comprehensive design methodology for lightweight structures. Analytical cellular models were established to provide computationally efficient property estimation, and various design factors such as size effect, stress concentration and joint angle effect were also investigated in order to provide additional design guidelines. In addition, it was also found that the geometry and microstructure of the cellular structures are dependent on both the process setup and the feature dimensions, which strongly support the argument to establish a multi-scale hierarchical cellular design tool.

Keywords: lightweight structure, additive manufacturing, cellular structure, unit cell, design

## Introduction

One of the objectives of structural design is to minimize the mass consumption and maximize the utilization efficiency of the materials. Therefore, lightweight structure design has always been sought after for almost all the engineering designs. Lightweighting brings about various technical advantages such as high strength to weight ratio, high energy absorption per weight ratio, low thermal conductivity, and large surface area to volume/weight ratio. These attributes could in turn translate into various economical and environmental benefits such as product reliability, system energy efficiency and product sustainability. However, as lightweight designs often involve high level of geometrical complexity, the realization of these designs has been a challenging task with traditional manufacturing technologies. It has been widely recognized that additive manufacturing (AM) technologies possess unique capabilities in realizing lightweight designs with little penalty from geometrical complexity, and extensive demonstrations are available for various applications such as fashion, arts and biomedicine as shown in Fig.1 [1-5]. However, the design of these lightweight structures beyond aesthetic purposes is in general not well-understood by most designers. The lack of understanding on the relationship between various engineering performance requirements (e.g. mechanical properties, thermal properties, biological properties, etc.) and the geometrical design often prevents efficient design of lightweight structures for functional purposes. In addition, there also exist very little literature in the guidance of optimal process selections in the fabrication of these structures utilizing different AM technologies.



a. Fashion shoes [6] b. Table [7] c. Skin shell [8] d. Artificial ear [9]

Fig.1 Lightweight designs realized via AM in art, fashion and biomedicine

While there exist various geometry design and optimization approaches and tools that generally allows for the creation of models with improved lightweight performance, currently none of them addresses the process designs adequately. Most of the lightweight design tools treat material as an ideal isotropic material and focus on geometry optimization only, which often results in a significant design deviation from reality. One of the unique characteristics of AM is that the material properties are often process and geometry dependent. Such coupling effect has significant impact in the design practice of lightweight structures, since these structures often have geometrical features that have varying dimensions and therefore potentially varying material properties. In addition, due to the intrinsic quality variations with many AM processes with small-dimension geometries, the difficulty of achieving accurate design is further signified. In this paper some of the works in the attempt to tackle this design dilemma is presented. A design methodology that includes geometrical design and material property design was proposed, and some of the issues during the establishment of this methodology was discussed.

## Geometrical design of AM lightweight structures

In the design of AM lightweight structures, two basic approaches are most commonly employed currently, which are topology optimization based design and cellular structure design. Each approach possess certain advantage and disadvantage compared to each other.

Topology optimization is a mathematical optimization methodology that achieves an optimized design by redistributing material voxels within a given design space with the objectives of maximizing/minimizing certain criteria such as weight, stiffness, compliance and conductivity while being subjected to design constraints. Unlike sizing optimization and shape optimization, topology optimization does not prescribe design topology, and is therefore capable of yielding at least locally optimized geometrical solutions [10]. During the optimization, individual voxels could be either removed, added or even partially filled when variable-densities are allowed [11-16]. The resulting structures often exhibit highly complex geometries that are challenging even for AM processes, and consequent re-design might be needed as shown in Fig.2. It was argued that despite the additional efforts needed, such design approach is still highly efficient in achieving optimized geometrical designs.

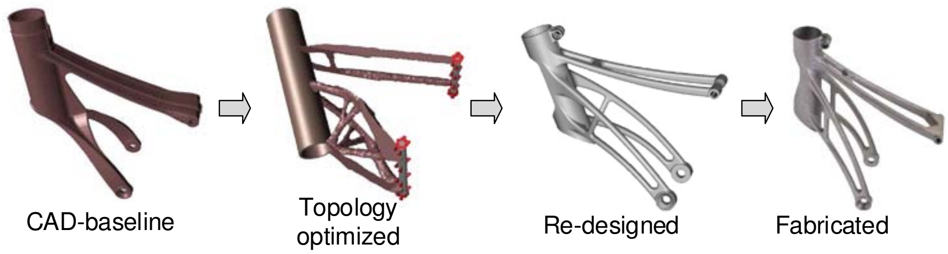



Fig.2 Topology optimization as design reference [17]

Currently topology optimization design approach faces multiple challenges. Among them are the lack of ability to handle certain optimization problems such as dynamic fatigue problems and multi-physics problems [18, 19], as well as the manufacturability issues. Besides the design limitations such as minimum feature sizes, orientation limits and support-free critical surfaces that could not be satisfactorily addressed due to the lack of definition with overall geometry, currently topology optimization also lacks the ability to handle anisotropic materials and materials with geometry-dependent material properties.

Cellular structure designs, on the other hand, take a design approach with significant geometrical constraints in general. Traditional cellular structure design theories for stochastic cellular structures focus mostly on porosity designs. Following Gibson-Ashby theory as shown in Eq.(1), various mechanical properties including elastic modulus (E), strength (σ) and shear modulus (G) can be determined via the relative density ($\rho_r$) of the cellular structures. In addition, various physical properties such as thermal transfer coefficient, coefficient of thermal expansion, electrical conductivity and mass transfer properties are also strongly dependent on $\rho_r$ [20-24]. Following this approach, additional experimental verifications are usually needed in order to determine the scaling factors of individually manufactured cellular structures, which then allows for further structural designs using the characterized cellular structures as an equivalent “material”. This design route is shown in Fig.3.

$$E \propto \rho_r^2 ,\ \sigma \propto \rho_r^{3/2} ,\ G \propto \rho_r^2 \quad (1)$$

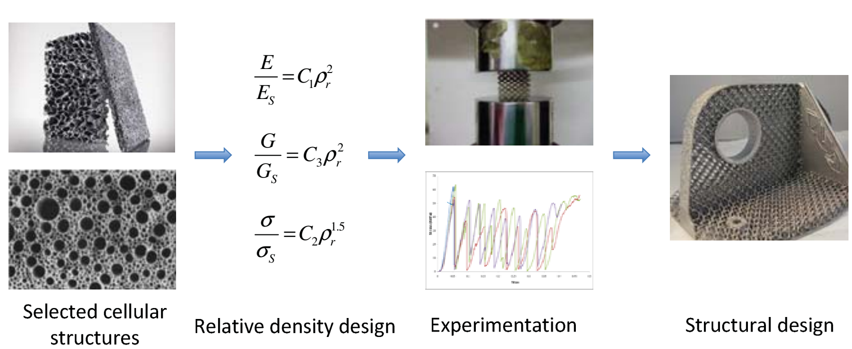


Fig.3 Relative density based cellular structure design

For non-stochastic cellular designs that exhibit higher level of geometrical determinacy, although relative density based design approach is still applicable, addition design factors could be incorporated to enable more efficient multi-objective lightweight designs. When the cellular structures exhibit spatial geometrical periodicity, unit cell based design approach is often taken, which utilizes the geometrically representative unit cell to simplify the design of the entire structures. Compared to topology optimization, although limited by geometrical design flexibility, the unit cell design appears to show more promises in accounting for AM material properties during the design process due to the high predictability of geometries. In this work, unit cell based cellular design was explored, and issues related to this design approach was discussed in details in the following section.

## Unit cell geometry design

The design of periodic cellular structures with unit cell is analogous to the design of 3D tiling patterns. When only one type of unit cell geometry is used for the designs, regardless of the actual unit cell design, the geometrical bounding volume (GBV) of the unit cell must satisfy space-filling requirement. Fig.4 shows some typical space filling 3D elements that could potentially be used for cellular designs. Cubic GBV is currently most commonly utilized for unit cell designs. As shown in Fig.5, various unit cell geometries can be designed with cubic GBV. In general, these unit cell geometries possess good spatial symmetries and could therefore be further simplified during the design modeling.

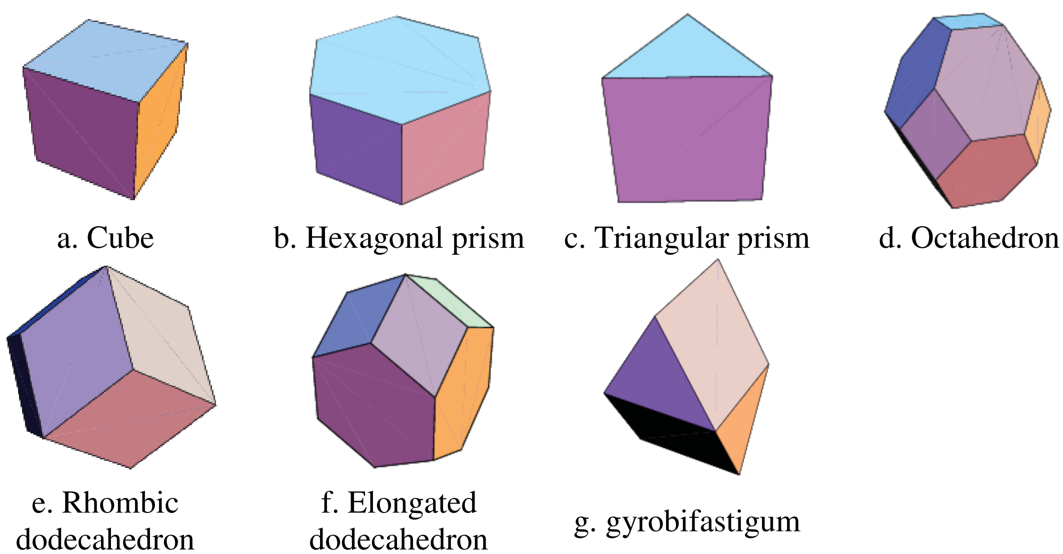
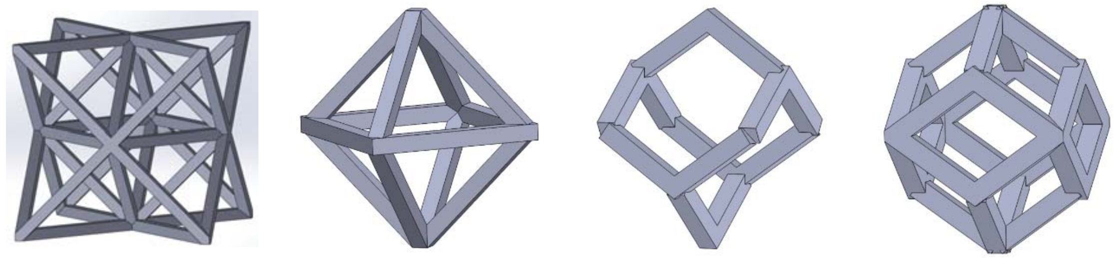


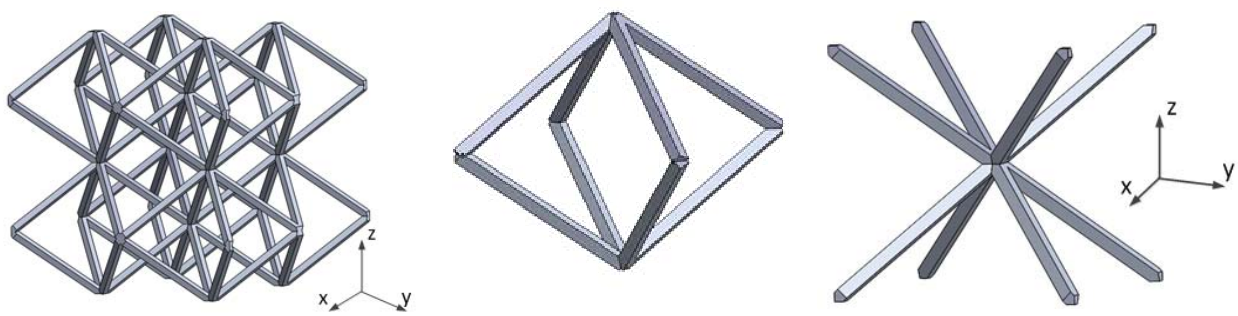

Fig.4 Typical space filling polyhedral [25]



a. Octet-truss b. Octahedron c. Diamond d. Rhombic

Fig.5 Several unit cell designs with cubic GBV

One such example of modeling is shown below in details for the BCC lattice which is shown in Fig.6 [26]. The unit cell geometry for the cellular structure shown in Fig.6a could be represented by either Fig.6b or Fib.6c. However the unit cell layout 2 is easier to model.




(a) lattice structure (b) Unit cell layout 1 (c) Unit cell layout 2

Fig.6 BCC lattice cellular structure [26]

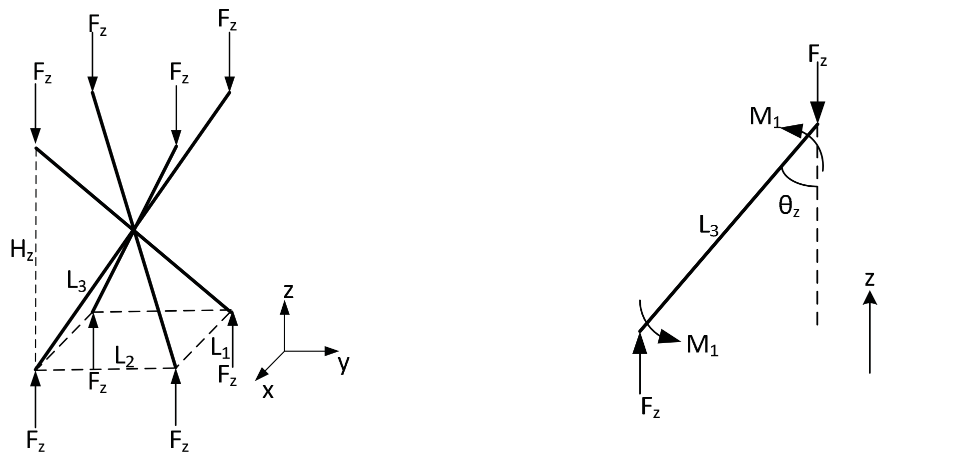
From the topology of the unit cell it is obvious that the uniaxial mechanical properties of the BCC lattice at all three principal directions could be modeled with identical formulations. Considering a remote compressive stress $\sigma_z$ applied on the structure along the z direction, the loading of the unit cell is shown in Fig.7a. Since all struts are subjected to identical loading conditions and boundary conditions, an arbitrary strut is taken for modeling, whose loading condition is illustrated in Fig.7b. From force equilibrium the force components shown in Fig.7b can be determined as:

$$F_z = \frac{1}{4}\sigma_z L_1 L_2 \quad (2.1)$$

$$M_1 = \frac{1}{2}F_z L_3 \sin\theta_z = \frac{1}{8}\sigma_z L_1 L_2 L_3 \sin\theta_z \quad (2.2)$$

where $L_1$, $L_2$, are the dimensions of the unit cell in x and y directions, and $L_3$ is the length of a half-strut, and $\theta_z$ is the slope angle of the strut in relation to the *z* axis:

$$\theta_z = \sin^{-1}\frac{\sqrt{L_1^2 + L_2^2}}{2L_3} \quad (2.3)$$




(a) Loading of unit cell (b) Analysis of individual strut

Fig.7 Octahedral unit cell under compression

Under the loading condition shown in Fig.7b, the strut undergoes a bending/shearing combined deformation. For metal cellular struts the axial deformation along the strut axis is relatively insignificant and therefore could be ignored [27]. Employing beam analysis, the deformation of the strut in the z direction and the direction perpendicular to the z direction can be obtained as:

$$\Delta z = L_3 \sin\theta_z \left( \frac{M_1 L_3}{6EI} + \frac{6F_z \sin\theta_z}{5GA} \right) \qquad (3)$$

$$\Delta z_{\perp} = L_3 \cos\theta_z \left( \frac{M_1 L_3}{6EI} + \frac{6F_z \sin\theta_z}{5GA} \right) \qquad (4)$$

where E, G are the modulus of elasticity and shear modulus of the solid material, I is the second moment of inertia of bending in the plane shown in Fig.7b, and A is the cross sectional area. If the deflection $\Delta z_{\perp}$ is further decomposed into deformations in the x and y directions, $\Delta x$ and $\Delta y$, then it follows that:

$$\Delta x = L_3 \cos\beta_z \cos\theta_z \left( \frac{M_1 L_3}{6EI} + \frac{6F_z \sin\theta_z}{5GA} \right) \qquad (5)$$

$$\Delta y = L_3 \sin\beta_z \cos\theta_z \left( \frac{M_1 L_3}{6EI} + \frac{6F_z \sin\theta_z}{5GA} \right) \qquad (6)$$

Therefore, the modulus of the unit cell can be determined as:

$$E_z = \frac{L_3 \cos\theta_z \sigma_z}{\Delta z} = \frac{H_z \sigma_z}{2\Delta z} = \frac{H_z}{2L_1 L_2 L_3 \sin^2\theta \left( \frac{L_3^2}{48EI} + \frac{3}{10GA} \right)} \qquad (7)$$

where $H_z = 2L_3 \cos\theta = 2\sqrt{L_3^2 - \frac{1}{4}(L_1^2 + L_2^2)}$, which is also shown in Fig.7a.

The strength of the BCC lattice could be roughly estimated by the initial yield strength of the strut. Such conservative estimation could sometimes be justified by the fact that metal AM cellular structures often exhibit significant quality variability. From Fig.7b the normal stress and shear stress of the strut could be determined as:

$$\sigma_1 = \frac{M_1 u}{I} + \frac{F_z \cos\theta_z}{A} = \frac{\sigma_z L_1 L_2 L_3 \sin\theta_z}{8I} u + \frac{\sigma_z L_1 L_2 \cos\theta_z}{4A} \quad (8.1)$$

$$\tau_1 = \frac{F_z \sin\theta_z D}{Ib} \quad (8.2)$$

Where u is the distance from the geometrical center of the cross section to the location of interest, D is the moment of area of the cross section, and b is the width of the cross section at the location of interest. Applying Von Mises Criterion, the maximum allowable stress level $\sigma_m$ that results in the onset of structure yield is:

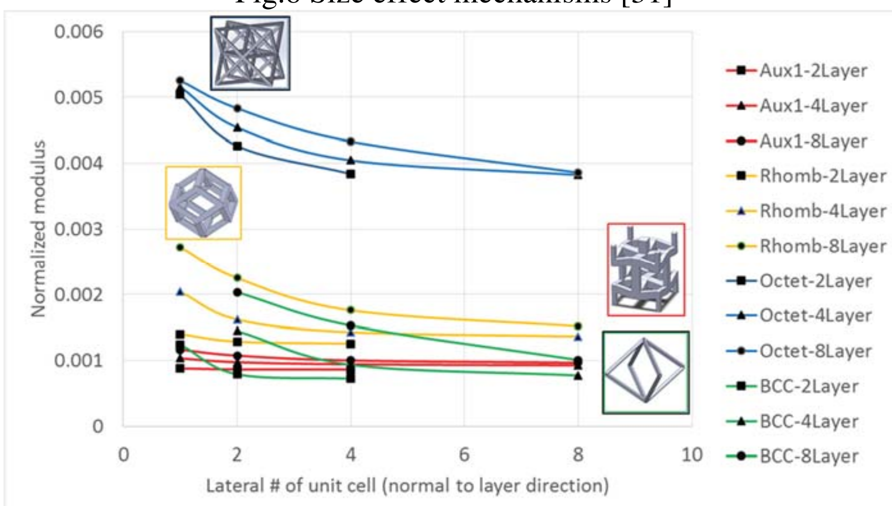
$$\sigma_m = \frac{4}{L_1 L_2 \sqrt{\frac{L_3^2 \sin^2\theta_z}{2I^2} u^2 + \frac{2\cos^2\theta_z}{A^2} + \frac{6\sin^2\theta_z D^2}{I^2 b^2}}} \sigma_Y \quad (9)$$

Following Eq.(7) and Eq.(9), through geometrical parameter design a range of mechanical properties could be achieved in particular direction of the BCC lattice structures. It is noted that although in Eq.(7) and Eq.(9) the material properties are constants, they could be readily substituted into material property functions, therefore potentially allows for multi-scale hierarchical designs with the cellular structures with material/process design factored incorporated. Also, for cellular structures that could not be treated as beam networks, other existing solid structure modeling theories could be used, which further increases the flexibility of this design methodology.

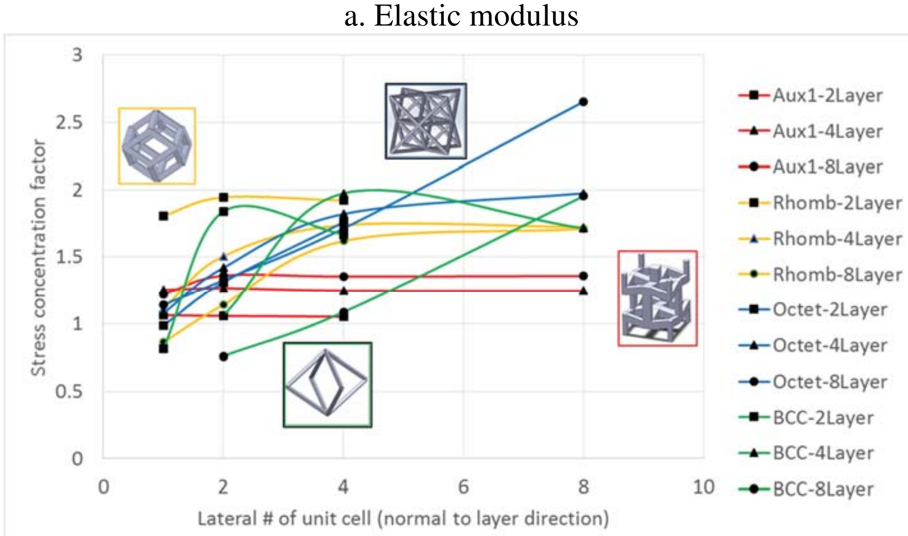
It must be noted that the underlying assumption for unit cell design approach is that the mechanical properties and responses of the unit cell are representative to the entire structures, which is only true when boundary conditions are ignored. However, for actual structures there always exist size effects. Size effects could be caused by both the lack of balancing forces at free boundaries and the boundary constraints as shown in Fig.8. Size effects vary from different unit cell designs and must be characterized either through experimentation or through modeling [28-30]. The size effects of several common AM cellular unit cell geometries, including the re-entrant auxetic structure, the octet-truss structure, the rhombic structure, and the BCC lattice structure, are shown in Fig.9. Different unit cell designs exhibit different magnitudes of elastic modulus and maximum stresses when subjected to same amount of loading. In addition, the size effects along different directions of each unit cell geometries are also significantly different. Some unit cell designs exhibit highly predictable size effects that could be readily incorporated during the structural designs as correction factors, while the others require more studies in order to establish quantitative size effect design rules [28, 31].

a. Free boundary b. Boundary constraints

Fig.8 Size effect mechanisms [31]



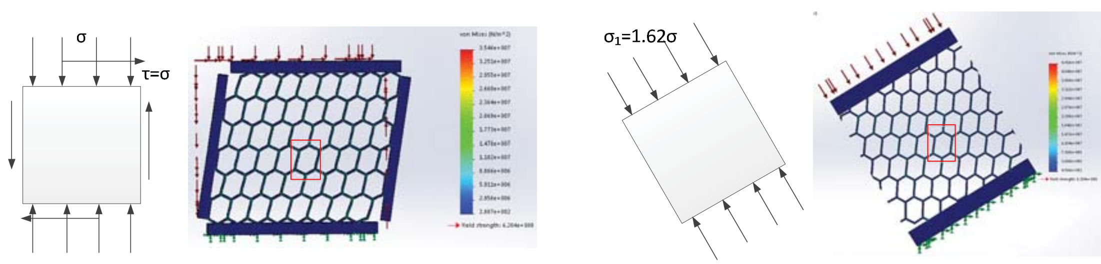

a. Elastic modulus




b. Maximum stress levels

Fig.9 Size effects of several unit cell geometries

Another assumption utilized in unit cell design that is often overlooked is the homogenization of cellular structures. It was often assumed that once the equivalent constitutive material properties of the cellular structures (i.e. elastic modulus, shear modulus and Poisson's ratios) are known, the cellular structures could then be effectively treated as a continuum for subsequent design. However, such homogenization treatment might need to be subjected to scrutiny. For example, for a regular hexagonal cellular structure shown in Fig.10, the two loading cases are equivalent for continuum according to principal stress rules when boundary conditions are ignored. If the cellular structures could be treated as continuum, then the two loading cases are approximately equivalent for the unit cell close to the center of the structure (highlighted in red box). However, it was observed that the differences of stress and deflection for a unit cell amount to about 25% and 45% respectively between the two cases. Although more studies are needed to further identify such effects, it was speculated that it might be largely caused by the semi-discontinuous and directional connectivity of the cellular structures. In addition, this also implies that the traditionally prevalent homogenization based methods might not always be as effective for cellular designs.




a. Under normal + shear stress
$\sigma_{max}$=35.5MPa
Unit cell distortion = 5.26x$10^{-3}$mm

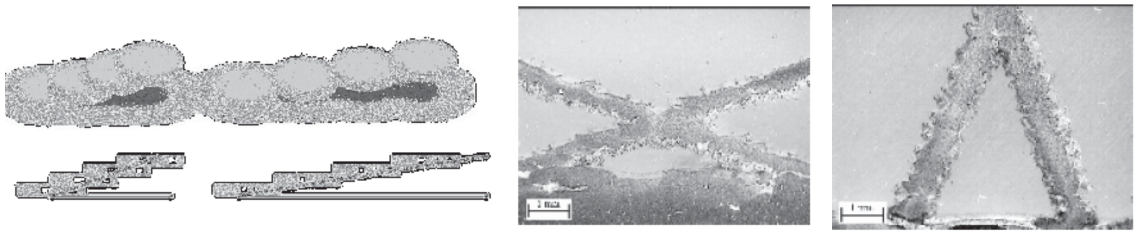
b. Under principal stress
$\sigma_{max}$=44.2MPa
Unit cell distortion = 3.61x$10^{-3}$mm

Fig.10 Comparison of cellular behavior under equivalent loading conditions

## Lightweight material design

In general much less is understood with the manufacturability of the lightweight structures, although it has been identified that factors such as energy density, energy beam power, scanning speed, part location, part orientation and scanning strategies all have potentially significant effect on the mechanical properties of the cellular structures [32-36].

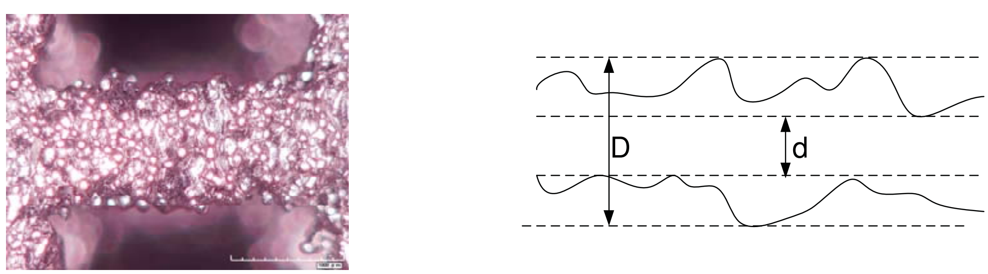
Staircase effect tends to be more significant for cellular structures due to the small dimensions of the geometries. It has been suggested that at smaller orientation angles (i.e. more aligned to horizontal plane) the staircase effect of struts could become significant enough to affect the structural integrity as demonstrated in Fig.11a [37]. As shown in Fig.11b-c, for thin struts fabricated by electron beam melting process, at 20° the cross section geometry of the strut exhibits more significant fluctuation compared to the 70° struts [38]. However, a recent work found contradictory trends for thin struts fabricated via laser melting process, in which lower-angle struts were found to be easier to fabricate due to their larger projected cross sectional areas [39].



a. Staircase effect with different orientation angles [37] b. struts at 20° angle [38] c. struts at 70° angle [38]

Fig.11 Staircase effect for cellular structures

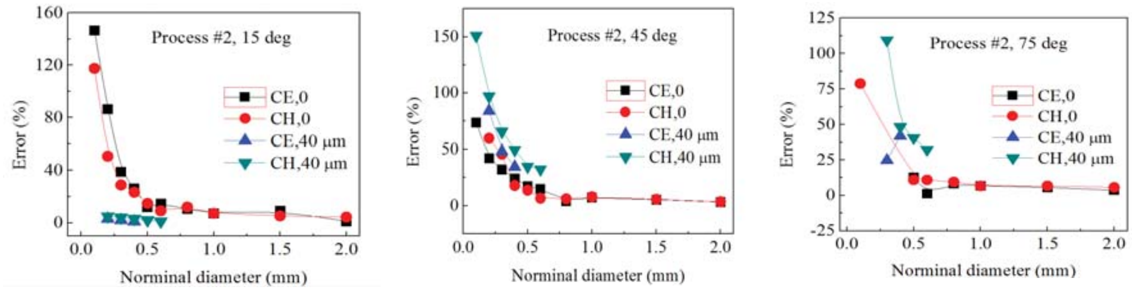
Another intrinsic effect that introduces geometrical error is the surface powder sintering for the powder bed fusion AM processes, which is caused by the heat dissipated away from the processed areas. As shown in Fig.12, these surface defects causes dimensional variations on the cellular struts. For the calculation of mechanical properties, it was found that the minimum strut dimension (d in Fig.12b) should be used in the modeling [40]. On the other hand, in order to calculate pore size, the largest strut dimension (D in Fig.12b) should likely be adopted. For bulky structures such surface roughness could potentially reduce fatigue performance, and for cellular structures, this issue could be more pronounced due to the large specific surface areas of these structures. Literatures have shown that the fatigue strength of Ti6Al4V AM cellular structures are generally lower compared to that of the bulky Ti6Al4V fabricated via the same AM processes [32, 41-43]. Due to the complex geometries and the extensive existence of internal features, cellular structures are generally difficult to perform surface treatment with. As a result, the fatigue performance of the metal AM cellular structures still poses a significant barrier for their structural applications.




a. A Ti6Al4V strut from EBM process b. Dimensional variation

Fig.12 Surface quality issue with thin struts [40]

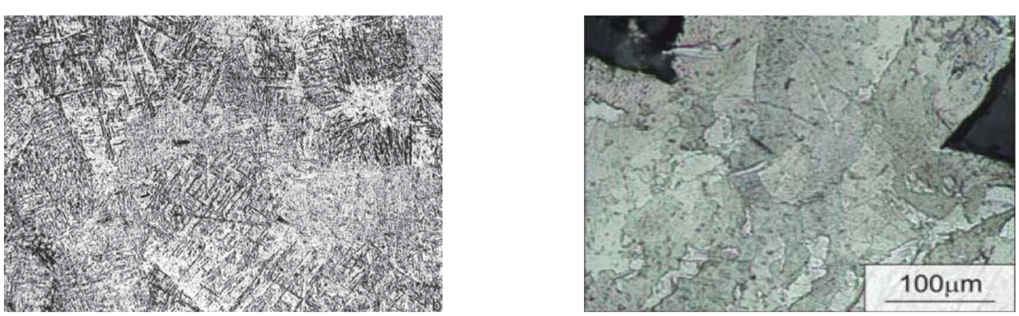
Due to the geometrical errors, the actual dimensions of the cellular struts often deviate significantly from the designs, especially when the dimensions become smaller. Fig.13 shows some of the preliminary works with Ti6Al4V fabricated by EOS M270 laser melting system. In this experimental based works, thin struts with different orientations and dimensions were processed with the same beam energy (80W) and scanning speed (400mm/s) and different scanning strategies (contour + hatch and contour + edge) and beam offsets (0 and 40μm). Significant dimensional errors occurred at all strut designs smaller than 0.5mm regardless of the orientation and other process conditions. It was also shown that when the beam offset was applied, the process was more capable of realizing lower-angle struts (15°) with higher accuracies. At dimensions larger than 0.5mm, the fabrication qualities of the struts become less sensitive to the selection of scanning strategies and beam offsets. Due to the intrinsic process variability, it was speculated that the random errors occur at smaller dimensions could not be effectively reduced. Therefore, such information should be used to provide lower threshold for the dimensional design of the struts in order to ensure the qualities.




a. 15° struts b. 45° struts c. 75° struts

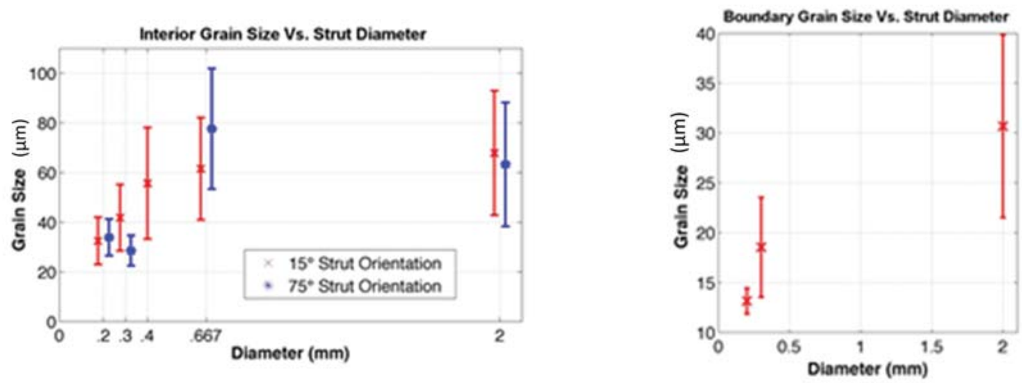
Fig.13 Dimensional errors for Ti6Al4V thin struts fabricated by EOS M270

The microstructure of the metal cellular structures fabricated via powder bed fusion AM often exhibits finer microstructrrual phases compared to the bulky structures. As shown in Fig.14, for Ti6Al4V cellular structures fabricated via electron beam and laser beam based powder bed fusion AM processes, the predominant microstructure is the fine-grained lath α' martensite, which is suggested to be contributed by the rapid cooling effect introduced by large surface area of the cellular geometries [44, 45]. In addition, it was observed that the size of the prior β grains in the microstructure is also a function of both strut orientation and strut dimensions [39]. As shown in Fig.15, for Ti6Al4V thin struts fabricated by laser melting process, with increasing feature dimensions, the microstructural grain size of the Ti6Al4V struts exhibit an increasing trend, while there also exist significant size differences between grains that are close to the exterior surface of the struts and those that are at the interior of the struts. On the other hand, smaller overhanging angle result in more consistent grain size distribution throughout the strut. Such microstructural variation likely corresponds to local mechanical property variations, which means that the mechanical properties of the cellular structures are likely coupled with their geometrical designs and process setup.




a. Electron beam melting [44] b. Laser melting [45]

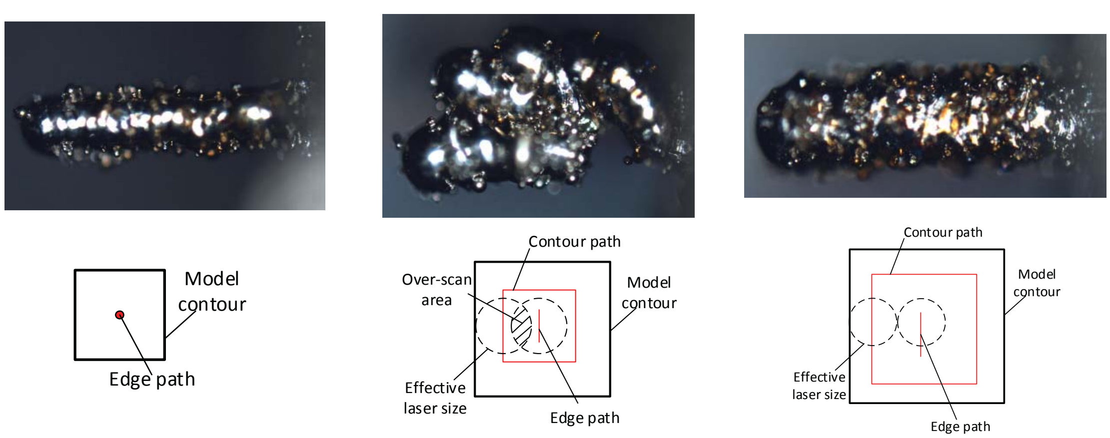
Fig.14 Microstructure of AM Ti6Al4V cellular struts




a. Interior grain size    b. Exterior/boundary grain size

Fig.15 Grain size dependency on orientation and strut diameter for Ti6Al4V fabricated by laser melting [39]

Very little works are currently available for the process optimization of cellular structures. In many metal powder bed fusion AM systems, the process parameters used for support structures are often more optimized towards cellular structures with very thin struts. However more systematic studies are needed. In addition, the scanning strategies could also become significant in determining the success of cellular structure fabrications. For example, it was observed that for the GP1 stainless steel fabricated with EOS M270, depending on the selection of scanning strategies, struts with certain dimensions might fail to be built as shown in Fig.16 [36]. This was contributed largely by the overlapping scanning paths of laser energy beams, which likely introduced certain types of defects into the structures and render the struts weak. The shearing effect of the powder spreader blade during powder recoating further signifies such defects and results in significant part distortion. For EOS M270 system, it was concluded that when contour + edge scanning were used, such critical dimensions exist and are closely associated with the overall beam offset [36]. Although these types of knowledge is often system specific, it could not be neglected, and further studies driven by physics based simulations might be helpful in establishing more generalized relationships between process strategies and the resulting microstructure and mechanical properties of the cellular structures.




a. 0.1mm    b. 0.2mm    c. 0.3mm

Fig.16 Thin strut fabrication using contour + edge scanning in EOS M270 [36]

To summarize, the knowledge for AM cellular structure design is still rather fragmented now. A regularly employed shortcut is to perform experimental based structure characterization which, if planned properly, could result in efficient development of structural design guidelines for a particular cellular design. Various design factors such as process/material property relationships and size effects would be incorporated into the design process as compound effects through experimentation, and provide a short-term solution for companies that need design improvements. On the other hand, a thorough understanding of different design aspects and the establishment of a systematic design methodology will benefit the design of cellular structures as a metamaterial for wider applications in the long term.

## Conclusions

In this paper, the challenges of AM lightweight structure were briefly reviewed. Compared to other design methodology such as topology optimization, unit cell based cellular design method appears to provide a good compromise between functionality and manufacturability. However, in order to pursue this design approach, various additional factors must be considered, such as size effects and material property dependency on both geometrical designs of the struts and the process planning. It was found that the homogenization treatment could not be readily applied to cellular structures in general, which poses a rather challenging obstacle in adopting this design method in the design of actual structures. Due to the complexity of cellular structures, it is currently inefficient to perform the designs using finite element simulation based methods. However, if the cellular structures could not be treated as continuous solid materials with equivalent properties, the limitation of analytical modeling must be overcome through over means.

## Acknowledgement

This work was partially supported by Office of Naval Research (ONR) grant #N00014-16-1-2394 and University of Louisville Intramural Research Initiation Grants. The authors would like to acknowledge the supports from Rapid Prototyping Center (RPC) at University of Louisville and from Center of Additive Manufacturing and Logistics (CAMAL) at North Carolina State University.

## Reference

[1] I. Zein, D. W. Hutmacher, K. C. Tan, S. H. Teoh. Fused deposition modeling of novel scaffold architectures for tissue engineering applications. Biomaterials. 23(2002), 4: 1169-1185.

[2] D. W. Rosen. Design for additive manufacturing: a method to explore unexplored regions of the design space. Proceedings of the Solid Freeform Fabrication (SFF) Symposium, Austin, TX, 2007.

[3] M. Castilho, M. Dias, U. Gbureck, J. Groll, P. Fernandes, I. Pires, B. Gouveia, J. Rodrigues, E. Vorndran. Fabrication of computationally designed scaffolds by low temperature 3D printing. Biofabrication. 5(2013), 3: 035012

[4] R. Kuhn, R. F. B. Minuzzi. The 3d printing's panorama in fashion design. Proceedings of 5th Documenta Fashion Seminar and 2nd International Congress of Memory, Design and Fashion, Sao Paulo, Brazil, 2015.
[5] B. Z. Wang, Y. Chen. The effect of 3D printing technology on the future fashion design and manufacturing. Applied Mechanics and Materials. 496-500(2014): 2687-2691. Accessed July 2016.
[6] http://www.3ders.org/articles/20120821-continuum-fashion-launches-custom-3d-printed-shoes.html. Accessed July 2016.
[7] Francis Bitonti Studio. http://www.francisbitonti.com/fiber-tables/. Accessed July 2016.
[8] Neri Oxman: Projects. http://www.materialecology.com/projects. Accessed July 2016.
[9] Wake Forest Institute of Regenerative Medicine. http://www.wakehealth.edu/WFIRM/. Accessed July 2016.
[10] M. P. Bendsoe, O. Sigmund. Topology Optimizaiton: Theory, Methods and Applications. Springer-Verlag, Berlin, Germany, 2003.
[11] Ing. T. Bechtold. Structural topology optimization for MEMS design. University of Freiburg, 2013.
[12] G. Chahine, P. Smith, R. Kovacevic. Application of topology optimization in modern additive manufacturing. Proceedings of Solid Freeform Fabrication (SFF) Symposium, Austin, TX, 2010.
[13] U. Maheshwaraa, C. C. Seepersad, D. Bourell. Topology design and freeform fabrication of deployable structures with lattice skins. Proceedings of Solid Freeform Fabrication (SFF) Symposium, Austin, TX, 2007.
[14] N. P. Fey, B. J. South, C. C. Seepersad, R. R. Neptune. Topology optimization and freeform fabrication framework for developing prosthetic feet. Proceedings of Solid Freeform Fabrication (SFF) Symposium, Austin, TX, 2009.
[15] A. Aremu, I. Ashcroft, R. Hague, R. Wildman, C. Tuck. Suitability of SIMP and BESO topology optimization algorithms for additive manufacture. Proceedings of Solid Freeform Fabrication (SFF) Symposium, Austin, TX, 2010.
[16] E. Biyikli, A. C. To. Proportional topology optimization: a new non-gradient method for solving stress constrained and minimum compliance problems and its implementation in MATLAB. Computational Engineering, Finance, and Science. 12(2015): e0145041.
[17] http://www.industrial-lasers.com/articles/print/volume-29/issue-3/departments/updates/first-metal-3d-printed-bicycle-frame-manufactured.html. Accessed June 2016.
[18] W. Gu. On challenges and solutions of topology optimization for aerospace structural design. 10th World Congress on Structural and Multidisciplinary Optimization. Orlando, FL, 2013.
[19] T. E. Burns. Topology optimization of convection-dominated, steady-state heat transfer problems. International Journal of Heat and Mass Transfer. 50(2007): 2859-2873.
[20] L. J. Gibson, M. F. Ashby. Cellular Solids: Structure and Properties. 2nd Edn. Cambridge University Press, 1997.

[21] M. F. Asbhy, A. G. Evans, N. A. Fleck, L. J. Gibson, J. W. Hutchinson, H. N. G. Wadley. Metal Foams: A Design Guide. Butterworth Heinemann, 2000.
[22] T. J. Lu, H. A. Stone, M. F. Ashby. Heat transfer in open-cell metal foams. Acta Materialia. 46(1998), 10: 3619-3635.
[23] T. J. Lu. Heat transfer efficiency of metal honeycombs. International Journal of Heat and Mass Transfer. 42(1999): 2031-2040.
[24] F. A. Acosta, A. H. Castillejos, J. M. Almanza, A. Flores. Analysis of liquid flow through ceramic porous media used for molten metal filtration. Metallurgical and materials Transactions B. 26(1995): 159-171.
[25] Wolfram Mathworld. http://mathworld.wolfram.com/Space-FillingPolyhedron.html. Accessed June 2016.
[26] L. Yang. Experimental-assisted design development for an octahedral cellular structure using additive manufacturing. Rapid Prototyping Journal. 21(2015), 2: 168-176.
[27] L. Yang. Design, Structural Design, Optimization and Application of 3D Re-entrant Auxetic Structures. PhD Dissertation, North Carolina State University. Raleigh, NC, USA, 2011.
[28] L. Yang, O. Harrysson, H. West, D. Cormier. Mechanical properties of 3D re-entrant honeycomb auxetic structures realized via additive manufacturing. International Journal of Solids and Structures. 69-70(2015): 475-490.
[29] P. R. Onck. E. W. Andrews, L. J. Gibson. Size effects in ductile cellular solids. Pat I: modeling. International Journal of Mechanical Sciences. 43(2001): 681-699.
[30] E. W. Andrews, G. Gioux, P. Onck, L. J. Gibson. Size effects in ductile cellular solids. Part II: experimental results. International Journal of Mechanical Sciences. 43(2001): 701-713.
[31] L. Yang. A study about size effects of 3D periodic cellular structures. Proceedings of Solid Freeform Fabrication (SFF) Symposium, Austin, TX, 2016.
[32] D. A. Hollander, M. von Walter, T. Wirtz, R. Sellei, B. Schmidt-Rohlfing, O. Paar, H.-J. Erli. Structural, mechanical and in vitro characterization of individually structured Ti-6Al-4V produced by direct laser forming. Biomaterials 27(2006): 955-963
[33] R. Stamp, P. Fox, W. O'Neill, E. Jones, C. Sutcliffe. The development of a scanning strategy for the manufacture of porous biomaterials by selective laser melting. Journal of Materials Science: Materials in Medicine. 20(2009): 1839-1848.
[34] W. Brooks, C. Sutcliffe, W. Cantwell, P. Fox, J. Todd, R. Mines. Rapid design and manufacture of ultralight cellular materials. Proceedings of Solid Freeform Fabrication (SFF) Symposium. Austin, Texas, 2005.
[35] S. Tsopanos, R. A. W. Mines, S. McKown, Y. Shen, W. J. Cantwell, W. Brooks, C. J. Sutcliffe. The Influence of Processing Parameters on the Mechanical Properties of Selectively Laser Melted Stainless Steel Microlattice Structures. Journal of Manufacturing Science and Engineering. 132(2010): 041011.
[36] L. Yang, H. Gong, S. Dilip, B. Stucker. An investigation of thin feature generation in direct metal laser sintering systems. Proceedings of Solid Freeform Fabrication (SFF) Symposium. Austin, Texas, 2014.

[37] O. Harrysson, O. Cansizoglu, D. J. Marcellin-Little, D. R. Cormier, H. A. West II. Direct metal fabrication of titanium implants with tailored materials and mechanical properties using electron bea melting technology. Materials Science and Engineering C. 28(2008): 366-373.
[38] O. Cansizoglu. Mesh structures with tailored properties and applications in hips stems. PhD Dissertation, North Carolina State University, Raleigh, NC, 2008.
[39] S. Zhang, S. Dilip, L. Yang, H. Miyanaji, B. Stucker. Property evaluation of metal cellular strut structures via powder bed fusion AM. Proceedings of Solid Freeform Fabrication (SFF) Symposium. Austin, Texas, 2015.
[40] L. Yang, O. Harrysson, H. West II, D. Cormier. Design and characterization of orthotropic re-entrant auxetic structures made via EBM using Ti6Al4V and pure copper. Proceedings Solid Freeform Fabrication (SFF) Symposium. Austin, Texas, 2011.
[41] S. J. Li, L. E. Murr, X. Y. Cheng, Z. B. Zhang, Y. L. Hao, R. Yang, F. Medina, R. B. Wicker. Compression fatigue behavior of Ti-6Al-4V mesh arrays fabricated by electron beam melting. Acta Materialia. 60(2012): 793-802.
[42] P. Edwards, M. Ramulu. Fatigue performance evaluation of selective laser melted Ti-6Al-4V. Materials Science and Engineering A. 598(2014): 327-337.
[43] H. Gong, K. Rafi, T. Starr, B. Stucker. Effect of defects on fatigue tests of as-built Ti-6Al-4V parts fabricated by selective laser melting. Proceedings of Solid Freeform Fabrication (SFF) Symposium. Austin, Texas, 2012.
[44] L. E. Murr, S. M. Gaytan, F. medina, E. Martinez, J. L. Martinez, D. H. Hernandez, B. I. Machado, D. A. Ramirez, R. B. Wicker. Characterization of Ti-6Al-4V open cellular foams fabricated by additive manufacturing using electron beam melting. Materials Science and Engineering A. 527(2010): 1861-1868.
[45] R. Stamp, P. Fox, W. O'Neill, E. Jones, C. Sutcliffe. The development of a scanning strategy for the manufacture of porous biomaterials by selective laser melting. Journal of Materials Science: Materials in Medicine. 20(2009): 1839-1848.