

Design of Mechanical Properties of Open-Cell Porous Materials Based on μ CT Study of Commercial Foams

Jakub Skibinski^a, Karol Cwieka, Tomasz Wejrzanowski and Krzysztof J. Kurzydowski

Faculty of Materials Science and Technology, Warsaw University of Technology, Poland

Abstract. In the present paper numerical design of mechanical properties of open-cell porous materials is addressed. A detailed knowledge of mechanisms and parameters determining mechanical properties (i.e. Young's Modulus, Poisson's Ratio) of foams is essential for applications such as energy absorbers or lightweight construction materials. The foam structures were designed using procedure based on Laguerre-Voronoi tessellations (LVT) with micro-computed tomography of commercial foams used as reference. Foam morphology was studied on post-processed computed tomography images and the parameters of LVT structures were compared with commercial materials. Subsequently finite element method (FEM) calculations were performed on both types of structures to validate the LVT design algorithm. The results show that the described design procedure can be successfully used for modeling mechanical properties of open-cell foam structures.

1 Introduction

Open porosity foams are multifunctional materials due to their unique properties combining high specific strength and stiffness [1,2] with light weight and excellent energy absorption [3,4]. Structural parameters of commercially available foams such as porosity, specific surface, mean strut diameter and mean pore diameter are commonly studied with use of μ CT [5-9]. Furthermore Open-Cell Porous Materials could imitate various natural materials where porosity is key parameter for structural characteristic [10,11]. On the other hand, determining of elastic properties, i.e. Young's modulus and Poisson's ratio, is a more complex process. Extensive research performed in recent years in this area includes experimental [12,13], analytical [14] and numerical [15,16] approaches. Numerical analysis uses both simplified model structures, and calculation models derived from X-ray micro-computed tomography (μ CT) data [17].

Most of geometrical models proposed in literature base on the assumption of equal volume of pores of different shapes [18-23]. In commercial practice foams are very frequently manufactured with narrow pore size distributions, which was confirmed by experimental observations [24]. Good approximation of such distribution can be obtained using Laguerre-Voronoi algorithm [25], where tessellations are performed on a set of spheres with pre-determined size distribution.

The aim of present work was to investigate utility of LVT for design of mechanical properties of open-cell foams. To this end, a set of porous structures with homogeneous pore size distribution was generated using

Laguerre-Voronoi tessellations. Elastic properties of these structure were calculated using finite element method. Validation of the LVT algorithm was performed by comparing Young's modulus and Poisson's ratio obtained for the modeled structures with values calculated for commercial foam materials.

2 Materials and methods

The design algorithm developed to model foam structures is based on the Laguerre-Voronoi tessellations method [24]. Tessellations are applied to a set of spheres, with specified size distributions, packed in a cube. The foam struts were generated by placing cylinders with defined radius along the cell edges. Utility of LVT for modeling of structure of open-cell foams was described in [26].

The algorithm for the modeling of foam structures employed in the present study consists of the following five steps:

1. Generation of spheres with a defined size distribution (in the computation log-normal distribution of volume was adopted with a pre-selected average value, and the variation coefficient)
2. Packing of the spheres,
3. Performing Laguerre-Voronoi tessellations,
4. Defining the triple edges of the cellular structure, and
5. Generation of struts along the triple edges.

Four random structures with homogeneous pore size distribution were generated using the procedure described above. Each structure was limited by a bounding box of cubic shape and consisted of 200 pores. For each structure strut diameter values were varied from 0.5 to

^a Corresponding author: j.skibinski@inmat.pw.edu.pl

2.0 mm, which resulted in porosity ranging from 74 to 97%.

Reference structures used in this study were commercially available aluminum foam specimens with nominal pore densities 10, 20, 30, 40 and 50 pores per inch. Micro-computed tomography was used to investigate structural parameters of reference materials. The three dimensional image acquisition was performed using X-Radia XCT-400 made by SkyScan under acceleration voltage of 150kV and current of 50A, which assured a voxel resolution in the range from 15 to 45 $\mu\text{m}/\text{voxel}$. 3D structural analysis was performed using SkyScan cTAN software. First, a median filter was used to remove the noise.

Numerical analysis of elastic properties of both designed structures and commercial materials was performed using finite element method implemented in ANSYS software. Finite element meshes were generated in order to perform numerical simulations corresponding to uniaxial compression tests. Examples of meshes generated on both LVT structures and commercial foam materials are shown on Fig. 1.

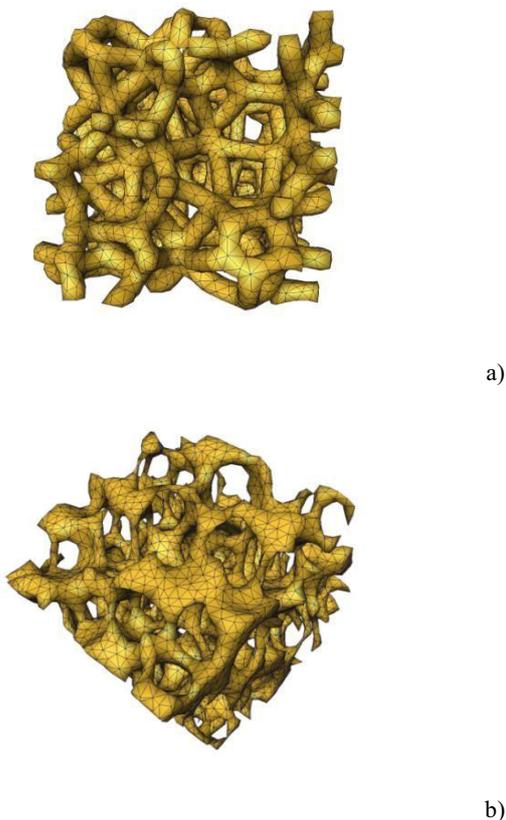


Figure 1. Example of meshed geometrical models for FEM analysis: a) LVT structures, b) μCT reconstructed commercial material.

Ideal elastic material model for matrix has been defined by following sets of isotropic Young's modulus and Poisson's ratio of $E=69\text{GPa}$, $\nu=0.33$ for aluminum. Investigated structures were subjected to numerical simulations of uniaxial compression. Each model was constrained on two nodal components located at the opposite sides – zero displacement at the bottom and displacement equal to 0.1% of initial edge length at the

top. Additionally one of the nodes from the bottom was constrained in three directions (u_x , u_y and u_z displacement were fixed). The value of macroscopic engineering stresses has been evaluated as a quotient of the sum of the nodal reaction forces ΣF_n divided by initial engineering cross-section area $A=a^2$.

$$\sigma = \frac{\Sigma F_n}{A} = \frac{\Sigma F_n}{a^2}. \quad (1)$$

The engineering strain values were obtained by dividing applied displacement by initial height of the computed structure.

3 Results and discussion

Complete set of structural parameters of both designed and commercial materials is listed in Table 1. The data for commercial foams does not refer to the entire specimen, because the scanning process could not cover the entire sample. Serious disturbances occurred on the borders of measured specimens. Additionally, the total scanned volume was related to the scanning resolution. 10 and 20 ppi foam scans were performed with resolution of 45 μm and resulted in a cubic shaped geometry of 35 mm edge length. Such resolution is sufficient for obtaining precise representation of complex foam geometry, and the obtained sample size seems sufficient to be treated as representative regarding the mean pore size of foams. The 30 ppi foam was scanned at 25 μm resolution (obtained edge length of 25 mm) due to smaller size of struts for this structure. 40 and 50 ppi foams required scanning resolution of 12 μm , because scans with lower resolution exhibited distorted foam topology. The obtained edge length of these foams was 15 mm.

Obtained structural parameters of commercial foam materials are in good agreement with literature data [8,17,27]. One of the most decisive parameters determining Young's modulus of porous materials is porosity, therefore LVT structures with mean strut diameter of 2 mm were chosen as correlated the closest to the reference materials. It has to be noted, that specific surface is significantly lower in case of the designed materials. This discrepancy can be assigned to different nature of triple point connections. Thicker triple point connections were observed in case of commercial materials.

Mechanical properties calculated using finite element method are listed in Table 2. Both designed and commercial open-cell foam structures are characterized by randomly distributed cells, therefore calculations were performed in 3 perpendicular directions. Anisotropy was detected for each specimen, however for purpose of comparison, average values from three directions is listed in Table 2, since anisotropy of properties is a subject of separate study.

Table 1. Structural parameters of LVT structures and commercial foam materials.

Structure	Porosity [%]	Specific surface Sv [1/mm]	Mean strut diameter [mm]	Mean pore diameter [mm]
Commercial 10 ppi	74,01	0,779	1,37	3,53
Commercial 20 ppi	71,82	1,132	1,21	2,29
Commercial 30 ppi	72,22	1,227	0,89	2,08
Commercial 40 ppi	73,62	1,448	0,52	1,63
Commercial 50 ppi	75,42	1,847	0,45	1,16
LVT No 1	73,96	0,42	2,00	1,64
LVT No 2	74,19	0,416	2,00	1,64
LVT No 3	73,76	0,423	2,00	1,62
LVT No 4	73,83	0,415	2,00	1,64
LVT No 1	83,51	0,367	1,50	1,95
LVT No 2	83,66	0,364	1,50	1,95
LVT No 3	83,38	0,37	1,50	1,93
LVT No 4	83,27	0,367	1,50	1,93
LVT No 1	91,78	0,285	1,00	2,22
LVT No 2	91,85	0,283	1,00	2,22
LVT No 3	91,71	0,288	1,00	2,21
LVT No 4	91,56	0,29	1,00	2,22
LVT No 1	97,7	0,161	0,50	2,41
LVT No 2	97,72	0,159	0,50	2,41
LVT No 3	97,72	0,159	0,50	2,40
LVT No 4	97,62	0,161	0,50	2,41

The results obtained for commercial foam materials are in accordance with data reported in literature for similar structures [8,17,28]. Mechanical properties of all the designed structures were calculated, however due to similarity of structural parameters explained above, only results for LVT materials with strut diameter of 2 mm will be discussed in comparison with commercial foam materials. Similar values of both Young's modulus and Poisson's ratio were obtained for the designed materials and reference commercial foams with similar structural parameters. Results obtained were considered as a validation of LVT algorithm for design of mechanical properties of open-cell porous materials.

4 Summary

We used the Laguerre-Voronoi algorithm and the finite element method as a tool for design of open-cell foam structures with defined structural parameters and mechanical properties. The design procedure developed was used to create a set of structures with structural parameters corresponding to commercial aluminum foam materials. Results verified the utility of LVT algorithm

for modeling of mechanical properties of foams. The described findings allow for studying the influence of various structural parameters, such as pore size distribution, strut shape or pore diameter, on Young's modulus and Poisson's ratio with use of the described design method.

Acknowledgment

The work was financially supported by the National Centre for Research and Development, contract no. BG1/GASLUPSEJSM/13.

Table 2. Mechanical properties of LVT structures and commercial foam materials.

Structure	Young's modulus [Gpa]	Poisson's ratio	Mean strut diameter [mm]
Commercial 10 ppi	7,25	0,25	1,37
Commercial 20 ppi	7,39	0,22	1,21
Commercial 30 ppi	7,99	0,24	0,89
Commercial 40 ppi	4,95	0,21	0,52
Commercial 50 ppi	5,44	0,20	0,45
LVT No 1	5,27	0,28	2,00
LVT No 2	4,98	0,28	2,00
LVT No 3	5,25	0,28	2,00
LVT No 4	5,31	0,27	2,00
LVT No 1	2,06	0,33	1,50
LVT No 2	1,96	0,32	1,50
LVT No 3	2,06	0,33	1,50
LVT No 4	2,12	0,32	1,50
LVT No 1	0,54	0,37	1,00
LVT No 2	0,5	0,38	1,00
LVT No 3	0,52	0,38	1,00
LVT No 4	0,54	0,37	1,00
LVT No 1	0,04	0,44	0,50
LVT No 2	0,04	0,43	0,50
LVT No 3	0,04	0,43	0,50
LVT No 4	0,04	0,43	0,50

References

1. J. Banhart, Manufacture, characterization and application of cellular metals and metal foams, Progress in Materials Science Volume 46, Issue 6, p. 557-632 (2001)
2. M.F. Ashby, A.G. Evans, N.A. Fleck, L.J. Gibson, J.W. Hutchinson, H.N.G. Wadley, Properties of Metal Foams, Butterworth-Heinemann, Burlington, MA (2000)
3. I.S. Golovin, H.R. Sinning, Internal friction in metallic foams and some related cellular structures, Materials Science and Engineering: A 370 (1), 504-511 (2004)
4. T. Fiedler, E. Solorzano, F. Garcia-Moreno, A. Öchsner, I.V. Belova and G.E. Murch, Computed Tomography Based Finite Element Analysis of the Thermal Properties of Cellular Aluminium, Materials Science and Engineering Technology 40, p. 139-143 (2009)
5. W. Regulski, J. Szumbariski, L. Wollk-Laniewski, K. Gumowski, J. Skibinski, M. Wichrowski, T. Wejrzanowski, Pressure drop in flow across ceramic foams – A numerical and experimental study, Chemical Engineering Science, Volume 137, p. 320-33 (2015)
6. C. Veyhl, I.V. Belova, G.E. Murch, T. Fiedler, Finite element analysis of the mechanical properties of cellular aluminium based on micro-computed tomography, Materials Science and Engineering A, Volume 528, Issues 13-14 p. 4550-4555 (2011)
7. A.M. Parvanian, M. Saadatfar, M. Panjepour, A. Kingston, A.P. Sheppard, The effects of manufacturing parameters on geometrical and mechanical properties of copper foams produced by space holder technique, Materials and Design Volume 53, p. 681-690 (2014)
8. N. Taherishargh N., M.A. Sulong M.A., I.V. Belova I.V., G.E. Murch G.E., T. Fiedler T., On the particle size effect in expanded perlite aluminium syntactic foam, Materials and Design Volume 66, pages 294-303 (2015)
9. J. Skibinski, T. Wejrzanowski, J. Szumbariski, K.J. Kurzydłowski, Computational design of the flow properties of foams, WIT Transactions on Engineering Sciences, Vol 74 p. 109-118, ISBN 978-1-84564-6004 (2012)
10. W.Y. Jang, S. Kyriakides, On the crushing of aluminum open-cell foams: Part I. Experiments, International Journal of Solids and Structures 46 (3) p. 617-634 (2009)
11. L. Kaczmarek, G. Machowski, M. Maksimczuk, T. Wejrzanowski 2015 – The use of high-resolution X-ray computed microtomography in structural

- analysis of the Miocene sandstones of the Carpathian Foredeep (in Polish with English summary). *Nafta-Gaz* 9, p. 15-22 (2015).
12. L. Kaczmarek, m. Maksimczuk, t. Wejrzanowski, a. Krzyzak, High-resolution X-ray microtomography and nuclear magnetic resonance study of a carbonate reservoir rock, 15th International Multidisciplinary Scientific GeoConference SGEM 2015, ISBN 978-619-7105-31-5/ISSN 1314-2704, June 18-24, 2015, Book1 Vol. 1, 779-786 pp,
 13. X. Badiche, S. Forest, T. Guibert, Y. Bienvenu, J.D. Bartout, P. Ienny, M. Croset, H. Bernet, Mechanical properties and non-homogeneous deformation of open-cell nickel foams: Application of the mechanics of cellular solids and of porous materials, *Materials Science and Engineering A* 289p. 276-288 (2000)
 14. H.X. Zhu, J.F. Knott, N.J. Mills, Analysis of the elastic properties of open-cell foams with tetrakaidecahedral cells, *Journal of the Mechanics and Physics of Solids* 45 (3), p. 319-343 (1997)
 15. C. Veyhl, I.V. Belova, G.E. Murch, T. Fiedler, Finite element analysis of the mechanical properties of cellular aluminium based on micro-computed tomography, *Materials Science and Engineering A* 528, p. 4550-4555 (2011)
 16. Y. An, C.E. Wen, P.D. Hodgson, C. Yang, Investigation of cell shape effect on the mechanical behavior of open-cell metal foams, *Computational Materials Science* 55, p. 1-9 (2012)
 17. T. Fiedler, I.V. Belova, G.E. Murch, μ -CT-based finite element analysis on imperfections in open-celled metal foam: Mechanical properties', *Scripta Materialia*, 67 455-458 (2012)
 18. Lord Kelvin (Sir William Thomson), On the division of space with minimum partitioned area, *Philosophical Magazine* 24 (151), p. 503-514 (1887)
 19. H.X. Zhu, J.F. Knott, N.J. Mills, Analysis of the elastic properties of open-cell foams with tetrakaidecahedral cells, *Journal of Mechanics and Physics of Solids* 45, p. 319-343 (1997)
 20. W.E. Warren, A.M. Krayniki, Linear elastic behavior of a low density Kelvin foam with open cells, *Journal of Applied Mechachnics* 64, p. 787-794 (1997)
 21. J.L. Grenestedt, Effective elastic behavior of some models for 'perfect' cellular solids, *International Journal of Solids and Structures* 36, p. 1471-1501 (1999)
 22. R.M. Christensen, Mechanics of cellular and other low density materials, *International Journal of Solids and Structures* 37, p. 94-104 (2000)
 23. I.Ch. Konstantinidis, S.A. Tsipas, Symmetry effects and their influence on the mechanical behavior of open and closed cell Al foams, *Materials & Design* 31, p. 4490-4495 (2010)
 24. C. Lautensack, T. Sych, 3D image analysis of open foams using random tessellations, *Image Analysis and Stereology* 25, p. 87-93 (2006)
 25. Z. Fan, Y. Wu, X. Zhao, Y. Lu, Simulation of polycrystalline structure with Voronoi diagram in Laguerre geometry based on random closed packing of spheres, *Computational Materials Science* 29, p. 301-308 (2004)
 26. J. Skibinski, K. Cwieka, T. Kowalkowski, B. Wysocki, T. Wejrzanowski, K. J. Kurzydowski, The influence of pore size variation on the pressure drop in open-cell foams, *Materials and Design* 87 (2015) pp. 650-655
 27. T. Wejrzanowski, J. Skibinski, J. Szumbariski, K.J. Kurzydowski, Structure of foams modeled by Laguerre-Voronoi tessellations, *Computational Materials Science* 67, p. 216-221 (2013)
 28. J. Groß e, B. Dietrich, G.I. Garrido, P. Habisreuther, N. Zarzalis, H. Martin, M. Kind, B. Kraushaar-Czarnetzki, Morphological characterization of ceramic sponges for applications in chemical engineering, *Industrial & Engineering Chemistry Research* 48 (23) p. 10395-10401 (2009).