www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 58 2013 Issue 4
DOI: 10.2478/amm-2013-0154

M. NOWAK*, Z. NOWAK*, R.B. PĘCHERSKI*, M. POTOCZEK**, R.E. ŚLIWA**

ON THE RECONSTRUCTION METHOD OF CERAMIC FOAM STRUCTURES AND THE METHODOLOGY OF YOUNG MODULUS DETERMINATION

METODA REKONSTRUKCJI STRUKTUR GEOMETRYCZNYCH PIANEK CERAMICZNYCH ORAZ METODOLOGIA OKREŚLANIA MODUŁU YOUNGA

In the present paper a finite element model was used to investigate the mechanical properties such as Young's modulus of open-cell ceramic foam. Finite element discretization was derived from real foam specimen by computer tomography images. The generated 3D geometry of the ceramic foam was used to simulate deformation process under compression. The own numerical procedure was developed to control finite element mesh density by changing the element size. Several numerical simulations of compression test have been carried out using commercial finite element code ABAQUS. The size of the ceramic specimen and the density of finite element mesh were examined. The influence of type and size of finite element on the value of Young's modulus was studied, as well. The obtained numerical results have been compared with the results of experimental investigations carried out by Ortega [11]. It is shown that numerical results are in close agreement with experiment. It appears also that the dependency of Young's modulus of ceramic foam on density of finite element mesh cannot be ignored.
Keywords: foams, 3D image analysis, cellular ceramics, FE modeling, porous alumina, mechanical properties

W pracy przedstawiono metodę określania własności mechanicznych np. modułu Younga porowatych pianek ceramicznych o otwartych komórkach. Wykorzystując obrazy z tomografii komputerowej rzeczywistej struktury pianki otrzymano siatkę elementów skończonych. Przestrzenny obraz geometrii pianki wykorzystano do symulacji numerycznej procesu deformacji w próbie ściskania. Opracowano własną procedurę numeryczną do generowania elementów skończonych o różnej wielkości i kontroli gęstości siatki elementów. Przeprowadzono szereg symulacji numerycznych procesu ściskania pianek z wykorzystaniem programu elementów skończonych ABAQUS. Ustalono wpływ rodzaju i wielkości elementów skończonych jak również wielkości samej próbki na wartość modułu Younga wyliczonego dla próby jednoosiowego ściskania. Otrzymane numerycznie wartości modułów Younga porównano z wartościami z doświadczeń opublikowanych w pracy Ortegi [11]. Otrzymane rezultaty z symulacji numerycznych są w dobrej zgodności z doświadczeniem. Ustalono, że wartości modułu Younga dla porowatych pianek ceramicznych zależy od gęstości siatki elementów skończonych i nie może być pomijana.

1. Introduction

More recently, interest has arisen in composites where both phases are continuous, resulting in an interpenetrating microstructure. One method to achieve such a structure is the infiltration of a molten metal into a porous ceramic body called a preform. In order to obtain the porous alumina material (α-Al_2O_3) a new method of manufacturing known as "gelcasting of foams" was applied, cf. Potoczek [1]. For better understanding of the mechanical properties of such composites the numerical simulations with use of the appropriate model of composite material should be conducted. According to the authors' knowledge, there is lack of such models in the literature. As a first step, the numerical model of ceramic preform has been investigated.

The 3D geometry has main influence on the mechanical behavior of porous materials. The relation between structure and properties in cellular materials is very difficult to determine due to the complex structure. There are several ways to build numerical model of such a material. One of them, which are studied in this paper, is to use computer tomography images [2, 3, 4, 5]. Another way is to model 3D geometry by using powerful CAD software package which allows user to write special script for capturing real topology of the foam [6]. There are also several methods which are based on unit cell models [7, 8, 9, and 10].

2. Construction of the image-based numerical model

The cellular ceramic investigated in this work is open-cell alumina foam manufactured by gelcasting. It offers the relative densities from 0.5 to 0.9. The foam is composed of approximately spherical cells interconnected by circular windows. The

* INSTITUTE OF FUNDAMENTAL TECHNOLOGICAL RESEARCH, POLISH ACADEMY OF SCIENCES, A. PAWIŃSKIEGO 5B, 02-106 WARSAW, POLAND
** RZESZÓW UNIVERSITY OF TECHNOLOGY, POWSTAŃCÓW WARSZAWY 8, 35-959 RZESZÓW, POLAND

cell wall material is Al_2O_3. In order to build numerical model, the real sample foam with 86% porosity has been investigated. The most common method of geometry reconstruction of ceramic foams is to use tomography images of foam structure. The typical cross-section image of this material is shown in Fig. 1.

The first step in numerical modeling is to convert each of the cross-section images to black and white images and then to binary images. Now the Fig. 2 shows the same cross-section image as in Fig. 1 after the binarization process (separation of voids and matrix phases). The Al_2O_3 material distribution is represented by white color.

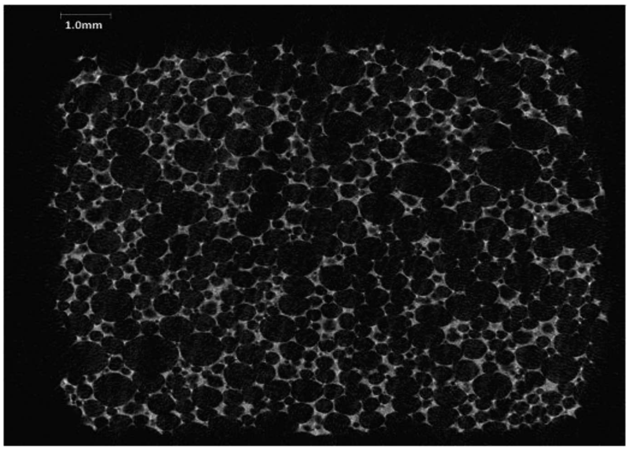

Fig. 1. Cross-section image of the real ceramic foam Al_2O_3 sample with 86% porosity

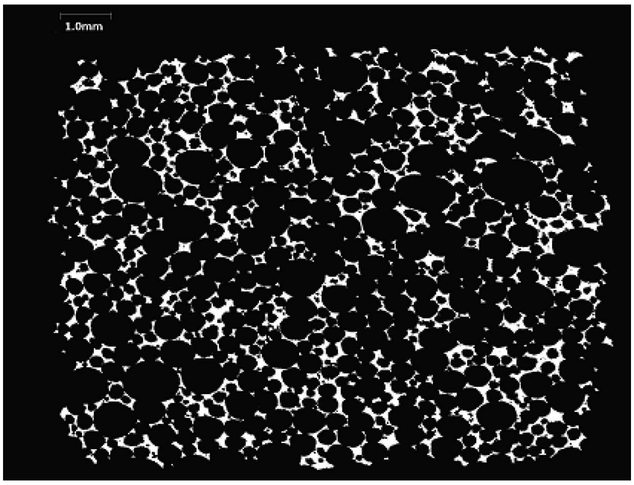

Fig. 2. Cross-section image of the ceramic foam sample with 86% porosity after binarization process. White color represents Al_2O_3 material

Then the voxel structure of the tomographic information is transformed into mesh of cubic elements by using PYTHON script in ABAQUS/CAE finite element program. The size of finite elements can be different depending on number of voxels they consist of. One voxel has approximately size of 8μm. Eight types of element sizes are presented in Fig. 3a. For instance, finite element type C consists of 27 voxels, so its dimensions are equal to 3×3×3 voxels. The part of generated finite element mesh based on element type A is shown in Figure 3b.

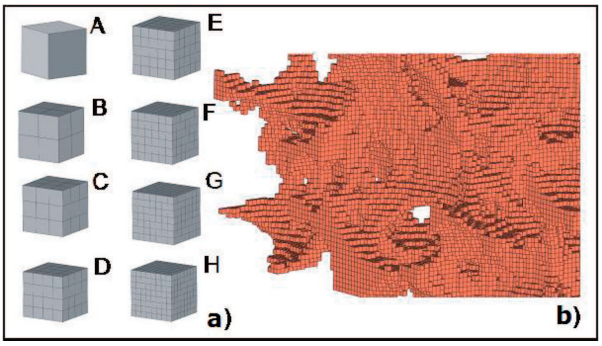

Fig. 3. (a) The finite elements based on different number of voxels, the elements A, B,..., H represent 1^3, 2^3,..., 8^3 voxels respectively, (b) the part of view for generated finite element mesh with element size A

3. Finite element model

In numerical simulation the representative volume element (RVE) size is changed and constructed from a cube with different sides. For each RVE boundary conditions were applied to the top and bottom faces (cp. Fig. 4, 5, 6). All degree of freedom of the bottom face were locked, and the vertical displacement of magnitude equal to 1% of foam height was applied to the top face. The material of cell wall was assumed isotropic and the Young's modulus and Posisson's ration of AL_2O_3 were evaluated to be 370 GPa and 0.22, respectively. The calculations of the FEM simulation were carried out on eight-core personal computer, working at 2.6 GHz, with 12 GB RAM.

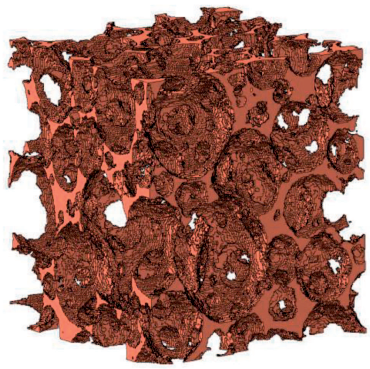

Fig. 4. Finite element model of ceramic foam (2×2×2 mm) created by using element of size A

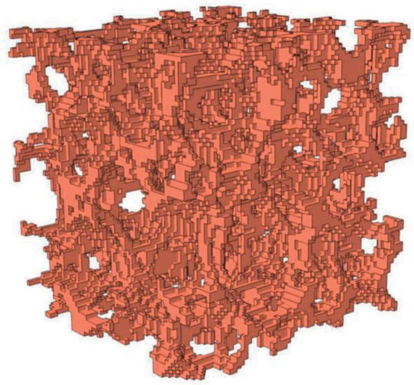

Fig. 5. Finite element model of ceramic foam (2×2×2mm) created by using element of size B

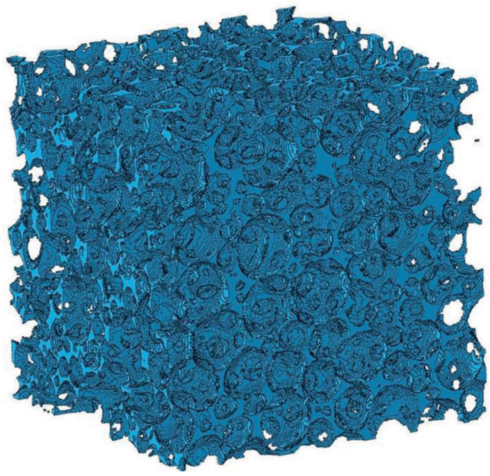

Fig. 6. Finite element model of ceramic foam (4×4×4 mm) created by using element of size A

4. Numerical results and discussion

Three types of RVE were examined. All of them have cubic shape but different sides (different number of voxels). The first RVE has dimensions equal to 2×2×2 mm, the second one 4×4×4 mm, and the third one 6×6×6 mm. For each of the RVE porosity variation, number of elements and number of degree of freedom (DOF) were calculated depending on type of element size (see Fig. 7, 8, 9). In our numerical simulations

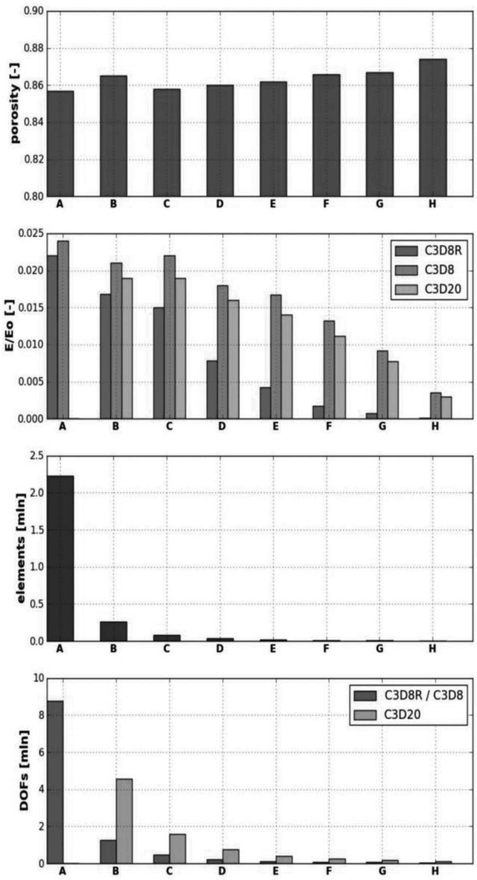

Fig. 7. Numerical results for porosity, relative Young's modulus, number of elements and DOF as a function of different element size. The dimensions of the foam cube are 2×2×2 mm

three types of finite elements were used (in ABAQUS element notation): linear cubic element (C3D8), linear cubic element with reduced integration (C3D8R) and quadratic cubic element (C3D20).

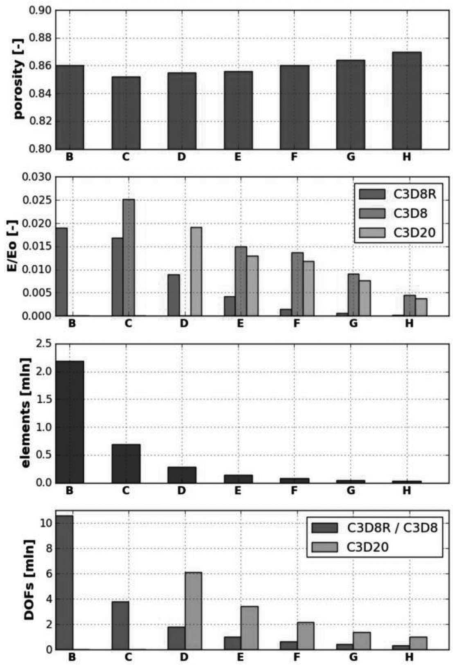

Fig. 8. Numerical results for porosity, relative Young's modulus, number of elements and DOF as a function of different element size. The dimensions of the foam cube are 4×4×4 mm

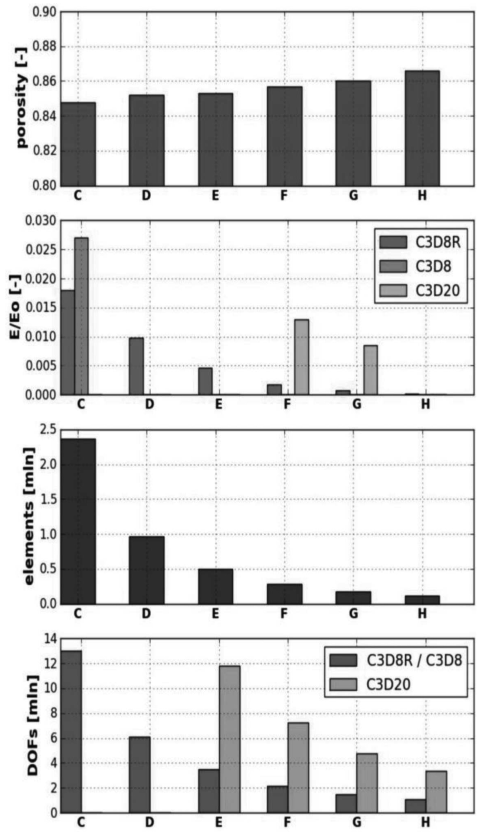

Fig. 9. Numerical results for porosity, relative Young's modulus, number of elements and DOF as a function of different element size. The dimensions of the foam cube are 6×6×6 mm

Compressive Young's modulus from the nominal stress (F/A_0) and engineering strain ($\Delta L/L_0$) was estimated. The same ceramics foams were investigated experimentally by Ortega [11]. The author of this paper measured Young's modulus for different porous Al_2O_3 foams. The experimental value of relative Young's modulus (E/E_0) for ceramic foam with 86% porosity is equal to 0.027. Fig. 7-9 show, that the numerical values of relative Young's modulus are different with respect to size and type of finite element. For the element of size A, the numerical value of relative Young's modulus is very close to the value from experiment.

5. Conclusions

The Young's modulus value of open-cell ceramic foam was investigated in this work. Three-dimensional model based on tomography images and accounting for different element size was developed. Several numerical simulations were performed in order to determine influence of finite element size, type and the size of RVE on the value of Young's modulus. The numerical results show strong dependency on those quantities. The obtained numerical value of Young's modulus in compression test for the element type A is close to the value which was obtained from experiment.

Acknowledgements

Financial support of Structural Funds in the Operational Program – Innovative Economy (IE OP) financed from the European Regional Development Fund – Project "Modern material technologies in aerospace industry", Nr POIG.01.01.02-00-015/08-00 is gratefully acknowledged.

REFERENCES

[1] M. Potoczek, Gelcasting of alumina foams using agarose solutions, Ceramics International **34**, 661-667 (2008).

[2] N. Michailidis, F. Stergioudi, H. Omar, D. Tsipas, FEM modeling of the response of porous Al in compression, Computational Materials Science **48**, 282-286 (2010).

[3] M. Panico, L.C. Brinson, Computational modeling of porous shape memory alloys, International Journal of Solids and Structures **45**, 5613-5626 (2008).

[4] M. Wicklein, K. Thoma, Numerical investigations of the elastic and plastic behaviour of an open-cell aluminium foam, Materials Science and Engineering **397**, 391-399 (2005).

[5] N. Michailidis, F. Stergioudi, H. Omar, D.N. Tsipas, An image-based reconstruction of the 3D geometry of an Al open-cell foam and FEM modeling of the material response, Mechanics of Materials **42**, 142-147 (2010).

[6] M. Kirca, A. Gul, E. Ekinci, F. Yardim, A. Mugan, Computational modeling of micro-cellular carbon foams, Finite Element in Analysis and Design **44**, 45-52 (2007).

[7] Y.X. Gan, C. Chen, Y.P. Shen, Three-dimensional modeling of the mechanical property of linearly elastic open cell foams, International Journal of Solids and Structures **42**, 6628-6642 (2005).

[8] M.H. Luxner, J. Stampfl, H.E. Pettermann, Numerical simulations of 3D open cell structures – influence of structural irregularities on elasto-plastic and deformation localization, International Journal of Solids and Structures **44**, 2990-3003 (2007).

[9] T. Fiedler, A. Ochsner, J. Gracio, G. Kuhn, Structural modeling of the mechanical behavior of periodic cellular solids: open-cell structures, Mechanics of Composite Materials **41**, 3 (2005).

[10] C. Redenbach, Modelling foam structures using random tessellations. Stereology and Image Analysis. Ecs10 – Proceedings of the 10th European Congress of ISS. ESCULAPIO Pub. Co., Bologna, 2009.

[11] F.S. Ortega, J.A. Rodrigues, V.C. Pandolfelli, Elastic Modulus of Gelcast Cellular Ceramics at High Temperatures, American Ceramic Society Bulletin **85**, 9101-9110 (2006).

Received: 20 November 2012.