



How to cite this article:

Authors: Piotr Dziewit, Jacek Janiszewski

Title of article: „Ocena jakościowa procesu deformacji regularnych struktur komórkowych wykonanych techniką druku 3D” („*Mechanik*, Vol. 91, No. 3 (2018): pages 250-252DOI: <https://doi.org/10.17814/mechanik.2018.3.41>

Qualitative evaluation of the deformation process of regular cellular structures manufactured using 3D printing

Ocena jakościowa procesu deformacji regularnych struktur komórkowych wykonanych techniką druku 3D

PIOTR DZIEWIT
JACEK JANISZEWSKI *

Presented are selected experimental results concerning the analysis of the deformation process of regular cellular structures manufactured using 3D printing under quasi-static loading conditions. The various structural topologies were designed and manufactured using the FDM (fused deposition modelling) and then tested in a uniaxial compression test. The starting point for the development of individual variants of structures was the honeycomb topology. In order to analyse the influence of the structure material on the deformation process, the samples were made from three commercially available materials: PC-10, ABSplus and Nylon12. Based on the results, the influence of the shape of the single cell and the type of material used on the deformation of the structure as well as the value of the plastic deformation energy were assessed.

KEYWORDS: regular cellular structures, FDM technique, 3D printing, strength tests, energy absorption, honeycomb, re-entrant honeycomb

Additive manufacturing techniques, commonly known as 3D printing, are among the significant technological advances of the last century. They shape the development of many key sectors of the economy, i.e. in automotive, aerospace, machines, tools and defense. Parts manufactured with additive technologies are also used in medicine, architecture, construction or industrial design. A wide spectrum of available manufacturing techniques in combination with a wide range of building materials allow to obtain specific mechanical properties of the manufactured objects. Fast prototyping techniques provide freedom of geometric design, making possible to obtain a shape that is often hard to manufacture using conventional methods [1-3].

Regular cellular structures are characterized by a topology with a repeating elementary cell. Because of that, it can be assumed that they exhibit isotropic or orthotropic mechanical properties [4]. In addition, they have a low relative density while maintaining high strength properties in comparison with the solid materials from which they are built [5]. Cellular materials are used as a controlled crushing areas in the constructions, vehicles or protective clothing

(e.g. helmets). They are also used as a filling of composite structures (sandwich), which show higher energy consumption than the solid materials with the same mass [6].

In this paper investigations on material and topology influence on the deformation and the ability to absorb deformation energy under quasi-static loading conditions were carried out. Structure samples were loaded with axial force in the in plane direction. For the needs of the research, rectangular structure samples were prepared and then manufactured with 3D printing technology, using the FDM method, from three polymeric materials: acrylonitrile-butadiene-styrene (ABSplus), polycarbonate (PC-10) and polyamide (Nylon12).

Characteristics of cellular material topology used in research

There are many scientific publications concerning the development and testing the strength properties of regular 2D cellular structures with honeycomb topology [5-8]. In this work, the authors focused on the comparison of the deformation process of the honeycomb structure and its derivatives. Fig. 1 shows the honeycomb structure (a) and its modifications (b, c).

In order to compare the influence of the topology on its energy-absorbing properties, the ratio of the values of plastic strain energy E_p to the relative density ρ_r was taken into consideration.

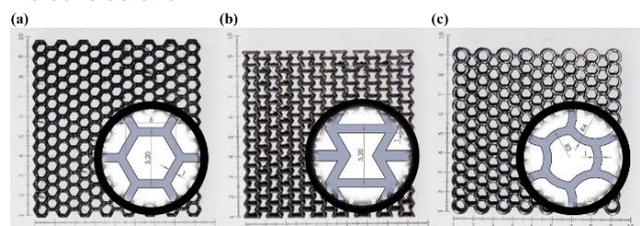


Fig. 1. Frontal profile of regular cellular structures with honeycomb-like topology (a) and its modifications: b) re-entrant honeycomb (auxetic structure), c) rounded honeycomb

At the initial stage of developing geometric models of structures in the CAD environment, the assumptions concerning the dimensions of the elementary cell, the thickness of its wall and the size of the sample were made. In order to ensure deformation process conditions in accordance with the guidelines presented in [9], it was

* Msc Piotr Dziewit (piotr.dzewit@wat.edu.pl), PhD Jacek Janiszewski prof. MUT (jacek.janiszewski@wat.edu.pl) – Institute of Armament Technology, Faculty of Mechatronics and Aviation, Military University of Technology, Poland

assumed that the structure should consist of at least six elementary cells in both axes – X and Y.

The modifications of the honeycomb structure shown in Fig. 1 are characterized by the differential shape of the elemental cell, which determines the value of its relative density. The relative density of a single cell of the analyzed structures is defined as follows:

- **cell of a cubic honeycomb** (fig. 1a):

$$\rho_r = \frac{t(2R + t)}{(R + t)^2}$$

where: t - wall thickness, R - radius of a circle inscribed into a cell; the considered structure model contains 203 cells and is defined by the following parameters: $t = 1$ mm, $R = 2.6$ mm, $\rho_r = 0.30$;

- **cell of an auxetic honeycomb** (fig. 1b):

$$\rho_r = \frac{7t^2 + 16Rt}{6R^2 + 14Rt + 7t^2}$$

– cell model was created as a result of the transformation of the honeycomb structure with the radius $R = 2.6$ mm of the circle inscribed in the cell; the considered structure model contains 188 cells, and its parameters are as follows: $t = 1$ mm, $\rho_r = 0.42$ mm;

- **cell of a rounded honeycomb** (fig. 1c):

$$\rho_r = \frac{\pi(R + t)^2 - \pi R^2}{(R + t)^2 \left[\pi - 3 \left(\frac{\alpha}{360} \pi - \frac{\sin \alpha}{2} \right) \right] + \frac{3R^2 \sqrt{3} - 2\pi R^2}{4}}$$

$$\alpha = \arccos \left(1 - \frac{R^2}{2(R + t)^2} \right)$$

– cell model was created as a result of the transformation of the honeycomb structure and rounding the cell walls to obtain an internal curvature with a radius of $R = 3$ mm; the analyzed structure model contains 188 cells and has been characterized by the following parameters: $t = 1$ mm, $\rho_r = 0.32$ mm.

Characteristics of the process of producing regular cell structures

For samples manufacturing the 3D Dimension SST 1200es and Fortus 900mc (Stratasys Corp.) commercial fast prototyping machines were used. In comparison to commonly available low-cost 3D printers, the Dimension SST 1200es is characterized by a closed working area with an additional heating system, which ensures unchanged temperature conditions and limiting samples contraction during the process [9]. In turn, the Fortus 900mc printer is a professional industrial device that allows to use a wider range of materials compared to 3D Dimension SST 1200es printer.

Methodology of experimental tests in quasi-static conditions

The tests were carried out using a MTS Criterion C45 machine. They were preceded by quasi-static tensile tests to determine the strength properties of base materials used for cellular structures under similar manufacturing conditions. For this purpose the normalized samples were prepared according to the ISO 527-2-1B standard.

The results of the static tensile test are presented in the tab. I.

TABLE I. The properties of the materials used to the manufacture of cellular structure samples (stratasys.com [10], experimental results - red)

Material	Density, g/mm ³	R_m , MPa	E , MPa	A , %
ABSplus (ABS)	1,04	31 (22)	2200 MPa	6% (8%)
Nylon12 (PA)	1,00	46 (37)	1282 MPa	30% (13,5%)
PC-10 (PC)	1,20	57 (47)	1944 MPa	4,8 % (6,7%)

Fig. 2 presents the force-displacement curves for the examined cellular structures, obtained for traverse speed of 1 mm/s. As the main criterion for the structure assessment, the value of plastic strain energy obtained during sample compression was assumed at the level of 40%.

Fig. 2a-b presents the test results obtained for the honeycomb structure - honeycomb (fig. 1a) – made of different the type of material. It can be noticed that in the first deformation stage, the slope of the force-displacement curve correlates with the Young's modulus values of individual materials, where ABS exhibits the highest elasticity (stiffness), while nylon - the smallest. The further stage of the deformation process is characterized by a sudden change in the value of force, which is the result of the progressive destruction of the structure. The number of peaks is directly related to the number of cell rows that collapse under loading. It is worth noting that the polyamide, with high ductility, exhibits gentle process of deformation compared to polycarbonate and ABS. Based on these observations, it can be assumed that the properties of the core material have a explicit influence on the deformation process of the honeycomb structure and together with the increase in the strength of the material, a higher energy absorption capacity of the plastic deformation is obtained.

The second considered variant of the topology was the structure with auxetic properties - re-entrant honeycomb (fig. 1b) - which shows a negative Poisson's ratio [11]. This structure (hexagon with two concave edges) is characterized by very high strength parameters at the first stage of deformation (fig. 2c). This effect results from the large number of elementary cells and the high relative density of the structure, which increases its stiffness. When the load exceeds the critical value, a rapid process of destruction of the cell row occurs, causing a sudden drop in strength. At the next stage of compression of the structures made of ABS and PA, the force-displacement curve is almost linear. This type of topology made from above mentioned materials is mainly deformed by bending, with no clear breaks in material cohesion. In case of polycarbonate (PC) the process of deformation progresses with high changes in force, which is determined by the brittle cracking of the sample. However, regardless of the second stage, the strength parameters of the core material still determine the nature of the structure deformation.

The results of the third variant of topology - rounded honeycomb (fig. 1c) – as in the case of previous topologies, indicate that the stiffness of the structure is determined mainly by the strength of the material. However, the initial force peaks at which the plastic deformation occurs is comparable for all three materials. It may mean that not the tensile strength but the geometry of the structure is responsible for the further process of deformation. In the analyzed case, the tendency to brittle cracking of polycarbonate and ABS structures was confirmed. In the case of polyamide, characterized by greater ductility, the deformation process is characterized by smaller fluctuations of the force. Analyzing the values of the energy needed to deform the tested structures (tab. II), it can be stated that for all three materials they are similar. From this it follows that the structure topology is one of the key factors determining the ability of this structure to absorb deformation energy.

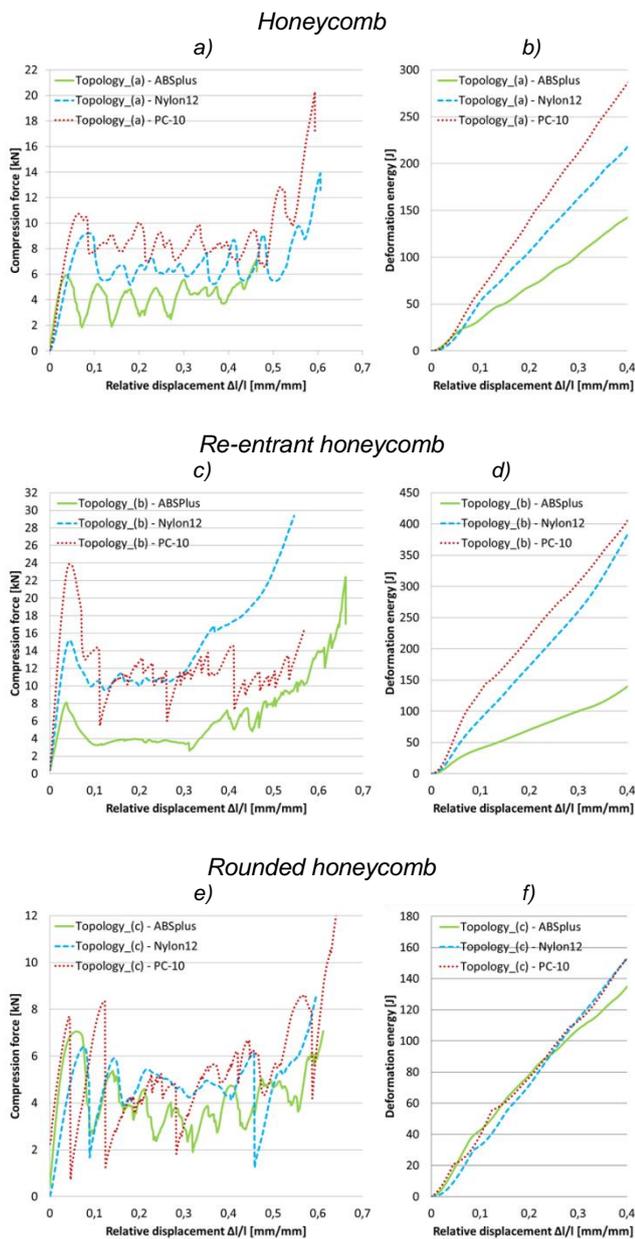


Fig. 2. Curves of deformation force (a, c, e) and plastic deformation energy (b, d, f) in a function of relative displacement of cellular structure in the uniaxial compression test for selected topologies: honeycomb; re-entrant honeycomb; rounded honeycomb

TABLE II. Results of the energy absorption analysis with respect to the relative density for the 5% strain (in brackets, the deformation energy without ρ_r taken into account)

	ABSplus, J	Nylon12, J	PC-10, J
Tensile sample (table I)	23,3	28,5	33,9
Honeycomb (fig. 1a)	72,9 (21,87)	66,4 (19,91)	97,7 (29,3)
Re-entrant honeycomb (fig. 1b)	52,3 (22,0)	96,6 (40,6)	152,9 (64,2)
Rounded honeycomb (fig. 1c)	81,4 (26,04)	51,0 (16,3)	72,0 (23,1)

Conclusions

On the basis of the presented results, it can be stated that the chosen technique of producing structures allows to quickly assess the energy absorption capacity depending on the topology of the structure. The use of three types of materials, significantly differing in mechanical properties, made it possible to formulate a conclusion (what was

expected) that the strength properties of the material used for the structure manufacturing have a significant impact on the maximum value of deformation energy. However, it should be emphasized that the topology is the dominant factor determining the process of structure deformation. Moreover, structures with auxetic properties exhibit small fluctuations in force, while other structures are being destroyed mainly as a result of breaking walls in the nodes of particular cell rows. In addition, it was confirmed that when selecting the structure material for absorbing the impact energy, one should look for a material with high ductility. Thanks to this, the destruction of the structure takes place by bending the walls, and hence, with smaller fluctuations in force (stress).

The authors express gratitude to dr. Eng. Pawel Platek from the Military University of Technology for help in printing cellular structures. The article contains the results of work funded by WML WAT with funds for science in 2017-2018, as a research project No. RMN/718/2017.

REFERENCES

1. Campanelli S.L., Contuzzi N., Ludovico A.D., Caiazzo F., Cardaropoli F., Sergi V. „Manufacturing and characterization of Ti6Al4V lattice components manufactured by selective laser melting”. *Materials*. 7, 6 (2014): p. 4803–4822.
2. Ozdemir Z., Hernandez-Nava E., Tyas A., Warren J.A., Fay S.D., Goodall R., Askes H. “Energy absorption in lattice structures in dynamics: Experiments”. *International Journal of Impact Engineering*. 89 (2016):p. 49–61.
3. Vaezi M., Chianrabutra S., Mellor B., Yang S. “Multiple material additive manufacturing. Part 1: A review: This review paper covers a decade of research on multiple material additive manufacturing technologies which can produce complex geometry parts with different materials”. *Virtual and Physical Prototyping*. 8, 1 (2013): p. 19–50.
4. Babaee S., Jahromi B.H., Ajdari A., Nayeb-Hashemi H., Vaziri A. “Mechanical properties of open-cell rhombic dodecahedron cellular structures”. *Acta Materialia*. 60, 6–7 (2012): p. 2873–2885.
5. Li Yang et al. “Low-energy drop weight performance of cellular sandwich panels”. *Rapid Prototyping Journal* (2005): p.433-442
6. Ajdari A., Nayeb-Hashemi H., Vaziri A. “Dynamic crushing and Energy absorption of regular, irregular and functionally graded cellular structures”. *International Journal of Solids and Structures* (2011): p.506-516
7. Lee J., Huang A. “Fatigue analysis of FDM materials”. *Rapid Prototyping Journal*. 19, 4 (2013): p. 291–299.
8. Hyun S., Torquato S. “Effective elastic and transport properties of regular honeycombs for all densities”. *Journal of Materials Research*. 15, 9 (2000): p. 1985–1993.
9. Lira C., Scarpa F. “Transverse shear stiffness of thickness gradient honeycombs”. *Composites Science and Technology*. 70, 6 (2010): p. 930–936.
10. <http://www.stratasys.com/> (dostęp: 01.09.2017).
11. Yang L., Harrysson O., West H., Cormier D. “Mechanical properties of 3D re-entrant honeycomb auxetic structures realized via additive manufacturing”. *International Journal of Solids and Structures*. 69–70 (2015): p. 475–490. ■

Translation of scientific articles, their computer composition and publishing them on the website www.mechanik.media.pl by original articles in Polish is a task financed from the funds of the Ministry of Science and Higher Education designated for dissemination of science.