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3D PRINTING OF THIN-WALLED MODELS - STATE-OF-ART

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Abstract

The paper presents an analysis of the state of the art regarding the production of thin-walled models using 3D printing technology. Data based on the Web of Science database was presented in quantitative terms and divided into individual areas of science. 189 publications were found in the years from 2013 to 2024, of which the most, i.e. 82 in the area of Mechanical Engineering. It was observed that some of the publications are grouped around issues related to the study of mainly mechanical properties of both samples and thin-walled cellular structures. Another group of works concerns methods of obtaining thin-walled models using 3D printing technologies. The article characterizes selected exemplary works representing individual areas of science. The need to perform tests of the mechanical properties of thin-walled elements, especially those with a thickness of less than 2 mm, was indicated. Appropriate examples were provided to demonstrate the lower mechanical properties of thin-walled elements compared to solid-type parts manufactured by 3D printing.

Keywords:

3D printing, thin-walled models, cell structure, manufacturing

1 INTRODUCTION

3D printing technologies have been developing very dynamically, especially in recent years, currently constituting one of the pillars of the modern industry 4.0. 3D printing technologies (also often called additive technology) can be used to produce thin-walled models with complex shapes that cannot be made using other methods or are very difficult to make. Modern industry already produces thin-walled products and prototypes, e.g. turbine blades [Dugar 2022; Ubando 2022; Rouway 2021; Thomas 2022], membranes [Thiam 2022; He 2024; Kratz 2019; Sarwar 2019; Qian 2022], thin structural elements [Kovacs 2023; Du 2023; Taylor 2019; Kopecki 2020; Kosin 2020], and orthoses, implants, and other parts for biomedical applications. [Rybansky 2023; Mikolajewski 2024; Van 2024; Rojek 2023; Gorski 2023; Lukaszewski 2023; Zakrecki 2024; Fang 2022; Wojciechowski 2019; Pico 2023; Walker 2023].

The production of thin-walled structures using 3D printing for applications in the aerospace industry is described in this paper [Dugar 2022]. In this work, metal-based 3D printing and additional machining (in a hybrid form) were used to produce engine turbine blades. In the analysis of the technological process, attention was paid to the aspect of problems and defects of the technological process, which is intensified in the aspect of manufacturing thin-walled structures.

The strength analysis of selected thin-walled structures, also for the aviation industry but not only, is described in the paper [Kopecki 2020]. Based on the typical torsion box fragment, they analyzed the influence of the printing direction on the strength of thin-walled structures, where differences of almost 50% were shown for the tensile strength parameter and a clear but smaller one for the Younge modulus.

When analyzing phenomena occurring in 3D printing, it is worth paying attention to the process of combining layers. Technologies such as SLM of FDM from the Powder Bed Fusion group are characterized by different technological parameters for several lower layers, for the core, side walls, and several upper layers, treating the manufactured model as a shell model with filling. However, each of the mentioned parts is characterized by different parameters of the technological process, which has a direct impact on the mechanical properties and dimensional accuracy of the manufactured models. In thin-walled structures, the problem appears in a situation when, due to the small thickness of the model, the entire technological process of manufacturing consists only of lower and upper parts of layers with different technological parameters of the manufacturing process. These characteristics and these

No.	Web of Science Categories	Record Count	%
1	Engineering Mechanical	82	43.4
2	Engineering Civil	71	37.6
3	Mechanics	66	34.9
4	Materials Science Multidisciplinary	52	27.5
5	Engineering Manufacturing	33	17.5
6	Metallurgy Metallurgical Engineering	15	7.9
7	Materials Science Composites	10	5.3
8	Physics Applied	9	4.8
9	Automation Control Systems	8	4.2
10	Chemistry Physical	7	3.7
11	Physics Condensed Matter	7	3.7
12	Multidisciplinary Sciences	5	2.7
13	Polymer Science	5	2.7
14	Engineering Multidisciplinary	4	2.1
15	Materials Science Biomaterials	4	2.1
16	Construction Building Technology	3	1.6
17	Engineering Biomedical	3	1.6
18	Engineering Electrical Electronic	3	1.6
19	Engineering Industrial	3	1.6
20	Engineering Marine	3	1.6
21	Robotics	3	1.6
22	Chemistry Multidisciplinary	2	1.1
23	Energy Fuels	2	1.1
24	Engineering Aerospace	2	1.1
25	Engineering Chemical	2	1.1
26	Engineering Environmental	2	1.1
27	Environmental Sciences	2	1.1
28	Materials Science Characterization Testing	2	1.1
29	Surgery	2	1.1
30	Biochemistry Molecular Biology	1	0.5

problems are one of the motivations why we started these studies of thin-walled models

Publications on thin-walled models can be divided into the following groups, including:

- studies of mechanical properties of thin-walled samples and models [Etemadi 2023; Zhang 2023; 2024; Yuksel 2024; Kucewicz 2019; Chen 2022; Demir 2024; Zarybnicka 2020; Piovan 2020; Wang 2022; Wang 2023a; 2023b; Isaac 2022; Yang 2022; Spignoli 2023; Bochnia 2023a; 2023b; 2023c; Luo 2023; Sindinger 2021; Wu 2023; Estrada 2023; Ma 2024; Mohammadnejad 2024; Rong 2024; Pan 2024; Mazlan 2023],

- designs and studies of properties of thin-walled cellular structures [Ji 2024; Dai 2021; Li 2024; Wang 2024; Stano 2024; Peng 2021; Fores-Garriga 2023; Jones 2021; Chen 2024; Challapalli 2023; Ghazlan 2020; Park 2024; Wang 2024],

- designs and studies of utility models [Grammatikopoulos 2020; Xing 2024; Gunasegeran 2023; Khaniki 2022; Calle 2020].

The results of the search in the Web of Science database of publications related to the title of the article are presented in Table 1, divided into individual scientific areas. A total of 189 publications were found in the years 2013-2024, with one publication appearing in 2013, which initiated the topic of thin-walled elements in 3D printing. In the following years, the number of these publications increased, reaching the highest number of 42 in 2022, as shown in Figure 1.

Tab. 1: List of publications from the Web of Science database (July 26, 2024) regarding thin-walled models manufactured by 3D printing.

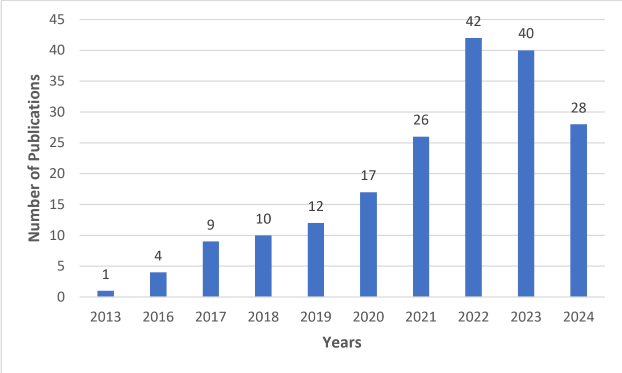

Fig. 1: Distribution of the number of publications in particular years.

Analyzing Figure 1, one can notice an increasing trend of scientific publications related to 3D printing technologies in the aspect of manufacturing thin-walled models. The data presented in Table 1 show that the largest number of publications on thin-walled models manufactured using 3D printing covers the following areas of science: Mechanical Engineering – 82, Civil Engineering – 71 and Mechanics – 66. Therefore, in the further part of the article, sample publications are mainly discussed from these areas.

The key motivation of the article is to draw attention to a large problem related to the production of many utility models using 3D printing technologies. As engineering practice shows, 3D printing is often used where structures with complex shapes are produced, many of which meet the criteria for classifying them in the thin-walled model group. This article shows how many stages should be considered when designing and producing a thin-walled model. We are talking about the large simulation aspect, for example, using CAD and CAE software, but also CAM, which does not take into account the aspects of thin-walled models for 3D printing. In the case of 3D printing, there is no distinction between sheet metal structures as is the case with conventional manufacturing methods. 3D printing as a thin-walled model should be treated with consideration of its specificity, and this is precisely what this publication draws attention to.

2 PUBLICATIONS ON THE MECHANICAL PROPERTIES OF THIN-WALLED MODELS

The articles describing the results of mechanical property tests of both thin-walled samples intended for static tensile testing and models of cellular structures built of thin walls, which were usually compressed using testing machines, were analyzed. Many works on the production of thin-walled elements using 3D printing technology do not always take into account the specific properties of these elements, which differ from solid-type parts. Usually, thin-walled elements have lower strength than solid-type elements, which should be taken into account in structural calculations or computer simulations by introducing separate coefficients. The co-authors of this article conducted studies of the mechanical proper-ties of various materials on thin-walled samples and demonstrated the differences in several publications [Bochnia 2020; 2021; 2023a; 2023b; 2023c] [41, 43, 44][71, 72].

The studies of mechanical properties of thin-walled samples most often showed anisotropy of mechanical properties due to the printing direction and the effect of wall thickness on the tensile strength value [Bochnia 2020; 2021] [71, 72]. These conclusions apply to practically all technologies used to produce thin-walled samples [Bochnia 2023b; 2023c] [43, 44]. Moreover, in the case of FDM technology, the occurrence of voids at the layers connections was found, which worsened the mechanical properties of the produced elements. Figure 2 shows sample stress-strain curves for two printing directions, while Figure 3 shows delamination in a thin-walled sample.

In the case of using thin walls to build cellular structures, the mechanical properties of the material were usually tested, i.e. separate samples were made for static tensile tests, while the properties of complex structural models were tested using static compression tests [Zhang 2024] [28]. Dynamic loads were also applied [Kucewicz 2029; Piovan 2020] [30][34], and bending tests were also performed on samples containing cellular structures [Zhang 2023] [27]. Figure 4 shows examples of cellular structures

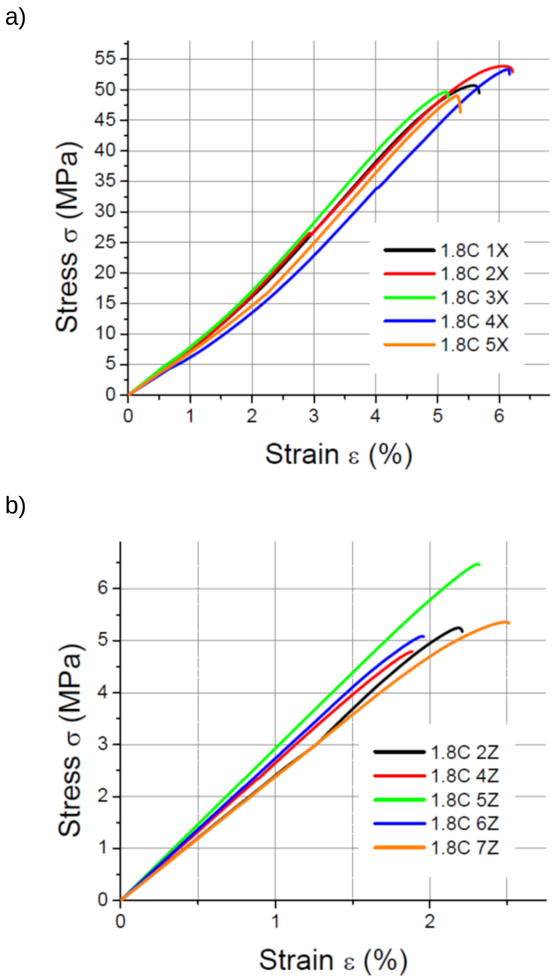

Fig. 2: Tensile test results for 1.8 mm thick specimens manufactured of PLA-CF printed in (a) the X orientation; (b) Z orientation [Bochnia 2021].

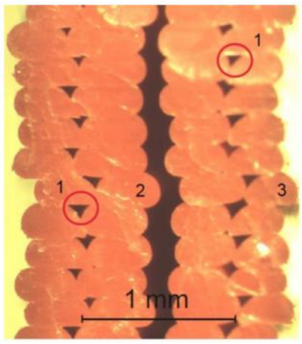

Fig. 3: Cross-sectional views of the 1.8 mm thick PLA specimen examined with a stereo microscope (x12 magnification). 1 - voids at the interface between the neighboring layers, 2 - a layer displaced inwards, 3 – a layer displaced outwards [Bochnia 2021].

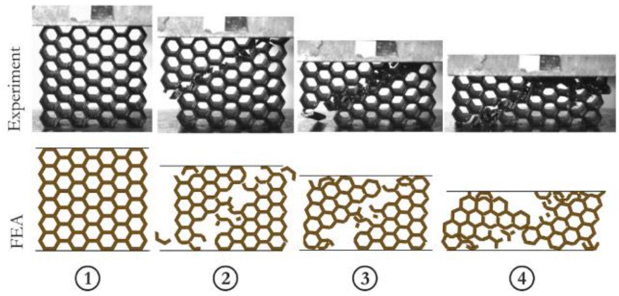

Fig. 4: Comparison of honeycomb structure deformation process between the FEA and the experiment (2400.0 mm/s velocity) [Kucewicz 2019].

Often, cellular structures printed, especially with FDM or FFF technology (currently also MEX – material extrusion) are made of thin walls less than 2 mm thick. The mechanical properties of thin elements are not always tested. The co-authors of this work drew attention to this in their publications, which have already been cited in this article. The cause of poorer mechanical properties of thin-walled elements are, among others, gaps created as a result of incorrectly generated paths of the applied filament by the 3D printer software, as shown in Figure 5

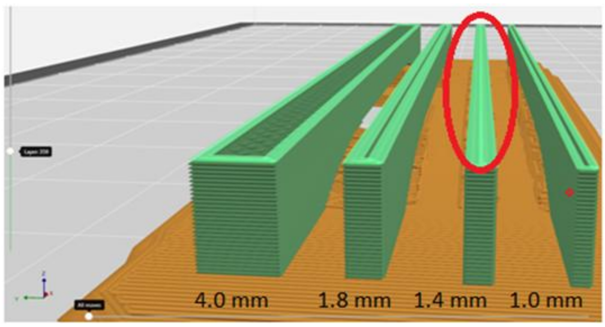

Fig. 5: Simulation showing defects in printing thin-walled elements [Bochnia 2023b].

Figure 5 shows cross-sections of thin-walled samples of different thicknesses and a solid reference sample obtained as a result of simulation performed using MakerBot software. Visible gaps in elements with thicknesses of 1.8 mm and 1 mm are caused by the stepper movement of the head applying the filament. In the sample with thickness of 1.4 mm (marked in red), all layers adhere to each other, but the measured thickness of the sample after its production is greater than that designed using CAD software. In Figure 5 it can be seen that the program introduced additional overlapping (see red loop) layers inside the model (as infill). For other types of specimens (1mm, 1.8 mm, and 4 mm), there was no overlapping of the layers within the model. During the tensile test, the gaps created at the production stage widen, creating delaminations shown in Figure 3, which reduce the strength of thin-walled elements. Attention was paid to this detail, which applies to all thin-walled elements manufactured by 3D printing because it is a defect that reduces the quality of finished products, sometimes utility products.

3 PUBLICATIONS ON COMPLEX THIN-WALLED STRUCTURES

Designing, manufacturing and testing thin-walled cellular structures is one of the most difficult research tasks because all the problems of manufacturing single samples using 3D printing technology add up, making it difficult to correctly manufacture more complex models. Therefore, some work has been devoted to developing a classification of structures and developing mathematical foundations that facilitate design. Cellular structures are also designed for a specific practical purpose, e.g. to absorb energy during dynamic loading, which can be useful in safety-related applications.

Figure 6 shows examples of basic cells that, when connected, create entire complexes generally called structures. These cells have been used to develop layered structures by designing and manufacturing complex two- and three-dimensional cellular cores connected to carbon fiber reinforced polymer (CFRP) shells.

Fig. 6: FFF three-dimensional cellular core designs used for hybrid sandwich panels [Fores-Garriga 2023].

In [Wang 2023] [36], fractals with simple basic cells and a degree of self-similarity were used to design an energy-absorbing structure. It was assumed that increasing the energy absorption capacity of lightweight composite structures reinforced with carbon fiber is of great importance in developing specific components. After printing and conducting tests, it was found that fractal composite bamboo components with a structure factor of 0.2 exhibit the highest energy absorption rates, with a satisfactory level of energy absorption capacity in potential engineering applications. An example of cells developed for energy absorption can be those shown in Figure 7.

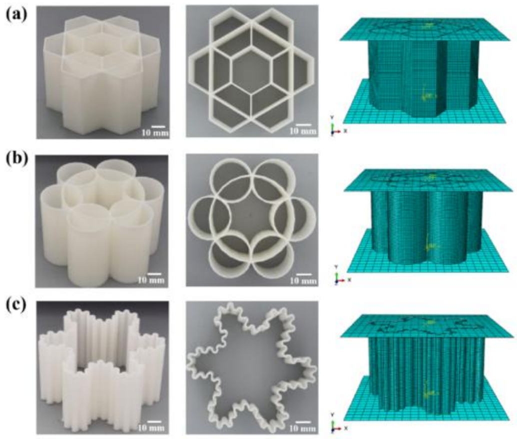

Fig. 7: 3D printed hierarchical fractal homogenous cells and their corresponding numerical models.
(a) a honeycomb fractal cell with α = 0.5, (b) a bamboo fractal cell with β = 0.5, and (c) a snake-like fractal cell with γ = 0.19 [Chen 2024].

The examples of cellular structures presented in Figures 6 and 7 show that they are a set of thin-walled elements that create different shapes through appropriate configuration. The mechanical properties of entire elements containing packages of structures depend on the properties of a single wall. Therefore, examples of thin-walled sample test results were given in Chapter 2, indicating the need to conduct appropriate tests that can improve 3D printing technology.

4 CONCLUSIONS

A brief analysis of the literature on the production of thin-walled models using 3D printing technology shows that in recent years there has been a growing interest in the design and production of complex thin-walled structures for various engineering applications. The number of works devoted to the study of the mechanical properties of thin-walled elements is growing, which is associated with the appearance on the market of newer materials used in 3D printing technologies.

There are also numerous attempts to develop mathematical foundations for the design of cellular structures, which is very useful in practical engineering applications.

It seems that 3D printer software manufacturers should take into account the possibility of adapting the 3D printing design process to the problems of thin-walled models such as the problem of layer connecting and the generation of single paths (g-code) in the model shell walls.

The production of thin-walled elements for utility purposes, including elements containing cellular structures, should be preceded by tests of the mechanical properties of thin walls in order to correct the design calculations and also, if possible, to correct the printing technology, e.g. by changing the G-codes controlling the movement of the filament application head.

In addition, in computer simulations related to the assessment of the strength of models produced by 3D printing, different material coefficients should be introduced, such as Younge's modulus, depending on the printing direction and other technological parameters such as layer thickness.

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