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ГРАТЧАСТІ (АУКСЕТИЧНІ) СТРУКТУРИ ОТРИМАНІ 3D-ДРУКОМ МЕТОДАМИ ПОШАРОВОГО НАПЛАВЛЕННЯ (FDM) ТА ФОТОПОЛІМЕРІЗАЦІЇ (LCD-SLA)

У роботі досліджено гратчасті ауксетичні структури, отримані методами адитивного виробництва: пошарового наплавлення матеріалу (FDM) та фотополімеризації із застосуванням LCD-SLA технології. Зразки виготовляли з TPU-філаменту та ABS-подібної фотополімерної смоли. Основну увагу приділено впливу способу 3D-друку на точність відтворення тонких ребер, вузлів і повторюваних ауксетичних комірок. Показано, що LCD-SLA забезпечує вищу геометричну точність, кращу якість поверхні та деталізацію дрібних елементів, що є важливим для дослідницьких і демонстраційних зразків. Водночас FDM-друк із використанням гнучких термопластів, зокрема TPU, може бути доцільним для функціональних ауксетичних структур, які працюють в умовах багаторазової деформації або ударного навантаження. Розглянуто основні технологічні труднощі обох методів, зокрема усадку й підвищення жорсткості фотополімерних зразків, а також проблеми адгезії першого шару, зміщення шарів і утворення дефектів під час FDM-друку. Отримані результати підтверджують, що вибір технології 3D-друку та матеріалу є визначальним для формування гратчастих ауксетичних структур із необхідною геометрією та деформаційною поведінкою.

Ключові слова: *ауксетичні структури, гратчасті структури, 3D-друк, FDM, LCD-SLA, TPU, фотополімерна смола, адитивне виробництво.*

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AUXETIC LATTICE STRUCTURES FABRICATED BY 3D PRINTING USING FUSED DEPOSITION MODELING AND LCD-SLA PHOTOPOLYMERIZATION

The paper presents a study of auxetic lattice structures fabricated by additive manufacturing using fused deposition modeling (FDM) and liquid crystal display stereolithography (LCD-SLA). The investigated samples were produced from TPU filament and ABS-like photopolymer resin. Particular attention was paid to the influence of printing technology on the accuracy of reproducing thin ribs, nodes, and repeating auxetic cells. It was shown that LCD-SLA provides higher geometric accuracy, better surface quality, and more precise reproduction of small structural elements, which is especially important for research and demonstration samples. At the same time, FDM printing with flexible thermoplastics, particularly TPU, may be more suitable for functional auxetic structures subjected to repeated deformation or impact loading. The main technological difficulties of both methods are discussed, including shrinkage and increased stiffness of photopolymer samples, as well as first-layer adhesion problems, layer shifting, and stringing during FDM printing. The results confirm that the choice of 3D printing technology and material is critical for obtaining auxetic lattice structures with the required geometry and deformation behavior.

Keywords: *auxetic structures, lattice structures, 3D printing, FDM, LCD-SLA, TPU, photopolymer resin, additive manufacturing.*

Introduction. The development of lightweight, strong, and functionally adaptive materials is a fundamental challenge in modern materials engineering. Advances in additive manufacturing have enabled a shift from solid structures to metamaterials with controlled topologies, among which auxetic (lattice) structures hold a special place. A distinctive feature of auxetics is their negative Poisson's ratio: under tensile loads, such materials expand in the transverse direction. This atypical effect is due exclusively to the cell geometry, which allows for a significant increase in the structure's resistance to failure, its shear stiffness, and its ability to dissipate energy [1]. The development of this field at the regional and global levels, including an analysis of the material and technical base and the prospects for implementing the latest additive methods in Ukraine, is covered in detail in domestic analytical reviews [2].

3D printing technology is most commonly used for the synthesis of lattice auxetics. The fused deposition modeling (FDM) method has become widely adopted due to its manufacturability and cost-effectiveness in reproducing complex geometries. Studies confirm the effectiveness of FDM for printing auxetics from basic thermoplastics (PLA, ABS), where the mechanical properties of the product directly depend on the printing parameters and the architecture of the cell itself [3, 4]. At the same time, to improve the characteristics of FDM-printed elements and overcome their internal anisotropy, post-processing and heat treatment methods are successfully applied, in particular microwave sintering of composite structures, which ensures increased interlayer cohesion [5]. On the other hand, photopolymerization methods (SLA, LCD-SLA) guarantee high precision and minimal layer thickness, making them in demand for the creation of microstructures, particularly for biomedical applications [6].

The raw material base for such structures is traditionally polymers and their composites. Polylactide (PLA) remains one of the most popular materials due to its high processability and stable mechanical properties [7]. However, for high-load systems, carbon-fiber-reinforced polyamides are increasingly being used, which allows for a dramatic improvement in strength characteristics [8]. Research on modifying polymer matrices with discrete fillers—such as silicon nitride particles [9], titanium nitride [5, 10], and basalt fibers for ABS plastic [11]—has made a significant contribution to expanding the range of composites for additive manufacturing. This enables precise control of the elastic, mechanical, and tribological properties of the base material.

A set of unique functional properties makes auxetic lattice structures promising for applications in the aerospace industry, implantology, transportation engineering, and modern impact protection systems [7, 12]. In this context, the material's damping potential is critically important. Acoustic studies of composites with refractory inclusions confirm their high ability to absorb and dissipate mechanical vibrations [10]. Moreover, it has been established that the intrinsic physical and mechanical characteristics of flexible polymer matrices play a decisive role in the overall energy capacity of three-dimensional auxetic lattice structures under compression [13], which opens new avenues for their targeted optimization under dynamic loads.

Despite the significant volume of research conducted in the field of modifying base polymers, a comparative analysis of the structural integrity and specific deformation behavior of lattice metamaterials produced using fundamentally different additive techniques requires more detailed study. In this regard, the aim of this work is a comprehensive study of the capabilities and technological features of 3D printing of lattice auxetic structures based on engineering plastics using fused deposition modeling (FDM) and liquid crystal-based stereolithography (LCD-SLA).

Objective. This study investigated the potential of 3D printing using fused deposition modeling and liquid crystal stereolithography to produce plastic-based lattice auxetics structures.

Materials and Methods. In our study, we used the Photon Mono 4 ULTRA photopolymer printer (ANYCUBIC, China) and the Ender 5 FDM 3D printer (Creality, China). Printing materials: ABS-Like Resin V2 photopolymer resin (Anycubic, China) and 1.75 mm diameter TPU filament (Creality, China).

Printing was performed using the following parameters:

1) photopolymer printer: layer thickness 0.050 microns, resin temperature ~40°C, print speed – 1 layer in 2.7 seconds, total number of layers 1,503 (the 50x50x50 model is positioned at a 45° angle on supports).

2) FDM printer: nozzle diameter 0.4 mm, nozzle temperature 215°C and build plate temperature 600°C, print speed The 3D model was designed and edited in Blender and Autodesk Netfabb and prepared for printing in Simplify3D.

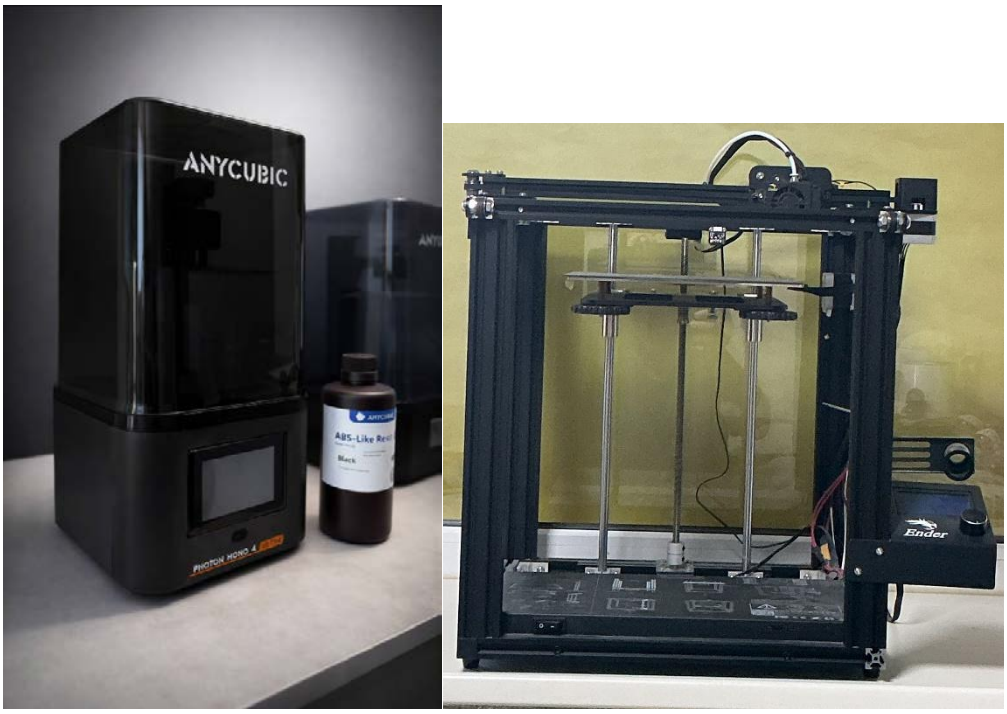

Fig. 1. **3D printers: a – Photon Mono 4 ULTRA, b – Creality Ender 5**

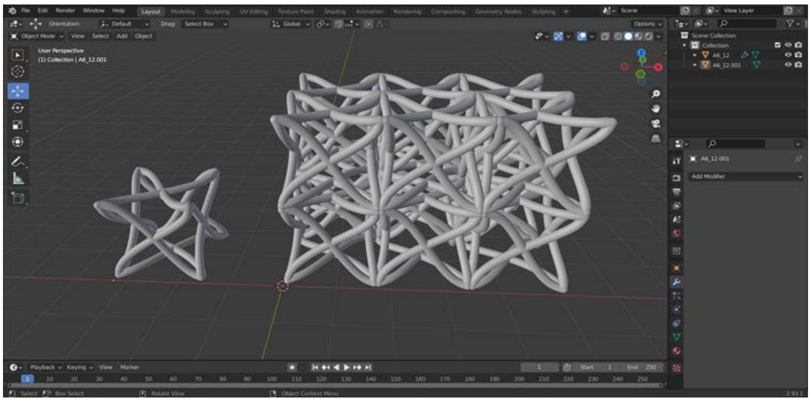

Fig. 2. **Model of an auxetic array measuring 30 mm × 20 mm × 20 mm.**

3D Printing of Lattice (Auxetic) Structures. As previously noted, auxetic structures have a negative Poisson's ratio, meaning that when stretched, they expand symmetrically across their width, and when compressed, they contract. The mechanical behavior of auxetic materials is determined not so much by the material itself as by the precision of the unit cell reproduction: the thickness of the edges, the radii at the nodes, and the uniformity of the auxetic cells throughout the volume. This is precisely why photopolymer printing is often more technologically advantageous than FDM for such structures. Reviews of auxetic structures and experimental work with SLA/DLP printing clearly indicate that additive methods are well-suited for manufacturing complex auxetic geometries, and DLP/SLA can provide more isotropic behavior than FDM due to better interlayer adhesion. The Photon Mono 4 Ultra has a sufficiently high resolution, which is quite important for photopolymer resin printing. Given that lattice structures are quite sensitive to geometric errors in thin bridges, internal corners, and cell repeatability, their accurate reproduction during 3D printing is a key factor in ensuring that the resulting lattice structures exhibit auxetic properties. A typical lattice structure produced by photopolymerization (LCD-SLA) is shown in Fig. 3.

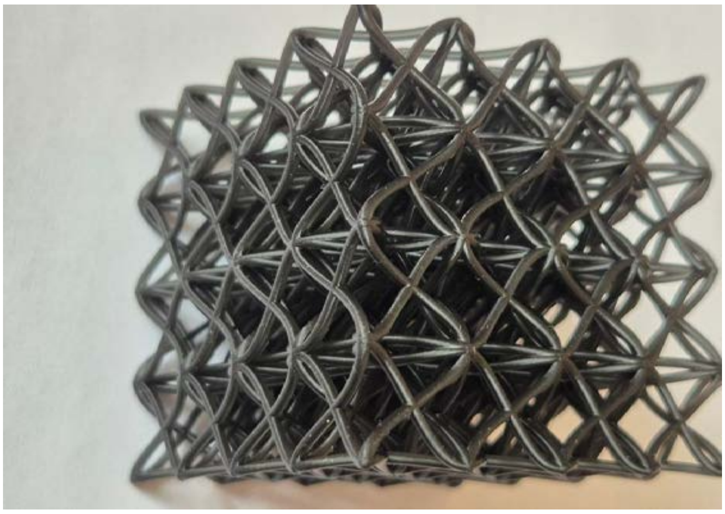

Fig. 3. **An array of auxetics made from ABS-Like Resin V2 photopolymer resin, printed on a Photon Mono 4 ULTRA.**

After printing with ABS-Like Resin V2 photopolymer resin, a high-quality sample of a lattice structure was obtained, but slight changes in geometry and properties were observed—the resulting sample shrinks in size, and the material becomes stiffer. Such changes may be acceptable for a standard demonstration sample, but for a metamaterial with thin hinges, such a change can be significant. Moving forward, these changes must be taken into account when selecting materials, as they can significantly affect the results of mechanical tests on lattice structures.

The desired outcome in 3D printing is to obtain a physical model that closely resembles the computer model; however, numerous issues often arise that cause the shape to deform. During the FDM printing process of an array of lattice auxetics-structures issues related to geometry were also identified, given the small size of the elements. To obtain a high-quality finished model, a lengthy process of adjusting the temperature, print speed, and retraction settings was required. The array of auxetics, in which the constituent elements of the lattice structure were 5 mm in size and made of TPU filament, did not always match the digital model after printing in Fig. 4a. By improving print accuracy and increasing the thickness of the axetic cell ribs, we were able to produce a high-quality object that retained its compressibility and exhibited axetic properties in Fig. 4b.

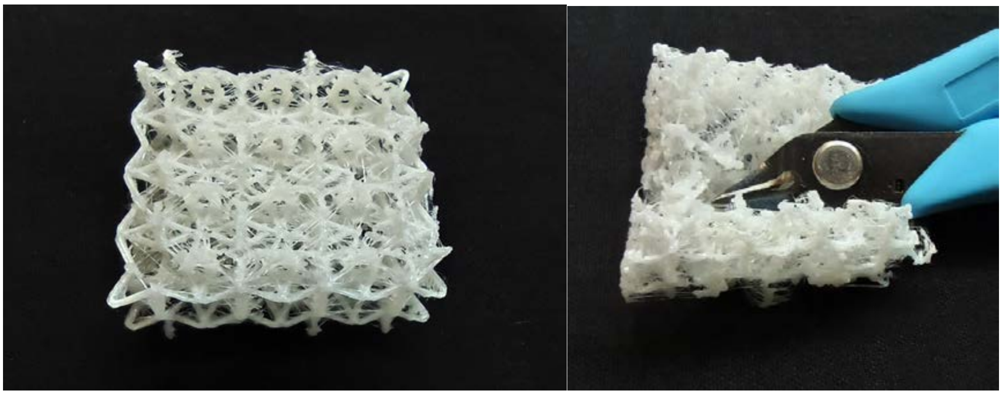

Fig. 4. **A lattice structure of auxetics made from TPU filament printed using the FDM method.**

Additionally, during printing, we encountered issues such as the first layer of the model's material peeling away from the platform, layer misalignment, and the presence of "strands" between elements—which are remnants of plastic on the nozzle and result from the extruder's movement between the model's elements. These difficulties are common regardless of the size and shape of the printed object when using the FDM method, and the solution lies in selecting the appropriate print settings for each material loaded into the printer, as filaments of the same plastic type from different manufacturers often have varying properties.

Comparing the two methods, we note that for the FDM method, the minimum feature size is effectively limited by the nozzle diameter, the width of the extrusion path, melt flow, and flow rate settings, whereas for LCD-SLA on the Photon Mono 4 Ultra printer, the limit is set by a 17-micron pixel and layer photopolymerization, so fine cells, thin hinge areas, and joints are reproduced more accurately. In FDM, strength depends heavily on the adhesion between filaments and layers; this is often a weak point, especially under tensile or bending stress across layers. This is problematic for auxetics because the structure deforms complexly and locally "twists" joints in different directions. For LCD-SLA, studies have shown more isotropic behavior compared to FDM due to better interlayer integration.

Therefore, for achieving the desired geometry, printing with photopolymer resin is preferable, but mechanically, standard photopolymers are often more brittle than typical FDM materials (TPU, PLA, PETG, or nylon). This is particularly important for auxetic structures, as they function through local twists, bends, and the redistribution of strain at nodes. If the resin is stiff and brittle, the structure will not exhibit the desired auxetic deformation but will simply crack at the nodes or along thin ribs. This means that for functional prototypes, it is better to use specialized materials (tough / ABS-like / engineering resin) rather than standard resin.

On the other hand, considering the possibility of recycling and the cost per printed part, as well as economic and environmental factors, the FDM method has a significant advantage over photopolymer resin printing.

Conclusion. To summarize the theoretical analysis, it can be stated that lattice auxetic structures open up new possibilities for engineering thanks to their programmable negative Poisson's ratio. Their ability to effectively absorb energy and adapt to complex geometric surfaces makes them indispensable in aviation, medicine, and protective technologies. However, the complexity of the internal architecture of such materials poses challenges for traditional manufacturing, highlighting the relevance of additive technologies.

When producing arrays of auxetic structures, it was found that for fine-celled, geometrically complex, research, or demonstration parts, LCD-SLA is generally superior to FDM because it provides higher precision, better surface quality and detail, as well as less pronounced weak interlayer bonding.

For functional, repeatedly deformed, impact-loaded, or elastic auxetic structures, FDM may be advantageous if an appropriate thermoplastic is used, particularly TPU or nylon, since standard resins often have inferior crack resistance. Additionally, this method is more environmentally and economically advantageous than LCD-SLA.

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