Study of isotropy of mechanical properties of the TPMS-based cellular structures

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Abstract. The study of isotropy of mechanical properties of cellular structures was carried out. The studied objects are based on triply periodic minimal surfaces ("Schwarz primitive") with various cell size parameter t. The mechanical loading was applied with different loading directions. It was shown, that triply periodic minimal surface (TPMS)-based materials have high isotropy of mechanical properties.

1 Introduction

1.1 Triply periodic minimal surfaces

Triply periodic minimal surfaces (TPMS) are surfaces that can be defined by two properties: constan (zero) mean curvature and invariance to translation in rank-3 lattice.

There are a lot of examples of triply periodic minimal surfaces in nature. For example, in the wings of some butterfly species, chitin is organized in the form of a cubic srs network or gyroid, where it functions as a photonic crystal, imparting color to butterflies [1-4]. In work 1, SEM and TEM images of the wings of Papilionidae and Lycaenidae species are presented, the authors tried to find the lattice parameters, but it turned out that the lattice is difficult to parameterize, according to estimates, it is 165-360 nm, the volume fraction lies in the range of 0.17-0.40. In [3], small-angle X-ray scattering and optical band gap modeling were used.

It has been shown that at the first stage, a "double gyroid" structure (Figure 1a) is formed in the wings of butterflies, which then transforms into a gyroid (Figure 1b), by deposition of chitin into the intracellular space.

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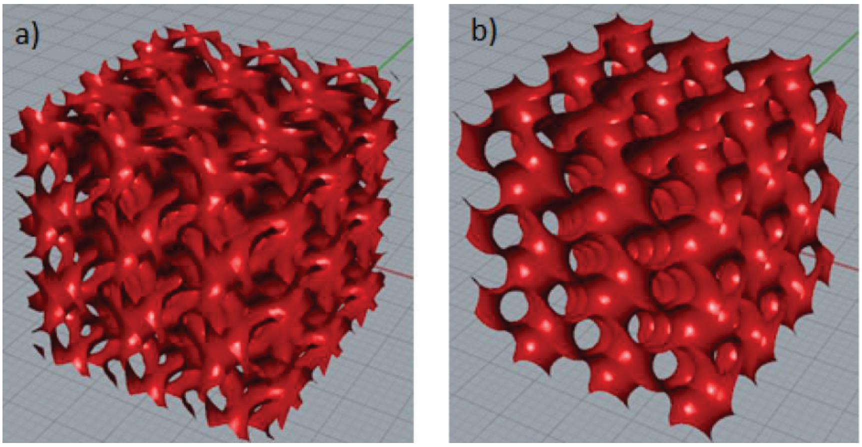

Fig. 1. Triply periodic minimal surfaces: a) double Schoen gyroid, b) single Schoen gyroid.

Other examples of physical systems that have TPMS as a spatial structure are self-assembly processes occurring in diblock copolymers [5–6]. In the work [5] TEM and computer simulation were used. For comparison with TEM images, two-dimensional projections of three-dimensional computer models were taken. This paper discusses three surfaces applicable to A/B copolymers: the double diamond, the first Shark surface, and the scaly catenoid structure, which seems to be a new type of periodic CMC (constant mean curvature) surface.

There are systems that thermodynamically, tend to organize the interface with the TPMS geometry. Examples of such systems are:

- The formation of structures with the TPMS geometry in lipid–water systems [8–11].
- Synthetic surfactants [12].
- Inorganic mesoporous systems synthesized in the presence of amphiphilic components has been shown [13].
- The work [14] showed the presence of TPMS in the alveolar structures of the lungs of rabbits.

Most of these examples have cubic symmetry, however, anisotropic non-cubic triply periodic surfaces are found in the structure of three block copolymers [7] and mesoporous silicate systems [15] and alveolar structures of light rabbits [14].

There is a perspective to use TPMS-based structures as acoustic materials.

1.2 Isotropy

Materials can be divided into isotropic and anisotropic. Isotropic materials exhibit the same physical and mechanical behavior regardless of the direction of application of the external load.

One of the disadvantages of classical honeycomb structures is the anisotropy of physical and mechanical properties, and therefore, the development and application of new cellular structures with high isotropy of physical and mechanical properties is currently relevant (Figure 2) [16].

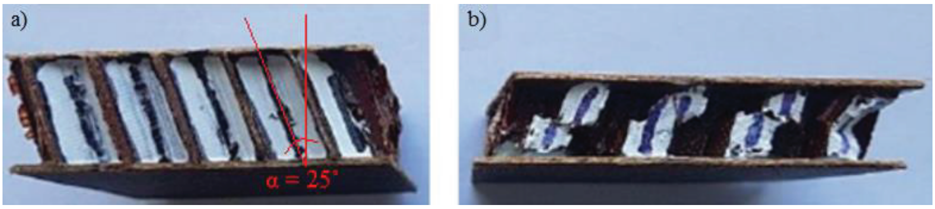

Fig. 2. A sample of a honeycomb three-layer material for testing at an angle of α = 25˚: a) before testing, b) after testing.

To create materials with isotropic physical and mechanical properties, it is necessary to use new approaches to create materials with a unique geometry. The development of computing power and production technologies make it possible to create new generation materials with improved performance.

Due to the periodicity in rank 3 lattice, materials with the TPMS geometry have a greater isotropy of physical and mechanical properties than classical honeycomb structures. And the development of additive technologies makes it possible to apply such cellular materials in practice and introduce them in industry.

2 Materials and methods

In order to study the isotropic properties of structures with the geometry of three times periodic surfaces of minimum energy, 3D models of the "Schwartz primitive" geometry samples with a different value of the parameter t (equation 1, figure 3) were created.

$$\text{Cos}(x)+\cos(y)+\cos(z)=t, \tag{1}$$

where "t" is the geometric parameter of the unit cell size.

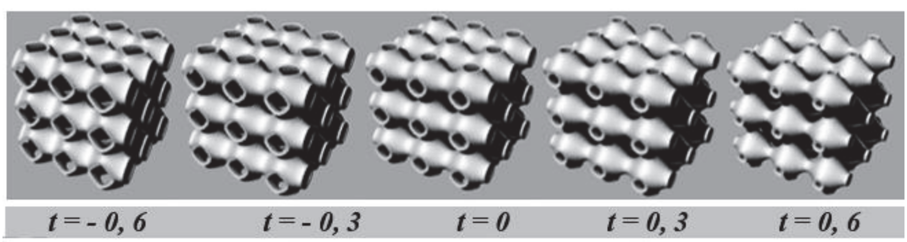

Fig. 3. Change in the geometry of the samples depending on the value of the parameter t in the equation, loading angle α = 0˚.

To study the isotropy of the mechanical properties of TPMS, 3D models of samples of the "Schwartz primitive" geometry were created with different angles α (15′, 30˚, 45′) and with different parameter t. An important factor in studying the properties of TPMS is the parameter t, which characterizes the geometry of the cell. With an increase in the parameter t, the characteristic size of the cell and, accordingly, the internal volume decreases, and the area of the dangerous section increases [17]. Test samples were made on a 3D printer using FDM technology on an Artillery Sidewinder X1 3D printer.

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3 Results and discussion

In accordance with [18], the first peak on the deformation curve, which corresponds to the transition of the sample to the region of plastic deformation, was taken as the strength of the samples. Deformation curves of samples with different parameter t, loading angle α = 0˚ are shown in Figure 4. The physical and mechanical properties of samples with the geometry of the TPMS are presented in Table 1 and Figure 5.

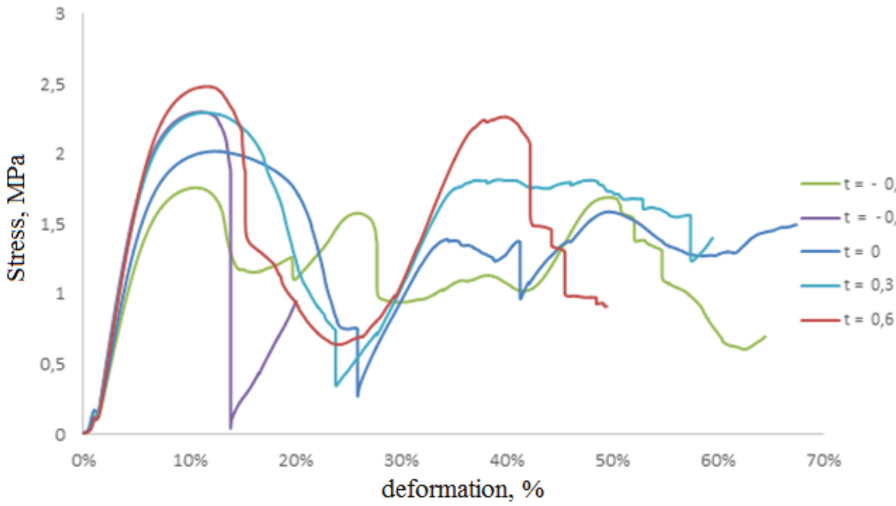

Fig. 4. Deformation curves for samples of geometry "primitive Schwartz" for various parameters t, α = 0˚.

Table 1. Results of physical and mechanical compression tests.

α	t	m	ρ	F	σ	Specific strength	ε	E
°		g	g /cm³	N	MPa	MPa · cm³/ g	%	MPa
0	-0,6	4,4	0,16	1583	1,76	10,9	11	29
	-0,3	4,9	0,18	2070	2,30	12,7	11	44
	0	4,7	0,17	1817	2,02	11,7	12	38
	0,3	4,7	0,17	2067	2,30	13,3	11	43
	0,6	4,4	0,16	2234	2,48	15,1	12	44
15	-0,6	4,1	0,15	1578	1,75	11,6	9	31
	-0,3	4,5	0,17	1767	1,96	11,8	11	36
	0	5,1	0,19	2218	2,46	13,2	10	52
	0,3	4,7	0,18	2064	2,29	13,1	10	48
	0,6	4,8	0,18	2271	2,52	14,3	9	56
30	-0,6	4,5	0,17	2089	2,32	13,9	9	57
	-0,3	4,9	0,18	2396	2,66	14,7	10	53
	0	4,6	0,17	2053	2,28	13,4	8	58
	0,3	4,7	0,17	2296	2,55	14,8	8	70
	0,6	4,6	0,17	1918	2,13	12,5	11	58
45	-0,6	4,7	0,18	2422	2,69	15,3	10	77
	-0,3	4,2	0,16	2229	2,48	15,9	9	68
	0	4,2	0,16	2423	2,69	17,4	15	74
	0,3	4,6	0,17	2915	3,24	19,1	11	84
	0,6	4,4	0,16	2302	2,56	15,7	9	69

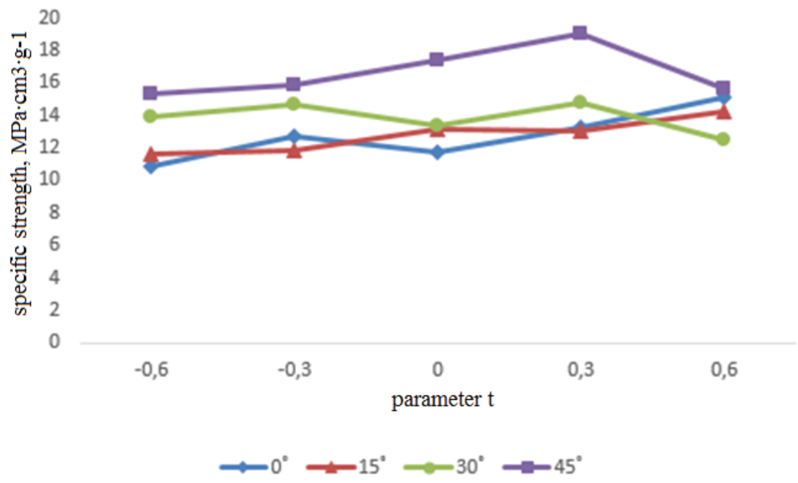

Fig. 5. Specific strength of specimens with "primitive Schwartz" geometry at different loading angle α and different parameter t.

To analyze the isotropy of the mechanical properties of samples with the geometry of TPMS ("Primitive Schwartz"), a radar chart was constructed for the specific strength of the samples depending on the loading angle (Figure 6).

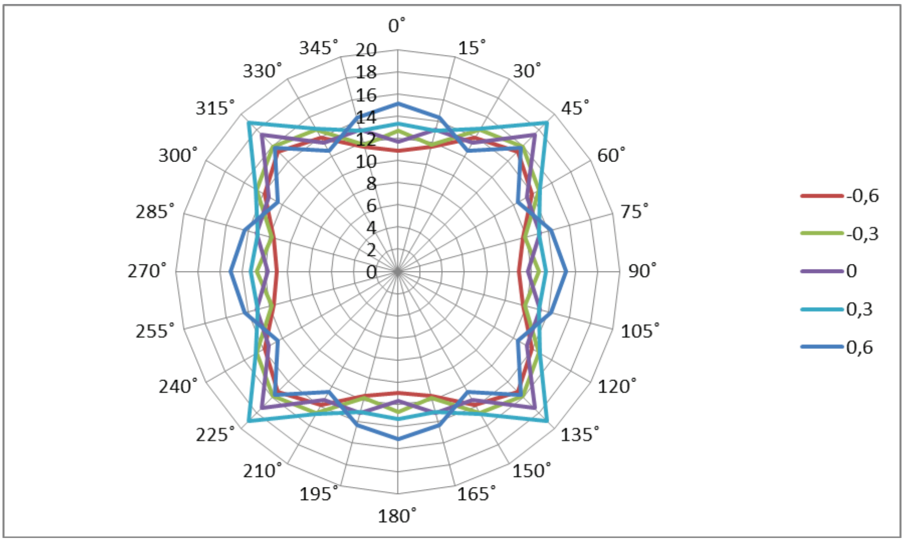

Fig. 6. Specific strength of samples with different parameter "t" loaded at different angles, MPa·cm3·g-1.

According to the radar charts of the specific strength of specimens with the "Schwartz primitive" geometry, it can be seen that the specimens exhibit the best specific strength when loaded at an angle of α = 45 (equivalent angles: 135, 225, 315) degrees.

The isotropy of the mechanical properties of classical honeycomb materials was studied in [19], the article shows that classical honeycomb materials have a low isotropy of mechanical properties.

Figure 7 shows a radar chart showing the strength of the honeycomb material when loaded at different angles [20].

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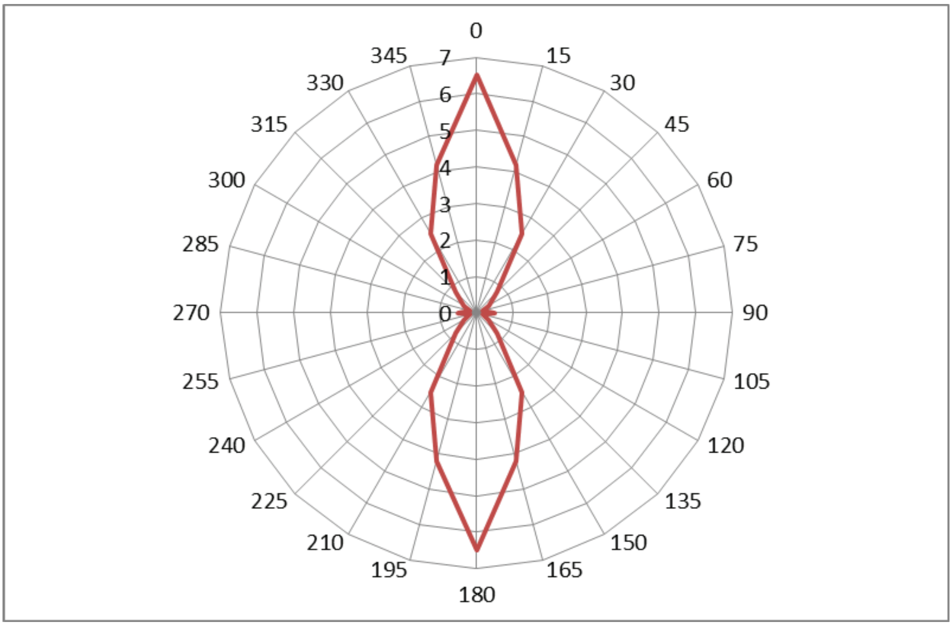

Fig. 7. Strength of honeycomb samples loaded at different angles, MPa.

Figure 7 shows that the strength of honeycomb materials varies greatly depending on the loading angle α; when loaded at an angle, the strength of the samples drops by a factor of 32 from 6.5 MPa to 0.2 MPa, which significantly reduces their scope. Cellular materials with TPMS geometry, on the contrary, demonstrate a higher isotropy of mechanical properties, their strength characteristics change by no more than 25% with a change in the loading angle α, which is a significant advantage compared to classical honeycomb structures.

4 Conclusions

Regardless of the angle of the applied load, samples with the “primitive Schwartz” geometry demonstrate high physical and mechanical properties. When the loading direction changes, the specific strength of samples with the TPMS geometry changes insignificantly, this confirms the assumption that the mechanical properties of cellular materials with the TPMS geometry are highly isotropic. Even with a change in the parameter t, despite deviations from the main property of TPMS, the minimality of the surface [20] - the isotropy of mechanical properties is preserved.

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