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Mechanical metamaterials – a fashion trend or a new approach to the development of materials?

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Abstract: The development of metamaterials of various types (electromagnetic, acoustic, mechanical) is characterized by a single approach – the response of the medium to external influences required for solving a specific problem is "designed" by using a system of elements organized in a certain way, made from ordinary, well-known materials. This approach is universal and allows successfully solving a wide range of problems in various fields of science and technology. It is used in wildlife to create materials that provide optimal adaptation of a living organism. Rationally designed mechanical metamaterials have a number of unusual properties. In particular, they can meet conflicting requirements by combining, for example, high rigidity with high fracture toughness and low density. This makes them extremely promising for the development of new structural materials based on them. It is concluded that additive technologies can be successfully used to create mechanical metamaterials with ultra-properties – ultralight and superrigid. The principles of creating auxetic metamaterials based on open-cell foams are described in detail.

Keywords: mechanical metamaterials; auxetics; superlattices; bulk modulus of elasticity; shear modulus; Poisso's ratio; additive.

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Механические метаматериалы – модный тренд или новый подход к разработке материалов?

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Аннотация: Показано, что разработка метаматериалов различного типа (электромагнитных, акустических, механических) характеризуется единым подходом. Требуемый для решения конкретной задачи отклик среды на внешнее воздействие «конструируется» путем использования системы, определенным образом организованных элементов, изготовленных из обычных хорошо известных материалов. Данный подход является универсальным и позволяет успешно решать широкий круг задач в различных областях науки и техники. Его использовала живая природа при создании материалов, обеспечивающих оптимальное приспособление живого организма. Показано, что рационально спроектированные механические метаматериалы обладают рядом необычных свойств. В частности, они могут удовлетворять противоречивым требованиям, сочетая, например, высокую жесткость с высокой вязкостью разрушения и малой плотностью. Это делает их крайне перспективными для разработки на их основе новых конструкционных материалов. Сделан вывод о том, что аддитивные технологии могут быть успешно использованы для создания механических метаматериалов с ультрасвойствами сверхлегких и сверхжестких. Подробно описаны принципы создания ауксетических метаматериалов на основе пенопластов с открытыми порами.

Ключевые слова: механические метаматериалы; ауксетики; сверхрешетки; объемный модуль упругости; модуль сдвига; коэффициент Пуассона; аддитивные технологии.

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1. Introduction

Currently, we are witnessing the birth of a new concept in materials science – mechanical metamaterials. A rationally designed structure (architecture) makes it possible to implement previously unattainable and unusual properties that can be used to create materials with new unique characteristics. This approach is especially relevant in connection with the rapid development of additive technologies, which are an almost ideal tool for solving this problem [1–6].

The paper aims to briefly review the achievements in the field of mechanical metamaterials, in terms of the possible application of this concept to solve problems of modern materials science.

The study was carried out within the framework of the "Strategic directions for the development of materials and technologies for their processing for the period up to 2030" [7].

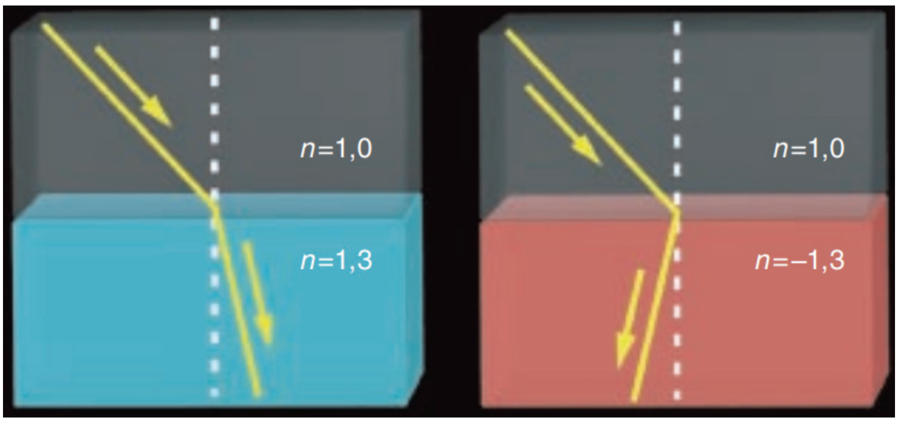
First, it is expedient to formulate a general concept that underlies the creation of all currently known metamaterials.

The refraction of an electromagnetic wave at the air/medium interface with simultaneously negative values of the dielectric and magnetic permeability (natural media with this property has not been found) was described by the Soviet, Russian physicist V.G. Veselago back in 1967 [8]. It was shown that, in this case, the refracted beam lies on the same side of the normal as the incident beam (Fig. 1), in addition, the phase and group velocities of such waves are directed in different directions. To assess how unusual this behavior is for a wave, one can follow the link in [9] to watching the video.

To produce a wave with "negative" refraction, it is necessary that the direction of movement of electrons in the material medium be opposite to the forces causing this movement [10.]

The solution to this paradoxical problem was found by D. Pendry, who used a periodic structure of metal wires and plates on which nested copper rings with discontinuities directed in different directions were printed [11]. Free electrons in a system of such circuits oscillated with their own (resonant) frequency, which depended on the geometrical parameters of the structure. In the case when the frequency of the incident wave was less than the resonant frequency, the direction of electron motion coincided in phase with the driving oscillations of the electric and magnetic fields. As the frequency increased, a moment came when the oscillations of the electrons and the driving fields occurred in antiphase, i.e. the dielectric and magnetic permeability of the structure of the contours in a fairly narrow frequency range became negative. Later, such a structure was created in 2000 by the authors of [12].

Figure 2 shows one of the possible implementations of an electromagnetic metamaterial created by Russian scientists at ITPE RAS. The measurements showed that the real parts of the dielectric and magnetic permeability take negative values in the range of 3.8–3.2 GHz [13].



(*a*) (*b*)

Fig. 1. The path of the refracted beam in an ordinary medium (*a*) and in an electromagnetic metamaterial (*b*) with a negative refractive index [10]

Fig. 2. "Medium" with negative values of dielectric and magnetic permeability [13]

In the future, electromagnetic metamaterials can be widely used in antenna technology [14, 15], visibility reduction technologies [16, 17], and the development of high-resolution optical systems [18].

No less valuable for materials science is the approach that was used by D. Pendry to create a metamaterial – the "unusual" response of the environment to external influences was "designed" by using a system of elements organized in a certain way, made from ordinary, well-known materials. A similar principle underlies the creation of not only electromagnetic, but also acoustic materials [19, 20].

Further, a number of specific examples will show the effectiveness of this concept for the development of materials with a given level of mechanical properties.

2. Mechanical Metamaterials

The mechanical properties of solid isotropic media are characterized by bulk modulus, shear modulus, and Poisson's ratio [21].

The relationship between bulk modulus (B) and shear modulus (G) can be expressed as [22]:

$$\frac{B}{G} = \frac{\mu + 1}{3(0.5 - \mu)},$$

where μ is Poisson's ratio.

Graphically, this dependence is shown in Fig. 3.

For the vast majority of natural materials Poisson's ratio values are positive and range from 0.17 for quartz glass to 0.44 for lead. Exceptions to this rule are extremely rare: cubic crystals of metals have a negative value of μ, as well as a number of anisotropic crystals: quartz at high temperatures, pyrolytic graphite [23–25]. A positive Poisson's ratio means that when compressive stresses are applied, the volume of the material increases.

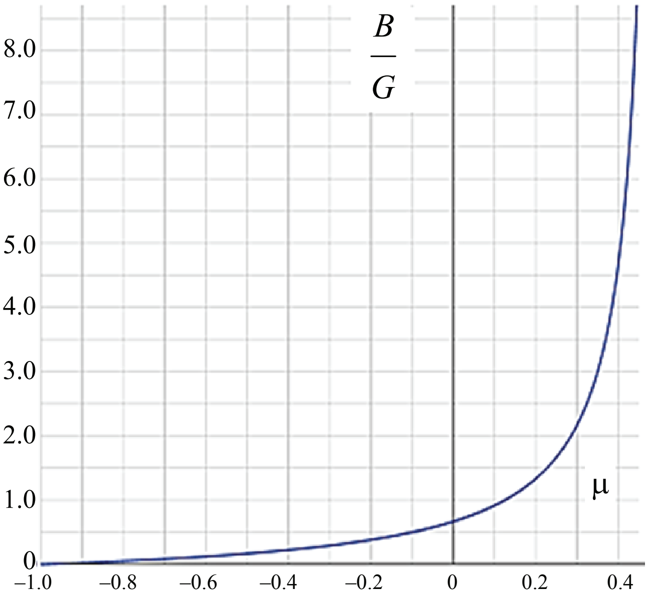


Fig. 3. Dependence of the ratio of bulk modulus and shear modulus on Poisson's ratio

As can be seen from the graph for a positive value of the B/G ratio, the value of Poisson's ratio satisfies the condition $-1 < \mu < 0.5$. The value of μ at the lower boundary means that the material easily changes its volume without changing its shape. At the upper boundary, the material easily changes its shape with a constant volume value. It is also worth noting that for materials with zero Poisson's ratio, absolutely brittle fracture is observed.

A targeted search for materials with a negative Poisson's ratio (auxetics) began in the late eighties of the last century, which was associated with the solution of the problem of increasing the resistance of foam plastics to compressive deformation.

Figure 4*a* shows an idealized model of the elementary cell of plastic foam. Under the action of compressive stresses, the edges of the polyhedron bend, which leads to their destruction and loss of material stability at small values of deformation.

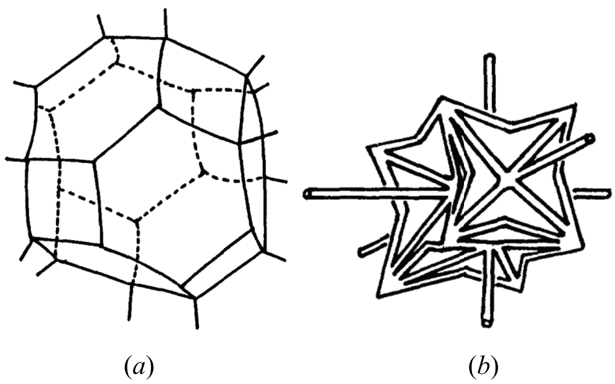


Fig. 4. Cell model of the original (*a*) and modified foam plastic (*b*) [26]

This effect can be avoided if the ribs are allowed to bend reversibly inside the cube (Fig. 4*b*). In this case, the application of compressive stresses leads to a decrease in the material volume, i.e. Poisson's ratio becomes negative.

To achieve such a response to compressive stresses, the authors of [27–28] heated open-cell thermoplastic foam to just above the glass transition temperature, and then subjected it to volumetric compression followed by cooling in the mold. During the process, the walls of the foam cells were bent into these cells.

Figure 5 shows a typical compression diagram of the original and modified foams. As can be seen from the presented graph, the modified foam remains stable at deformations up to 40 %, while the original material loses its stability at deformations less than 10 %.

Figure 6 shows micrographs of the original (*a*) and modified foams (*b*).

When modifying the foam, the same principle was used that was used in the development of electromagnetic metamaterials. The material response required to solve the problem (foam compaction under compressive stresses without damaging the ribs) was “designed” by changing the geometry (physical modification) of already existing cells by bending their ribs into the elementary cell.

The modified silicone foams had a Poisson's ratio of –0.09÷ –0.2 depending on the direction of the loading axis (factor of the initial material + 0.5), a lower modulus of elasticity of 11.8 MPa | (in the initial state 26 MPa) and a higher density of 30 kg·m^{-3} (in the initial state 15 kg·m^{-3}).

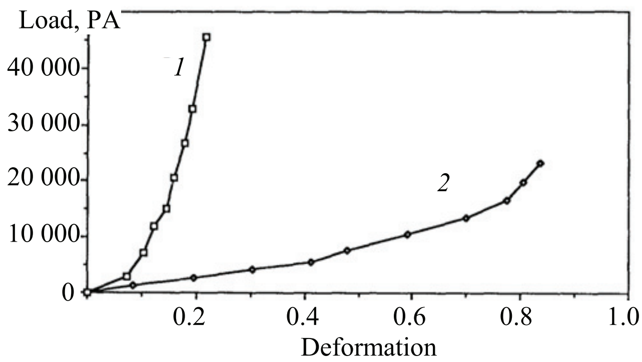
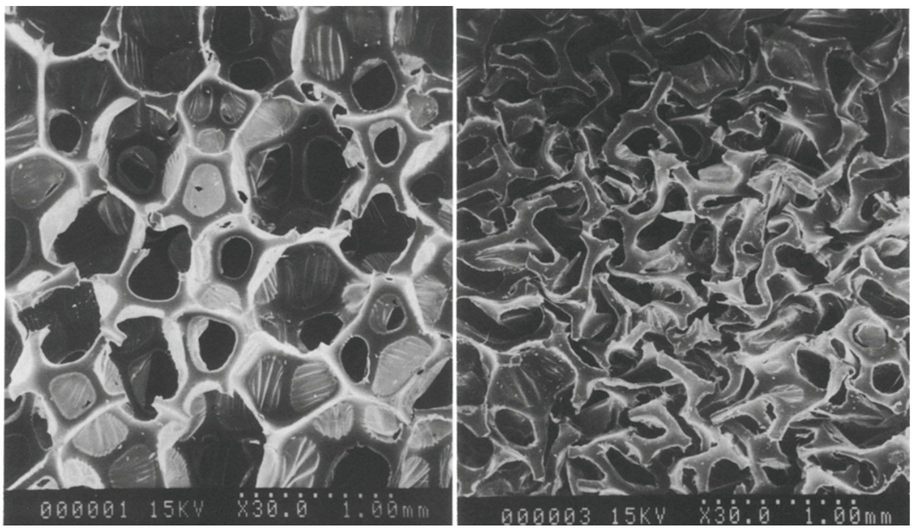


Fig. 5. Load-strain diagram for the original *1* and modified polyurethane foam *2* [26]

An extremely attractive feature of auxetic foams is their high ability to dissipate the energy of an external action. According to the results obtained by the authors of [29], copper foam modified by all-round compression absorbs 13 times more energy than the original foam with the same density.

In addition to foams, porous polytetrafluoroethylene [30], ultrahigh molecular weight polyethylene [31], and polypropylene [32] can be used as starting materials for the production of polymeric auxetics. The microstructure of such materials consists of quasi-spherical particles connected by fibrils. During the preparation process (orientation step), the particles adhere closely to each other. When fibers made from such a material expand, the particles reorient themselves, resulting in an increase in fiber diameter.

One of the models of the mechanism of the auxetic behavior of materials is the joint deformation of elements of the “bow-tie” type (Fig. 7) [33].



(*a*) (*b*)

Fig. 6. Microstructure of the original and modified polyester-based foams [26]

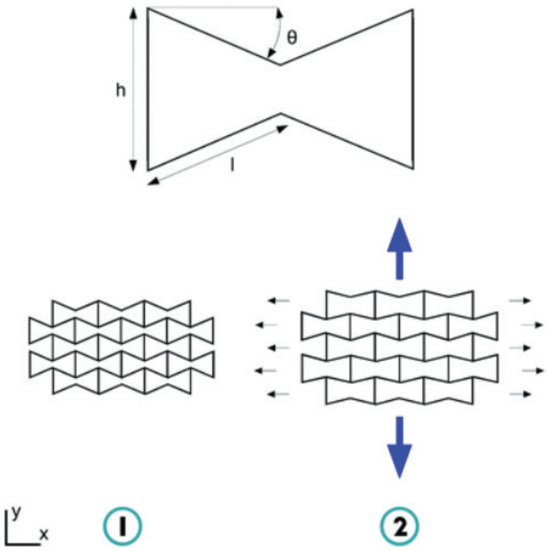


Fig. 7. Model of the mechanism of auxetic behavior of structures from “bow-tie” type elements [33]

As can be seen from the presented figure, when such a structure is stretched, the inward angle increases, which leads to an increase in the volume of the metamaterial. It was found that for hexagonal honeycombs of the “bow-tie” type, the minimum value of Poisson's ratio is –0.99 at an angle θ (Fig. 7) equal to 14.5° and a cell rib length ratio of 0.5 [34].

Based on the development of such models, an alternative approach to the creation of auxetic materials is currently being actively developed, which is inextricably linked with the development of additive technologies [35, 36].

Thus, the authors of [37] synthesized 3D auxetics using the methods of additive technologies (layer-by-layer melting of a metal powder by an electron beam) (Fig. 8).

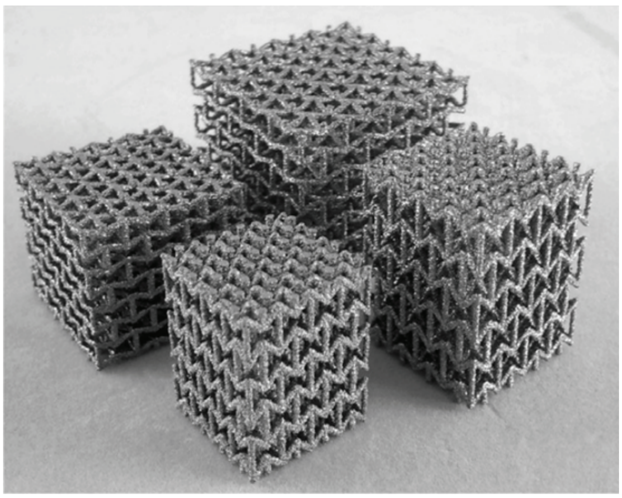


Fig. 8. 3D auxetic synthesized using additive technologies [37]

The study showed that the compressive strength of auxetic structures at the same density increases with decreasing Poisson’s ratio.

A similar material can be obtained using the laser lithography method [38]. The fabricated sample showed the lowest known Poisson’s ratio of –1.18.

The main disadvantage of the described structures is the limited range of deformations in which these structures exhibit auxetic properties, which is associated with the rigidity of the joints and cell edges. To solve this problem, the authors of the work used printing using two materials, which provided structures with soft joints and hard ribs [39].

Auxetic materials can be used to create “soft” actuators for robotics [40], biomedicine [41], flexible electronics [42], and acoustics [43]. It is likely that the rapid development of additive technologies will make it possible to produce more advanced auxetic materials with a given level of properties. Auxetic materials will undoubtedly find wide application in the field of automobile and aviation due to their unique vibration-proof properties [44, 45]. Extremely attractive is the high fracture resistance of auxetics [46].

An ideal structural material should have high stiffness and tensile strength characteristics, high resistance to impact loads and, at the same time, have a low mass. It should be noted that a number of these requirements contradict each other [47].

It is known that the ratio of module for a solid and porous isotropic material is expressed by the formula $E/E_s \sim (\rho/\rho_s)^n$, where E and ρ are the modulus and material density, the index s denotes a porous material, and n exponent varies from 2 to 3 [48]. It is clear that reducing the value of n to 1 will increase the weight efficiency of the use of structural material.

To solve this problem, it is necessary to create a structure of elements that allows [49]:

– localizing the material along the lines of principal stresses (elementary cell edges are the main bearing elements);

– converting the bending deformations of the ribs into compressive tensile deformations due to the design of the elementary cell.

The task of creating such materials at the macro level has long been solved. Suffice it to recall the openwork arches of railway bridges and the graceful ligature of the Shukhov tower. The modern development of additive technologies allows us to apply the same approach, but already at the micro level.

The authors of [48] proposed to use such a material in the form of a structure of elements, each of which is an icosahedrons surrounded by eight tetrahedral Fig. 9*a*–*c*.

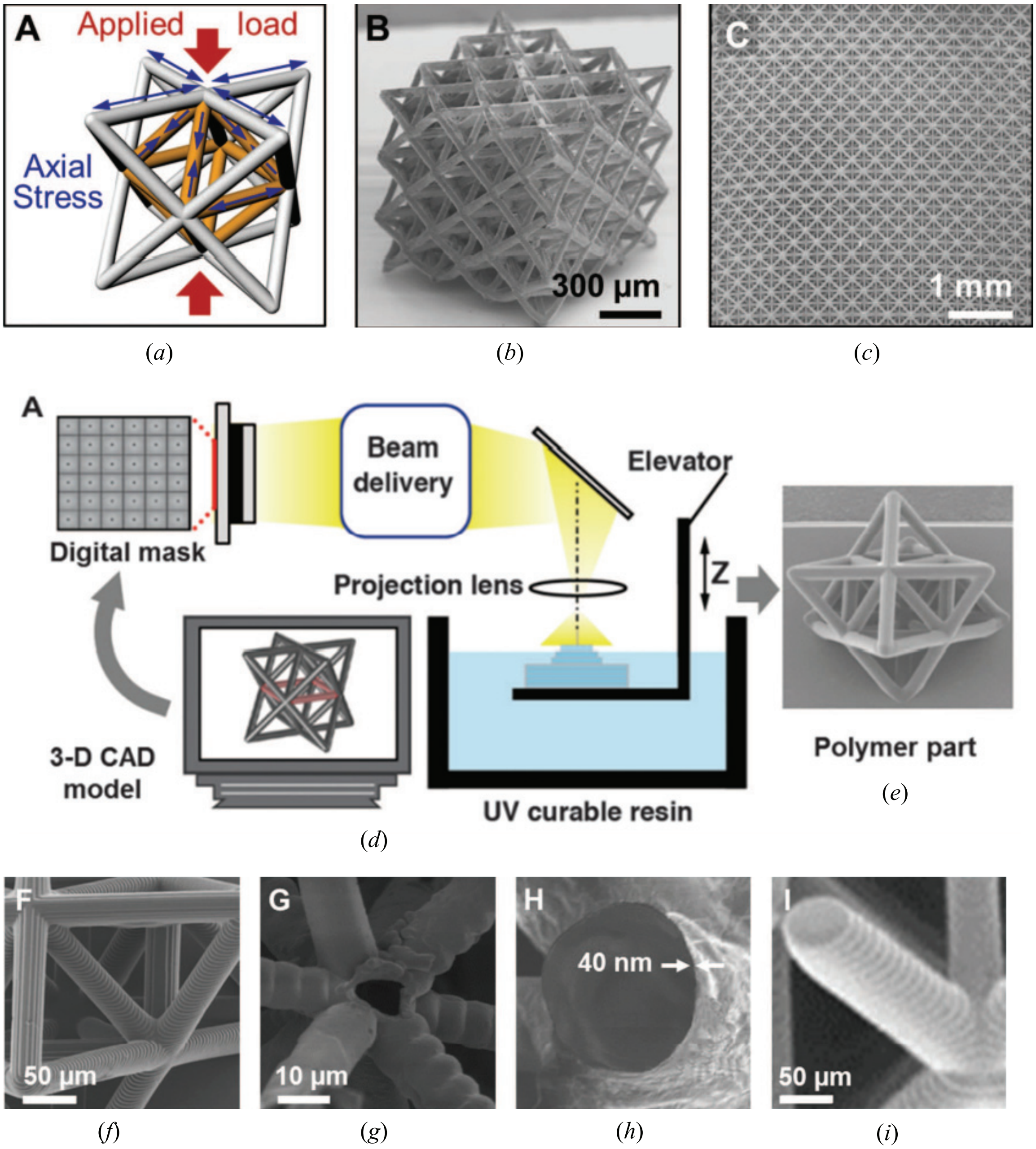


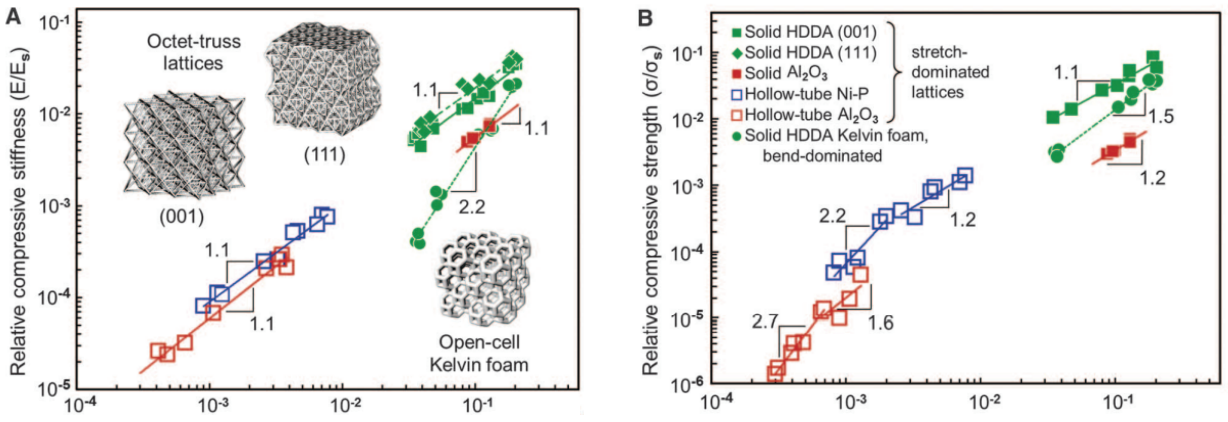
Fig. 9. Diagram for lattice creation and their micrographs [48]

Initially, the lattice was made by layer-by-layer polymerization of a UV-curable polymer. Next, a nickel layer was deposited on the prepared template by electrochemical deposition. To obtain ceramic superlattices from aluminum oxide, the method of atomic layer deposition was used [50, 51]. Subsequently, the polymer matrix was removed during heat treatment, while the lattice edges were hollow tubes with a wall thickness of 40 nm. The final density of the obtained materials ranged from 1 to 10 kg·m^{-3}. The results obtained by the authors are shown in Fig. 10.

As can be seen from the data presented, for the lattices with a predominance of tension under mechanical load, the exponent n is 1.1, which is close to the theoretical limit. For a lattice dominated by bending, the exponent n is 2.2.

It is noteworthy that the dependence of the relative strength on the relative density during uniaxial compression of hollow lattices deviates from the linear law. In addition, the relative strain for lattices of this type ranges from 8 to 20 %, which turns out to be significantly higher than for gratings with solid ribs. This is probably due to a decrease in the size of microcracks at a nanometer thickness of the rib wall [52].

Thus, the use of a system of elements organized in a certain way, made of conventional materials to



(*a*) (*b*)

Fig. 10. Dependence of the relative stiffness (*a*) and strength (*b*) of microlattices under uniaxial compression on the relative density of the material [48]

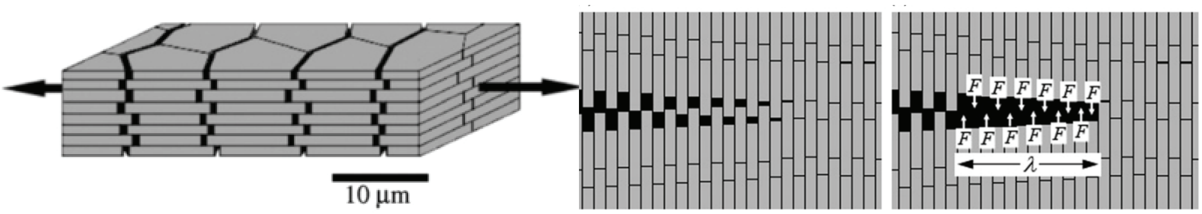


Fig. 11. Structure of natural mother-of-pearl [54]

"design" its required response to external influences, is an extremely promising approach for the development of new materials.

In a number of cases, it is precisely this path that evolution in wildlife chooses to create materials that ensure the survival of the organism. One of the classic examples of this approach is the structure of the mollusks shell [53]. In the three-dimensional structure of mother-of-pearl, plates of solid calcium carbonate are connected by a "soft" layer of proteins and polysaccharides (Fig. 11).

When a crack occurs and propagates, the plates (Fig. 11) can slide relative to each other, providing not only a high level of energy dissipation, but also the occurrence of stresses that tighten the crack mouth [54].

3. Conclusion

Based on the data presented, it can be concluded that the development of metamaterials of various types (electromagnetic, acoustic, mechanical) is characterized by a single approach - an "unusual" response of the environment to external influences, which determines the unusual properties of metamaterials, is created by using a system of elements organized in a certain way made from common, well-known materials. In fact, the development of metamaterials represents a new approach in materials science, when the structure and properties of a material are determined not by chemical, physical, thermodynamic properties of atoms, but by the task being solved and controlled by a person. It was this approach that evolution used to create materials that ensure the optimal adaptation of a living organism.

Additive technologies are an optimal tool for implementing this approach. It should be expected that their rapid development will lead to the creation of new metamaterials with unique properties that will largely determine the technological image of the 21st century.

4. Funding

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5. Conflict of interests

The authors declare no conflicts of interest.

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