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COMPUTER MODELING AND EXPERIMENTAL STUDIES OF PLASTIC REGULAR STRUCTURES OBTAINED BY ADDITIVE TECHNOLOGIES

Research article

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Abstract

The results of modelling regular structures made of plastics and studying their destruction can be effectively used as a starting method for development of a technology for manufacturing composite materials. Numerical experiments and field tests helped to determine the most preferred types of structures – plastic-based honeycomb structures with the following strength properties: Young's modulus, E = 342.3 MPa, compressive strength, σ = 20.4 MPa, specific strength, σ_{sp} = 81 MPa cm^3/g. Plastic 3D models were utilized in manufacturing of metal composites using a technology combining selective laser melting of titanium frame from powders and infiltration with more fusible alloys. The values of the bending strength change within the range from 1440 to 1560 MPa, the values of the Young's modulus – from 49500 to 54000 MPa, hardness – 400HB. The increased strength values can be explained by the composite structure of the material formed by the combination of two mutually penetrating frameworks.

Keywords: additive technologies, plastic prototypes, regular structures, metal composites, infiltration, strength properties.

КОМПЬЮТЕРНОЕ МОДЕЛИРОВАНИЕ И ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ ПЛАСТИКОВЫХ РЕГУЛЯРНЫХ КОНСТРУКЦИЙ ПОЛУЧЕННЫХ АДДИТИВНЫМИ ТЕХНОЛОГИЯМИ

Научная статья

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Аннотация

Результаты моделирования регулярных конструкций из пластмасс и изучения их разрушения могут быть эффективно использованы в качестве отправной точки для разработки технологии изготовления композиционных материалов. Численные эксперименты и полевые испытания помогли определить наиболее предпочтительные типы конструкций – сотовые конструкции на основе пластика со следующими прочностными характеристиками: модуль Юнга Θ = 342,3 МПа, прочность на сжатие σ = 20,4 МПа, удельная прочность σsp = 81 МПа см3/г. Пластиковые 3D-модели были использованы при изготовлении металлических композитов с использованием технологии, сочетающей селективное лазерное расплавление титанового каркаса из порошков и пропитку более легкоплавкими сплавами. Значения прочности при изгибе изменяются в пределах от 1440 до 1560 МПа, значения модуля Юнга – от 49500 до 54000 МПа, твердость – 400HB. Повышенные показатели прочности можно объяснить композитной структурой материала, образованной сочетанием двух взаимопроникающих каркасов.

Ключевые слова: аддитивные технологии, пластиковые прототипы, регулярные конструкции, металлические композиты, инфильтрация, прочностные свойства.

Introduction

Additive technologies of 3D printing methods by fused deposition modelling (FDM) have a number of advantages over other traditional processing methods for manufacturing composites: powder metallurgy, fabric and woven prepregs, investment casting, etc. They enable obtaining complex spatial structures with unprecedented geometry and high performance in accordance with a computer model. Their use makes it possible to form so-called lattice structures formed by repeating regular geometric cells in space (stochastic and regular) – arranged by 3D printing, this architecture gives polymer, metal, or ceramic materials a unique combination of properties that cannot be achieved by traditional methods: increased values of specific strength, specific surface area, heat transfer coefficient, elastic modulus, etc. As a result, we have extended prospects for application in various fields: manufacture of geometrically-complex parts for mechanical engineering, aerospace industry, biomedicine, oil and gas industry, etc. [1], [2]. A number of papers provide data on the effect of the composition and structure of the arrangement of layers on the physical and mechanical properties and suggest options for topological optimization of surfaces of the gyroid and honeycomb structures to obtain products for various purposes with properties set at the design stage. The works [1], [2], [3], [5] provide examples of the practical use of the FDM method in creating contour-complex solid parts made of plastics, metals, and alloys. Despite a significant amount of studies and applied work in the field of additive technologies, the problems of topological optimization of structures obtained by 3D printing are still relevant, first of all, due to the need to adapt them to the shape, size and operating conditions of a particular product, and the modelling of parts with complex geometry requires further improvement and development. In addition, topological optimization on plastic prototypes reduces the amount of experimental tests and speeds up the procedure of subsequent transformation and adaptation in relation to structures made of metals and alloys. In the field of additive technologies, designers have also developed other methods to increase the density and strength of materials obtained by Selective laser melting (SLM). Metal compositions based on titanium and its alloys [6], [7] etc. can also be produced by a combination of printing technology and application of an intermediate liquid layer of a binder between the layers of the base material. Residual porosity in materials obtained by layer-by-layer deposition can also be eliminated by infiltration, i.e. impregnation with a melt of other (more fusible) material [8], [9], [10]. The aim of this study is to model regular structures made of plastics and the processes of their destruction as a starting method in the development of a technology for manufacturing metal composite.

Results of numericaland experimental studies of regular structures made of plastics

The first stage of research was to analyze the state of the problem, and promising directions and designs of regular structures for subsequent manufacture of composite materials. Preliminary numerical calculations (Cura, Prusa, and Solidworks Simulation software products) to determine the stress-strain state of various types of structures are necessary to reduce the number of field experimental studies. The images of the models, the topology of the samples, and the assessment of the stresses arising in the samples' volumes are shown in Fig. 1. The numerical analysis of the strength of various types of structures according to the model showed that the longitudinal construction of layers is preferable to the transversal (35%), and the honeycomb structure provides strength higher than the gyroid one (75%).

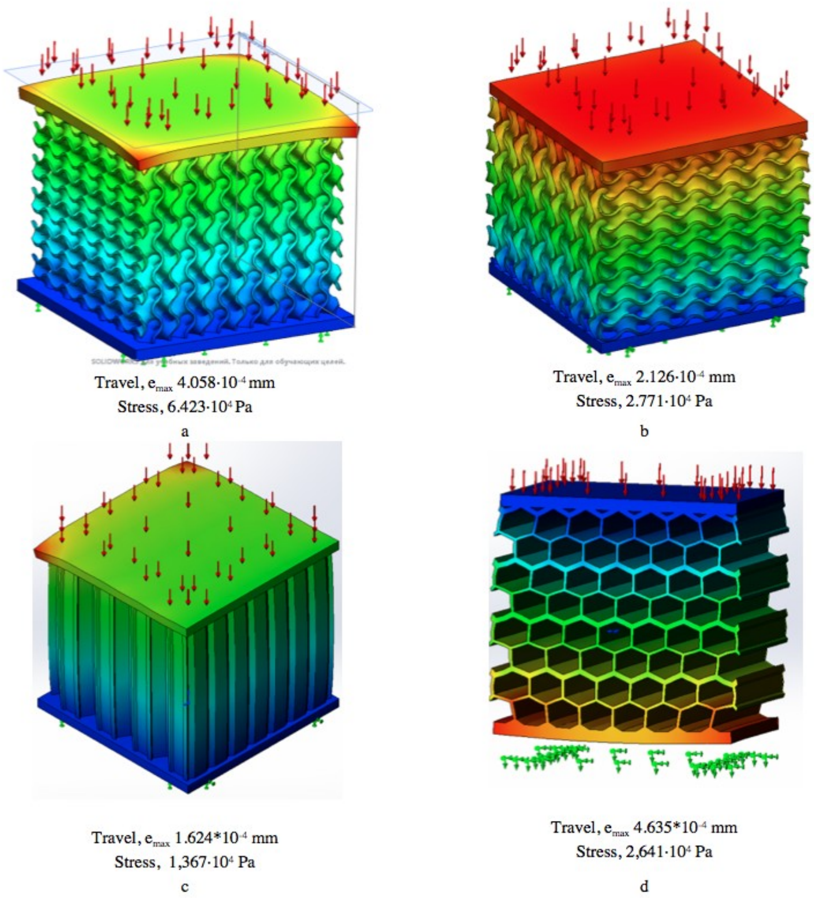

Figure 1 - Types of structures:
a – gyroid, transversal along the normal to the construction axis; *b* – gyroid, longitudinal along the construction axis; *c* – honeycomb, longitudinal along the axis of construction; *d* – honeycomb, transversal along the normal of the axis of construction

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A numerical assessment of the strength properties was carried out on samples of ten different types of structures made of plastics – acrylonitrile butadiene styrene (ABS) and polylactide (PLA). Using the FDM technology and a Hercules printer, our team made 40x40x40 mm samples with cell sizes from 1 mm to 5 mm (large honeycomb) for compression testing. An experimental analysis of the strength properties was carried out on the samples of ten different types of structures made of ABS and PLA plastics.

The compression tests of the samples were carried out in accordance with ISO 604:2002 on a Tinius Olsen 100ST universal testing machine, which enables to measure deformations with a video extensometer (Fig. 2a). The specific strength was calculated taking into account the fact that the density of the samples when filled with plastic material for 20% of the total volume is 0,25 g/cm^3 for the honeycomb, and 0,21 g/cm^3 for the gyroid.

The Tinius Olsen H25KT universal testing machine was used to determine the bending strength (Fig. 2b). The VT6 titanium samples with an aluminium or bronze binder had dimensions and shape in accordance with ISO 3325:1996: length: 50 mm; width: 10,0 ± 0,1 mm; height: 5,0 ± 0,10 mm. Rockwell hardness was measured on a TP50-14 on a C scale with a load of 1500 N subject to ISO 6508-86. Determination of the density and calculation of the porosity of the samples was carried out according to the standard method of hydrostatic weighing on an EX205 analytical balance by Mettler Toledo with a hydrostatic weighing kit. The study of the morphology of the initial powders, microstructure and elemental composition of the obtained samples was carried out by the methods of secondary electrons and energy dispersive microanalysis using a JEOL JSM-7001F scanning electron microscope equipped with an INCA Penta FETx3 X-ray spectrometer by Oxford Instruments. The microstructure of the samples was studied on polished surfaces using a JEOL JSM-7500FA scanning electron microscope.

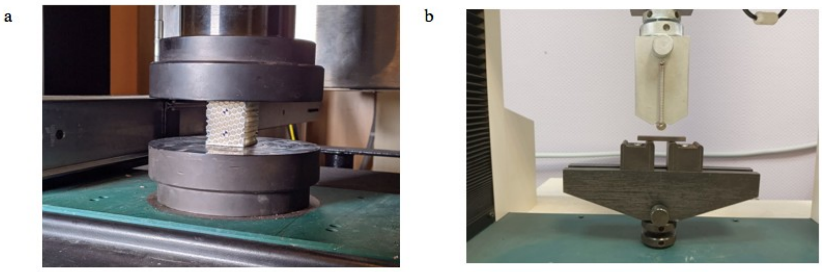

Figure 2 - Testing equipment:
a – for compression tests; *b* – for bending strength
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It is worth noting that the deformation processes and the destruction pattern of most samples with structures of different topologies occur in accordance with the forecasts based on the model and classical concepts of destruction of materials, for example, along the direction of the shear planes (Fig. 3). This indicates a fairly high quality of 3D-print construction of the regular structures.

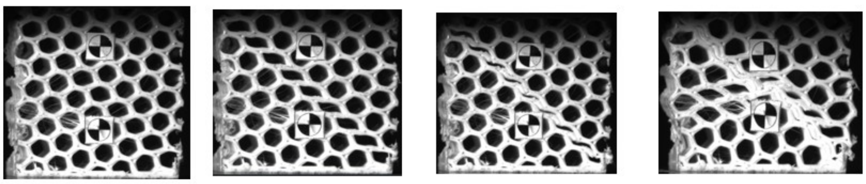

Figure 3 - Stages of destruction of the walls of the honeycomb under loading
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The corresponding experimental deformation diagrams in the load-displacementl and stress-deformation coordinates for some samples of honeycomb and gyroid structures with different topologies are shown in Fig. 4 and 5.

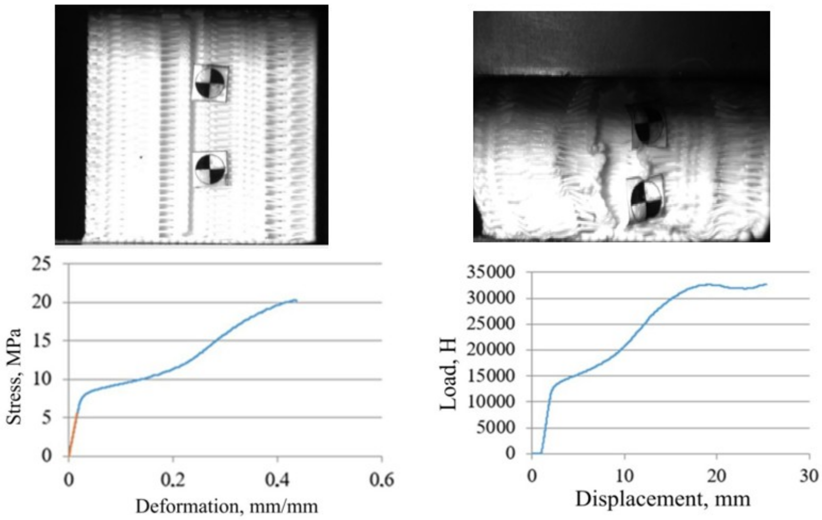

Figure 4 - Measurement results of sample 3
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Note: PLA2 honeycomb, longitudinal along the growth axis

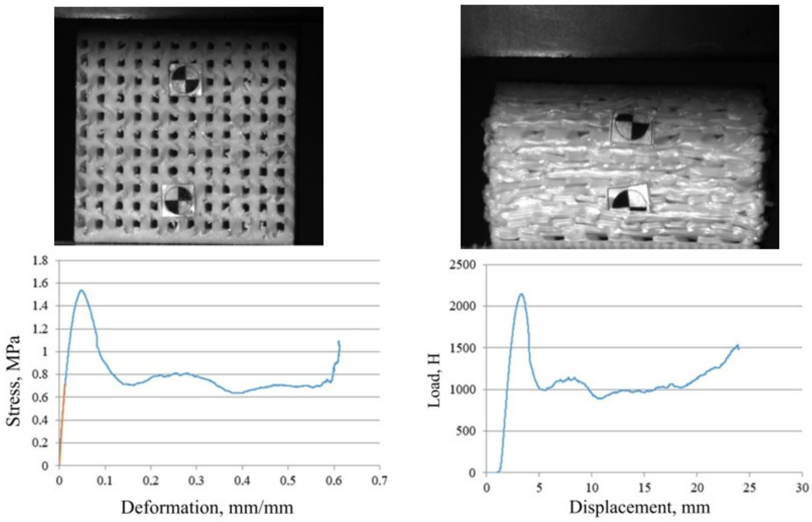

Figure 5 - Sample 8 – ABS4 gyroid, longitudinal along the growth axis
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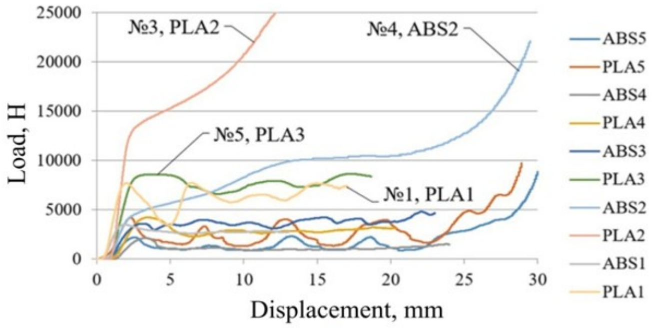
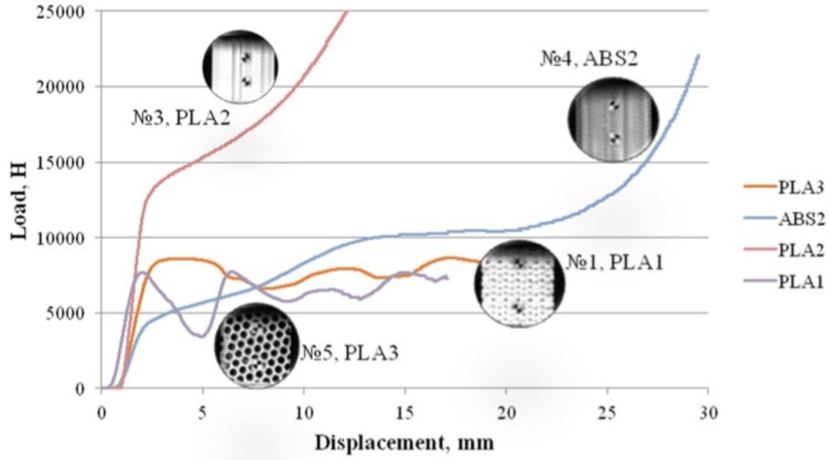
A more visual representation of the measurement results and differences in the behaviour of the samples with different topological honeycomb and gyroid structures and materials under load is shown in Fig. 6. The analysis of the obtained curves and their nonmonotonic nature indicates the staging of fracture in most of the samples.



a



b

Figure 6 - Deformation patterns during compression:
a – for all samples; *b* – for samples with the best strength values
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Obviously, according to the diagrams in Fig. 6a), the most preferred material for the manufacture of frame structures is PLA, which provides a higher level of strength properties (curves 1, 3, 5, 7, 9) for all types of structures in contrast to the ABS samples (curves 2, 4, 6, 8, 10). Comparison of the samples of different topologies shows the advantages of the honeycomb structures with their location parallel to the loading axis (samples 3, 4 in Fig. 6a and Fig. 6b). Regardless of the material, reliable load strengths for the PLA and ABS samples lie in the range from 10 to 25 kN, which is the main governing factor. For the samples with other topology – a gyroid and a transverse honeycomb (samples 1 and 5 in Fig. 6b) made of PLA – the operability zone is from 5 to 10 kN. The curves for the remaining samples have insignificant differences, the maximum load strength lies in the region under 5 kN. But their distinctive feature is the pronounced cyclicity (discreteness) of the destruction processes, and numerous peaks, which is explained by the layered structure. In [1], [5], the authors observed similar effects on the gyroid and Schwartz primitive structures, and explained them by the fact that each of the peaks-extrema corresponds to the destruction of one of the layers of cells lying in a plane perpendicular to the loading axis. At the same time, they considered the first peak on the deformation curve, which corresponds to the transition of the sample to the region of plastic deformation, as the strength of the samples. For the structures studied in this work, however, this approach is not entirely correct since each of the numerous peaks on the curves, in our opinion, corresponds to the gradual folding of the walls in the adjacent (most stressed) layers of the sample following the mechanism of elastic-plastic deformations (irreversible upon reaching *peak* stresses on the curves at which a load drop is observed). A further increase in the load and the appearance of extrema on the curves refers to the next stage of the deformation processes of other successive layers of the structure along the compression axis. At the same time, honeycomb structure (curves 3 and 4 – Fig. 6) have a more monotonous nature, similar to the behaviour of plastic materials under load, which is their main advantage. Thus, the results of processing all experimental data (table 1) indicate that the most preferred structure is the longitudinal honeycomb, and the most preferred material is PLA (sample 3), which provide the best combination of elastic and strength properties. Besides, the experimental results show a satisfactory agreement with the model prediction.

Table 1 - Physical and mechanical properties of the obtained samples

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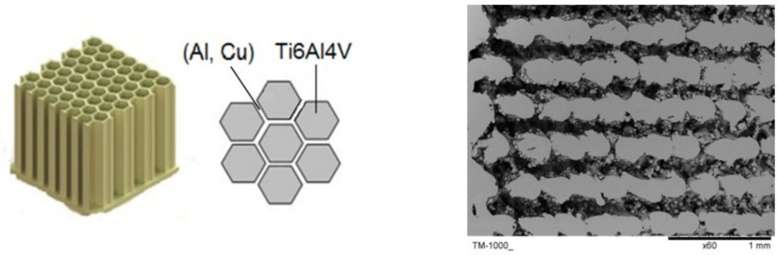
Sample	Material	Structure type	Young's modulus, MPa	Tensile strength, MPa	Specific strength, MPa · cm³/g
1	PLA1	Transverse honeycomb along the normal of the growth axis	206,9	5,58	22,32
2	ABS1		94,8	2,6	13,0
3*	PLA2	Longitudinal honeycomb along the growth axis	342,3	20,4	81,2
4	ABS2		136,78	13,8	69,0
5	PLA3	Transverse gyroid along the normal of the growth axis	144,13	5,52	22,08
6	ABS3		82,15	2,48	12,4
7	PLA4	Longitudinal gyroid along the growth axis	124,28	3,01	12,04
8	ABS4		58,21	1,54	7,7
9	PLA5	Transverse honeycomb (large cells) along the normal of the growth axis	80,5	2,63	10,52
10	ABS5		42,9	1,38	6,9

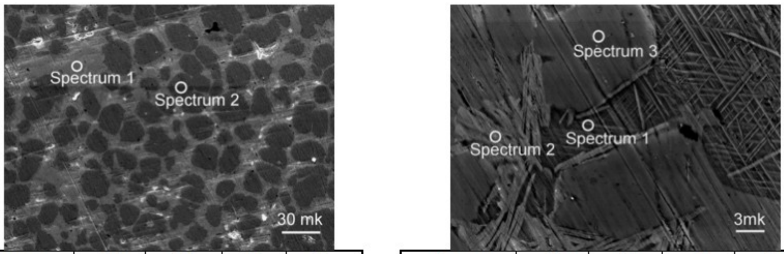
Thus, based on numerical analysis and experimental tests, we determined the most preferred types of structures – PLA honeycomb structures with the following strength properties: Young's modulus, E = 342,3 MPa, compressive strength, σ = 20,4 MPa, specific strength, σ_{sp} = 81 MPa• cm³/g (when 20% of the total volume of the honeycomb structure is filled with plastic material, and the same for the gyroid structure is 21%). The achieved level of properties is comparable with the results of other researchers given in [1], [2], [4], [5] in terms of specific strength, but almost 2 times exceeds them in terms of the ultimate load taken to failure. Besides, the experimental results show a satisfactory agreement with the model prediction, which makes it possible to recommend the method of creating plastic models using Cura, Prusa, Solidworks Simulation for further practical application when manufacturing products from metal powders.

Results of experimental studies of metal composites produced by SLM-method

That is why, we used computer models of particularly these porous regular structures with the best strength indicators to manufacture TI6AL4V titanium alloy samples by additive technologies (SLM) and then infiltrate them with a melt of a more fusible aluminium bronze as a binder. The results of studies of the microstructure of Ti6Al4V+aluminium bronze composite materials are given in Fig. 7. Application of the phase contrast method revealed the presence of two main phases: Ti6Al4V (Fig. 7c) – spectrum 2; and aluminium bronze (Fig. 7c) – spectrum 1. The results of scanning electron microscopy of the microstructure of the regular honeycomb samples impregnated with an aluminium bronze melt (composite material), and determination of relative density (98% of the theoretical density) indicate a fairly high efficiency of filling the honeycomb voids and the elimination of residual porosity (Fig. 7b). Images of the microstructure and chemical analysis of phase components indicate a fairly high uniformity of the structure and efficiency of infiltration (Fig. 7d) – spectrum 1-3); density and residual porosity (less than 1%) confirm this fact. A very interesting effect, which was found during the study of the microstructure of the low-temperature-melting phase, is the formation of an acicular structure with marked elongated crystallized grains – "whiskers" with a cross-sectional size of 0,1 µm (Fig. 6d). The appearance of this reinforced fragmentary-nanostructured phase in a composite material gives cause to assume the possibility of dispersion strengthening of aluminium bronze and, as a result, of the composite as a whole. The fracture surface of the samples after bending tests has a quasi-plastic pattern, which can be explained by the dominant influence of the properties of the infiltrated material (aluminium bronze). Similar structures are formed during ordinary sintering of hard alloy composites obtained from bimodal powder mixtures of WC-Co-Al(Al_2O_3) [8] and copper-based pseudoalloys [9]. The density, porosity, the patterns of the phase components distribution, strength, microhardness, and Brinell hardness were studied on samples in conformity with the standard methods.



a b



Spectrum	Al, atom. %	Ti, atom. %	V, atom. %	Cu, atom. %
Spectrum1	12,79	50,90	-	36,31
Spectrum2	3,28	93,29	2,30	1,13

c

Spectrum	Al, atom. %	Ti, atom. %	V, atom. %	Cu, atom. %
Spectrum1	10,10	54,30	11,61	23,99
Spectrum2	2,27	46,73	1,74	49,26
Spectrum3	12,09	51,41	-	36,50

d

Figure 7 - Microstructure of Ti6Al4V+aluminium bronze composite materials:
a – scheme of infiltration; *b* – surface of the composite material infiltrated with aluminium alloy; *c* – images of the microstructure with selected areas of chemical analysis and their composition; *d* – acicular structure by volume of the binder with selected areas of chemical analysis and their composition
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Note: c — x500; d — x3500

In addition to increasing the density, the level of strength properties of honeycomb structures made of titanium alloy also increases, since aluminium bronze provides a redistribution of stresses that occur in the titanium frame under load. Measurements of the bending strength of the Ti6Al4V-bronze samples obtained using the infiltration technology showed an up to 25% increase in strength in comparison to the “green model” (table 2). Bending strength values vary in the range from 1440 to 1560 MPa, Young’s modulus varies from 49500 to 54000 MPa depending on the composition of the composite material, and SLM modes – radiation power and beam movement speed.

Table 2 - Strength properties of TI6AL4V composites
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Sample №	Composites	Young’s modulus, MPa	Ultimate tensile strength, MPa	Hardness, HB
1	Ti6Al4V – (bronze)	54737,4	1443,6	390
2	Ti6Al4V– (bronze)	50447,9	1453,4	390
3	Ti6Al4V– (bronze)	49459,06	1567,7	410

To some extent, the anomalously high hardness values can be explained by the disperse strengthening of the bronze phase and the composite structure of the material formed by a combination of two mutually penetrating structures – the titanium frame printed using the SLM method and the binder of aluminium bronze. The composite structure, in accordance with the mechanics of the phases and the known provisions of the material failure theory, should have higher strength properties.

Conclusion

In the process of complex numerical and experimental studies, our team found the patterns of deformation processes and destruction of various types of regular structures 3D-printed of plastics in accordance with the computer model and the most preferred materials and honeycomb structures from the point of view of strength properties. The results of preliminary tests on plastic prototypes were used in the development of compositions and manufacturing technologies for metal composite materials based on Ti6Al4V titanium alloy powders. The study of the strength properties of Ti6Al4V structures obtained by 3D printing in combination with infiltration with aluminium bronze confirmed the effectiveness of the adopted design and technological solutions – an increase in bending strength by 20-25% compared to the base Ti6Al4V, and up to 1,5 times increase in the hardness values. Electron microscopy confirmed the homogeneity of the phase distribution in the composite structure, and the absence of residual porosity.

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Конфликт интересов

Не указан.

Conflict of Interest

None declared.

Рецензия

Все статьи проходят рецензирование. Но рецензент или автор статьи предпочли не публиковать рецензию к этой статье в открытом доступе. Рецензия может быть предоставлена компетентным органам по запросу.

Review

All articles are peer-reviewed. But the reviewer or the author of the article chose not to publish a review of this article in the public domain. The review can be provided to the competent authorities upon request.

Список литературы на английском языке / References in English

1. Chen L.-Y. Additive manufacturing of metallic lattice structures: Unconstrained design, accurate fabrication, fascinated performances, and challenges / L.-Y. Chen, S.-X. Liang, Y. Liu [et al.] // Materials Science and Engineering: R: Reports. — 2021. — Vol. 146. — P. 100648.
2. Najmon J.C. Review of additive manufacturing technologies and applications in the aerospace industry / J.C. Najmon, S. Raeisi, A. Tovar // Additive manufacturing for the aerospace industry. — 2019. — P. 7–31.
3. Henderson L. Towards bio-inspired structural design of a 3D printable, ballisticallydeployable, multi-rotor UAV / L. Henderson, T. Glaser, F. Kuester // IEEE Aerospace Conference, IEEE. — 2017. — P. 1–7.
4. Mosaddek A. Design and testing of a recycled 3D printed and foldable unmanned aerial vehicle for remote sensing / A. Mosaddek, H. Kommula, F. Gonzalez // International Conference on Unmanned Aircraft Systems, IEEE. — 2018. — P. 1207–1216.
5. Balabanov S.V. 3D printing and mechanical properties of polyamide products with “primitive Schwartz” topology / S.V. Balabanov, A.I. Makogon, M.M. Sychev [et al.] // Journal of Technical Physics. — 2020. — Vol. 90. — Issue 2. — P. 223–227.
6. Xiong Y. Fabrication of porous titanium implants by three-dimensional printing and sintering at different temperatures / Y. Xiong, C. Qian, J. Sun // Dental Materials Journal. — 2012. — Vol. 31. — Issue 5. — P. 815–820.
7. Sheydaeian E. (2017) Material process development for the fabrication of heterogeneous titanium structures with selective pore morphology by a hybrid additive manufacturing process / E. Sheydaeian, K. Sarikhani, P. Chen [et al.] // Materials & Design. — Vol. 135. — P. 142–150.
8. Gordeev Y.I. Investigation into the peculiarities of structure formation and properties of copper-based powder pseudoalloys modified by ZnO and TiN nanoparticle additives / Y.I. Gordeev, A.K. Abkaryan, A.V. Surovtsev [et al.] // Russian Journal of Non-Ferrous Metals. — 2019. — Vol. 60. — P. 68–75.
9. Gordeev Y.I. Study of the formation features of hard metal composites structure obtained from bimodal powder mixtures / Y.I. Gordeev, V.B. Yasinskiy, N.E. Anistratenko [et al.] // In IOP Conference Series: Materials Science and Engineering. — IOP Publishing. — 2019. — Vol. 511. — Issue 2. — P. 12032. — DOI: 10.1088/1757-899X/511/1/012032.
10. Kernan B.D. Homogeneous steel infiltration / B.D. Kernan, E.M. Sachs, S.M. Allen [et al.] // Metallurgical and Materials Transactions. — 2005. — Vol. 36. — № 10. — P. 2815–2827.