Materials and Coatings Fabricated Using the Additive Manufacturing Technologies
Материалы и покрытия, получаемые методами аддитивных технологий

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Additive manufacturing of functionally graded products by selective laser melting: A review

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Abstract. This paper presents a review of recent advances in functionally graded additive manufacturing using selective laser melting (SLM, also referred to as laser powder bed fusion, LPBF). The fundamental principles of producing functionally graded products by SLM are discussed, including approaches to forming compositional and structural gradients. Particular attention is given to the formation of the transition layer in the synthesized material, which is crucial for achieving the desired properties of the products. Methods of design and numerical modeling of functionally graded structures are analyzed, including the use of artificial intelligence and machine learning. It is demonstrated that applying bio-inspired design principles enables the development of parts with enhanced mechanical, thermal, and functional properties. Examples are provided of successful fabrication of multi-material products with tailored property anisotropy, as well as products with controlled porosity gradients. The promising application areas of functionally graded products are identified, including aerospace, medicine, mechanical engineering, and energy.

Keywords: selective laser melting, functionally graded materials, multi-materials, metamaterials, design, artificial intelligence

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Аддитивное производство изделий с функционально-градиентной структурой по технологии селективного лазерного сплавления Обзор

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Аннотация. Представлен обзор современных достижений в области функционально-градиентного аддитивного производства по технологии селективного лазерного сплавления (СЛС). Рассмотрены основные принципы создания изделий с функционально-градиентной структурой методом СЛС, включая способы формирования градиентного состава и структуры. Описан процесс формирования переходного слоя синтезируемого материала, который является ключевым для обеспечения требуемых свойств изделий. Проанализированы методы проектирования и моделирования изделий с функционально-градиентной структурой, в том числе с использованием искусственного интеллекта и машинного обучения. Показано, что применение природоподобных принципов строения позволяет создавать изделия с улучшенными механическими, тепловыми и функциональными свойствами. Рассмотрены примеры успешного получения мультиматериальных структур с заданной анизотропией свойств, а также изделий с контролируемым градиентом пористости. Определены перспективные направления применения изделий с функционально-градиентной структурой, включая аэрокосмическую отрасль, медицину, машиностроение и энергетику.

Ключевые слова: селективное лазерное сплавление (СЛС), функционально-градиентные материалы, мультиматериалы, метаматериалы, проектирование, искусственный интеллект

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Introduction

Functionally graded materials (FGMs) are an advanced class of materials distinguished by a continuous variation of composition, structure, and properties along one or more directions [1]. The concept was first introduced in Japan in the 1980s for aerospace applications, as a means of producing heat-resistant materials capable of withstanding steep thermal gradients and high mechanical loads [2]. Unlike conventional composites, where sharp interfaces separate the constituent phases, FGMs exhibit smooth transitions in properties. This reduces stress concentrations at the interfaces and improves the overall reliability of parts [3]. In recent years, additive manufacturing – particularly selective laser melting (SLM, also referred to as laser powder bed fusion, LPBF) – has become one of the most effective approaches for fabricating FGMs [4]. The ability to precisely control process parameters and material composition at the microscale makes it possible to design functionally graded products with tailored distributions of density, porosity, hardness, thermal and electrical conductivity, corrosion resistance, biocompatibility, and other properties [5]. Such control enables practical solutions to engineering challenges, including reducing structural weight without sacrificing strength, enhancing thermal cycling resistance, improving damping capacity, and producing biomedical implants with porosity gradients to promote osseointegration [6].

The potential of FGMs is further expanded through bio-inspired design principles. Bio-inspired materials emulate strategies refined by nature over millions of years of evolution [7–11]. Natural systems achieve exceptional performance and multifunctionality by combining heterogeneous structures in complex hierarchical architectures. While biological materials are limited to naturally available constituents, modern researchers can draw from a vast range of synthetic options [12; 13]. Organisms organize materials from the nano- to the macroscale, displaying distinct mechanical, electrical, optical, and surface properties, as well as adaptive shape-changing capabilities. Notable examples include fish scales with excellent protective functions, spider silk and nacre with outstanding strength, and plants or animals capable of shape transformation for survival [14–17]. Inspired by these natural designs, engineers are developing commercial parts across mechanical engineering, robotics, aerospace, and architecture. The degree to which biomimetic concepts can be realized, however, depends directly on the precision of available fabrication technologies [18–23].

Research on the design and production of functionally graded products is now being actively pursued worldwide. The Fraunhofer Institute in Germany has accumulated extensive expertise in fabricating such structures from metals, ceramics, and polymers. Similar research is carried out at the University of Minho (Braga, Portugal), Washington State University, Harbin Engineering University, Huazhong University of Science and Technology, Delft University of Technology, Singapore University of Technology and Design, and Peter the Great St. Petersburg Polytechnic University, among others.

This review summarizes current progress in functionally graded additive manufacturing using SLM. It highlights the fundamental principles of gradient formation in structure and composition, the role of transition layers in synthesized materials, advances in design and modeling methods, and emerging directions for application.

Functionally graded materials with variable microstructure

The key SLM process parameters that determine the microstructure and properties of fabricated parts include laser power, scanning speed, hatch distance, and layer thickness. Their combined effect defines the volumetric energy density delivered to the material, which in turn governs the melting mode, cooling rate, microstructural evolution, and defect formation. Depending on the selected scanning strategy and parameter set, the resulting structure may consist of oriented grains with a preferred crystallographic orientation, more uniformly distributed equiaxed grains, or a combination of both [24]. A functionally graded component incorporating regions of fine-grained and highly oriented coarse-grained microstructures demonstrates the feasibility of producing materials with user-defined functional characteristics in different zones of a single part. At the same time, the anisotropy of mechanical properties is strongly influenced by the prevailing texture [25].

In the case of Inconel 718 fabricated by SLM, heat treatment preserves the as-built grain texture and morphology without signs of recrystallization. However, it promotes the formation of acicular δ-Ni_3Nb precipitates and untransformed Laves phases, which reduce ductility while improving yield strength by creating barriers to dislocation motion [26]. Even after hot isostatic pressing (HIP), a sharp microstructural boundary between fine- and coarse-grained regions is retained, along with a dominant (100) texture in the coarse columnar grain zones. Mechanical properties are markedly improved due to the dissolution of undesirable Laves and δ phases and the elimination of pores, strengthening the grain-size dependence of yield strength in accordance with the Hall–Petch relationship. The combined "HIP + heat treatment" approach provides superior mechanical performance compared with both cast and wrought Inconel 718 [28].

The developed technology for creating graded structures in nickel alloys also enables control over the propagation of fatigue cracks as they pass through the interfacial zone between different microstructures, thereby slowing crack growth and delaying failure [26]. It has been shown that when a fatigue crack propagates across such an interfacial zone, its trajectory changes, which results in a reduced growth rate (Fig. 1).

Functionally graded materials with variable composition

Recent advances have enabled the fabrication of multi-material products with enhanced mechanical properties in a single production cycle by SLM [29]. However, this requires significant modifications to the printer design and the development of technologies for feeding and distributing two or more powder materials, as well as their subsequent separation [30]. In addition, the selected materials must be metallurgically compatible and capable of forming reliable, defect-free bonding [31]. Studies of the "heat-resistant bronze – heat-resistant nickel alloy VZh159 – BrKhZrTV" system produced by SLM have shown that a substantial increase in energy input markedly reduces porosity in the interfacial zones of multi-material samples (Fig. 2, *a*). Elemental distribution within the interfacial zone is characterized by Ni–Cu interdiffusion across the interface (Fig. 2, *b*), while microhardness gradually changes from alloy VZh159 to BrKhZrTV over a distance of about 300 μm (Fig. 2, *c*) [32–34].

Complete mixing of the alloys, in which both materials are detected in the *X*-ray patterns, continues

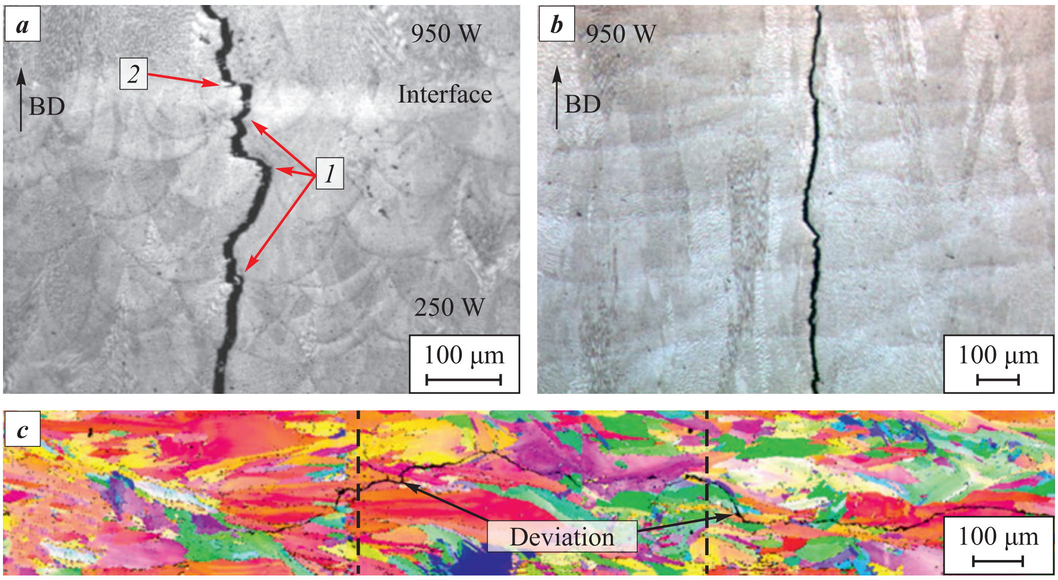

Fig. 1. Crack path deviation as a function of microstructural parameters [26], based on optical (***a***, ***b***) and scanning electron (***c***) microscopy [27]

Рис. 1. Изменение траектории движения трещины в зависимости от параметров структуры [26], по результатам оптической (***a***, ***b***) и сканирующей электронной (***c***) микроскопии [27] up to the 6th layer of BrKhZrTV. At the 7th layer, a transition to pure BrKhZrTV is observed, which confirms an interfacial zone width of about 300 μm at a layer thickness of 50 μm (Fig. 2, *d*). Mechanical testing showed that the multi-material sample exhibits a tensile strength more than twice that of BrKhZrTV, although it does not reach the level of VZh159. To eliminate the lack-of-fusion defect during composition changes within a single layer, an overlap zone of approximately 350–400 μm must be ensured. Fig. 3 shows a prototype of a component that can be fabricated based on the VZh159/BrKhZrTV multi-material system.

The study of a multi-material AlSi10Mg/Al–Si–Mg–Cu sample fabricated by SLM revealed that the AlSi10Mg region contained only Al and Si without additional phases, whereas the Al–Si–Mg–Cu region also exhibited a small amount of the Al_2Cu phase, as confirmed by chemical composition analysis [35]. Microhardness measurements after heat treatment showed that the Al–Si–Mg–Cu zone had a hardness about 30 % higher than that of the AlSi10Mg zone.

Investigations of a titanium alloy multi-material system (VT6/VT1-0) produced by SLM demonstrated that in the interfacial zone, the contents of Al and V

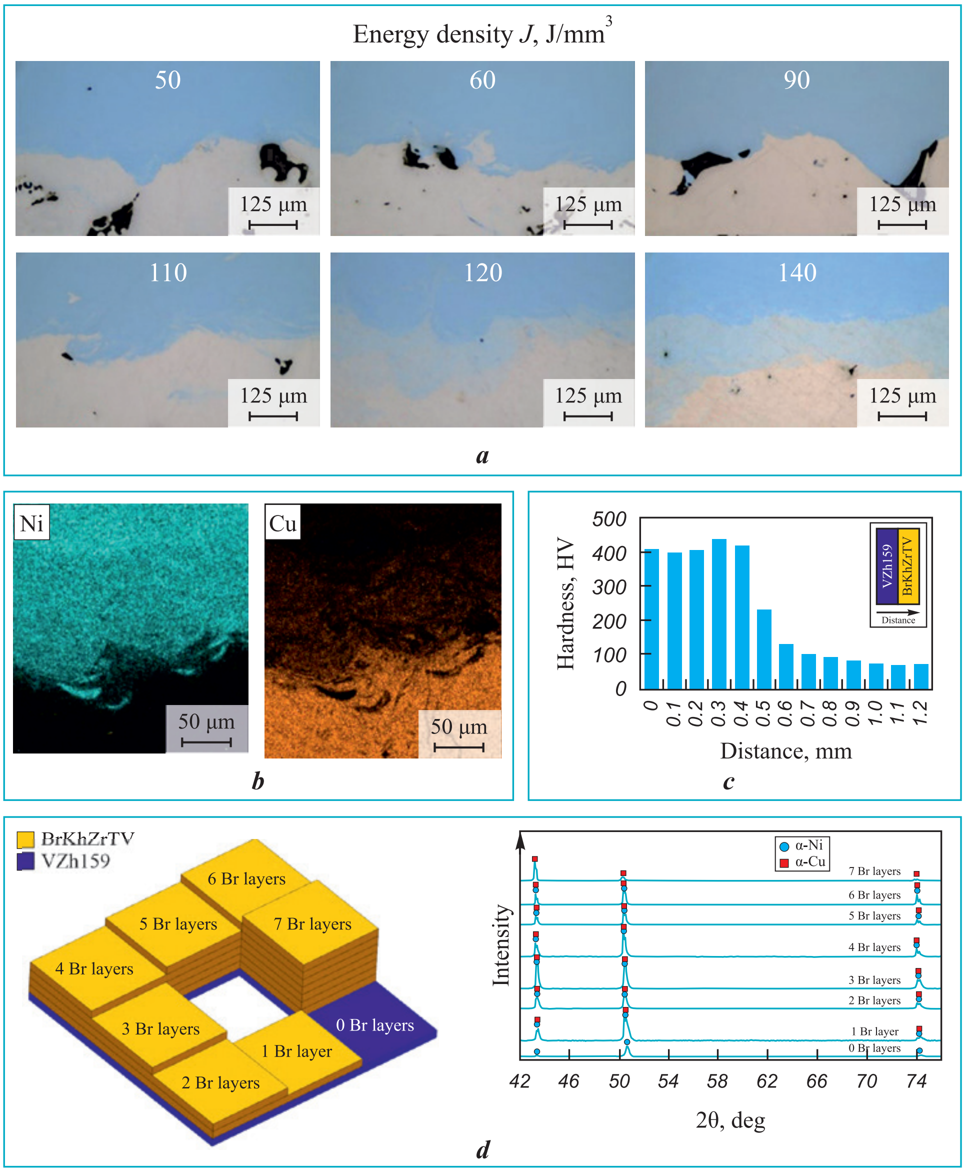

Fig. 2. Results of the investigation of the multi-material system VZh159/BrKhZrTV [32–34]

a – defect analysis in the interfacial zone; ***b*** – elemental distribution in the interfacial zone;
c – microhardness profile; ***d*** – measurement of interfacial zone width

Рис. 2. Результаты исследования мультиматериальной системы ВЖ159/БрХЦрТВ [32–34]

a – анализ дефектов в переходной зоне; ***b*** – распределение элементного состава в переходной зоне;
c – исследование твердости; ***d*** – оценка ширины переходной зоны

Fig. 3. Multi-material prototypes with lattice elements and tailored properties

Рис. 3. Мультиматериальные модели с сетчатыми элементами и заданными свойствами

gradually increased from the VT1-0 side toward VT6 (Fig. 4, *a*), with the interfacial zone width being approximately 200 μm [36; 37]. The effect of the interfacial zone location on mechanical properties was examined, along with the influence of the multi-material architecture on fracture toughness, particularly the fatigue crack growth rate (Figs. 4, *b* and *c*).

The study of a unique 316L/FeNi36 multi-material system with a shape-change effect fabricated by SLM [38] identified three distinct compositional regions: an FeNi36 zone, an interfacial zone, and a 316L zone, with the interfacial zone measuring about 50 μm in width. Hardness values ranged from 163 HV in the FeNi36 region to approximately 200 HV in the interfacial zone and 214 HV in the 316L region. The most effective temperature range for achieving maximum displacement was found to be 25–215 °C.

In the Ti6Al4V/Inconel 718 system of otherwise non-weldable alloys produced by SLM [39; 40], defect-free parts were successfully fabricated by introducing transitional layers of Cu and Cu + Nb. These layers showed no significant defects, although some alloy mixing was observed. Chemical composition analysis of multi-materials with a Cu transitional layer revealed that the interfacial zone between Cu and Ti6Al4V was wider than that between Cu and Inconel 718. When a Cu + Nb transitional layer was used, the Ti6Al4V/Nb

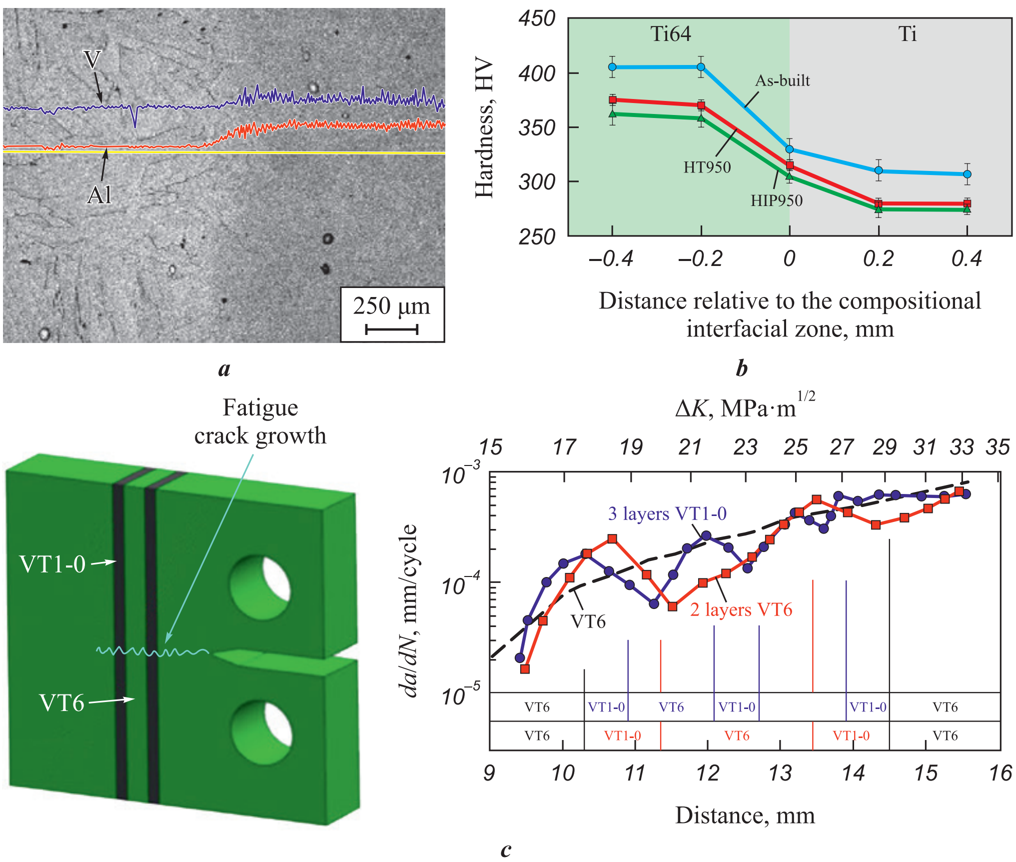

Fig. 4. Investigation of the VT6/VT1-0 multi-material system [36; 37]
a – distribution of V and Al in the interfacial zone; ***b*** – variation of Vickers hardness (*HV*) with depth; ***c*** – results of fatigue crack growth tests

Рис. 4. Исследование мультиматериальной системы ВТ6/ВТ1-0 [36; 37]
a – изменение содержания V и Al в переходной зоне; ***b*** – изменение твердости *HV* по глубине поверхности;
c – результаты испытаний на рост усталостной трещины

and Inconel 718/Cu interfacial zones were relatively narrow, with a smooth compositional gradient between Nb and Cu. Mechanical testing further demonstrated that samples with Cu + Nb transitional layers achieved superior strength (ultimate tensile strength of 910 MPa) compared with those containing Cu alone (790 MPa). Although these values were lower than those of the base alloys, the fracture surfaces exhibited a stepwise morphology, with distinct fracture zones for each alloy reflecting their characteristic fracture mechanisms.

In the 316L/NiTi system incorporating a transitional layer of the high-entropy CoCrFeNiMn alloy [41], localized macrosegregation was observed in the interfacial zone, attributed to the Marangoni effect. Combined phase and chemical analyses, together with hardness measurements, suggested the formation of FeTi intermetallics in these macrosegregated regions, which, according to the authors, could promote crack initiation due to their embrittling influence.

Alternative strategies for producing multi-material products include methods that enable the design of composites with unique property combinations while retaining high functionality in the final product. Powder blending can be used to create systems with transitional layers, although some samples show limitations in dimensional accuracy [42]. For instance, Ti5Al2.5Sn and Ti6Al4V samples demonstrated defect-free interfacial zones suitable for critical applications, unlike the incompatible Ti6Al4V and IN718 alloys, unlike the non-weldable Ti6Al4V and IN718 alloys [43; 44]. The combination of SLM and powder metallurgy has produced nacre-like structures in titanium alloys with improved strain hardening [45], while multi-materials of Inconel 718 and 316L stainless steel achieved a tensile strength of 751.82 MPa with 25.14 % elongation [46]. Such systems have been applied in high-performance heat exchangers (316L/CuZr) for electronics and bio-inspired implants (Ti6Al4V/NiTi) for medical use [47; 48].

SLM processing of SS316L and CuSn10 alloys has been shown to significantly improve their functional performance [49], while the fabrication of bio-inspired structures from 18Ni300, CoCrMo, 316L, and CuSn alloys enables controlled anisotropy depending on the loading direction [50].

Functionally graded materials with shape memory effect

SLM technology is considered a highly promising method for the industrial production of products from shape memory alloys (SMAs) with tailored functional characteristics. Its value lies in the flexibility to control not only geometric parameters during fabrication but also the functional behavior of the final component through process design. This approach is particularly valuable in high-tech fields that demand the manufacture of miniaturized parts with complex geometries, such as medical stents and implants [51], as well as aerospace actuators [52]. The possibility of achieving the desired structure and functional properties of NiTi (commonly referred to as nitinol) has been demonstrated by adjusting SLM process parameters [53; 54]. An increase in energy density or the use of a double-laser scanning strategy reduces the nickel content in the alloy and increases the phase transformation temperatures [53].

The formation of tailored structural parameters strongly influences the properties of nitinol. For instance, adjusting the hatch spacing makes it possible to control the development of a directional grain structure, dislocation density, the phase transformation temperature range, and the thermo-cyclic stability of NiTi alloys [55]. In the context of 4D printing of metallic materials, the phase transformation temperature range and the microstructure – closely linked to the thermomechanical response – are the two key factors that determine SMA performance. It has been shown that larger grain sizes lead to lower phase transformation temperatures [56]. Building on this effect, the creation of crystallographically oriented, directional structures in NiTi enables a substantial expansion of the superelastic region [57] and improves the stability of the shape memory effect by reducing irreversible plastic deformation (Fig. 5).

In a NiTi alloy with reduced nickel content (49.4 at. %) and a <001> texture produced by additive manufacturing, record superelasticity was achieved up to 453 K, with a broad transformation temperature range of 110 K. This behavior is attributed to high deformation resistance and improved phase compatibility between austenite and martensite. The developed approach simultaneously enhances superelasticity and stabilizes the shape memory effect by promoting the formation of textured martensite and suppressing dislocation motion through Ti_2NiO_x precipitates. Heat treatment primarily affects nanoscale precipitates and atomic defects, while having little influence on grain size or morphology. Direct aging after SLM facilitates the formation of Ti_2NiO_x within grains, whereas homogenization annealing dissolves metastable titanium in the NiTi matrix and reduces defect density. All heat treatment modes reinforce phase transformations by increasing the Ti/Ni atomic ratio and lowering defect density [58].

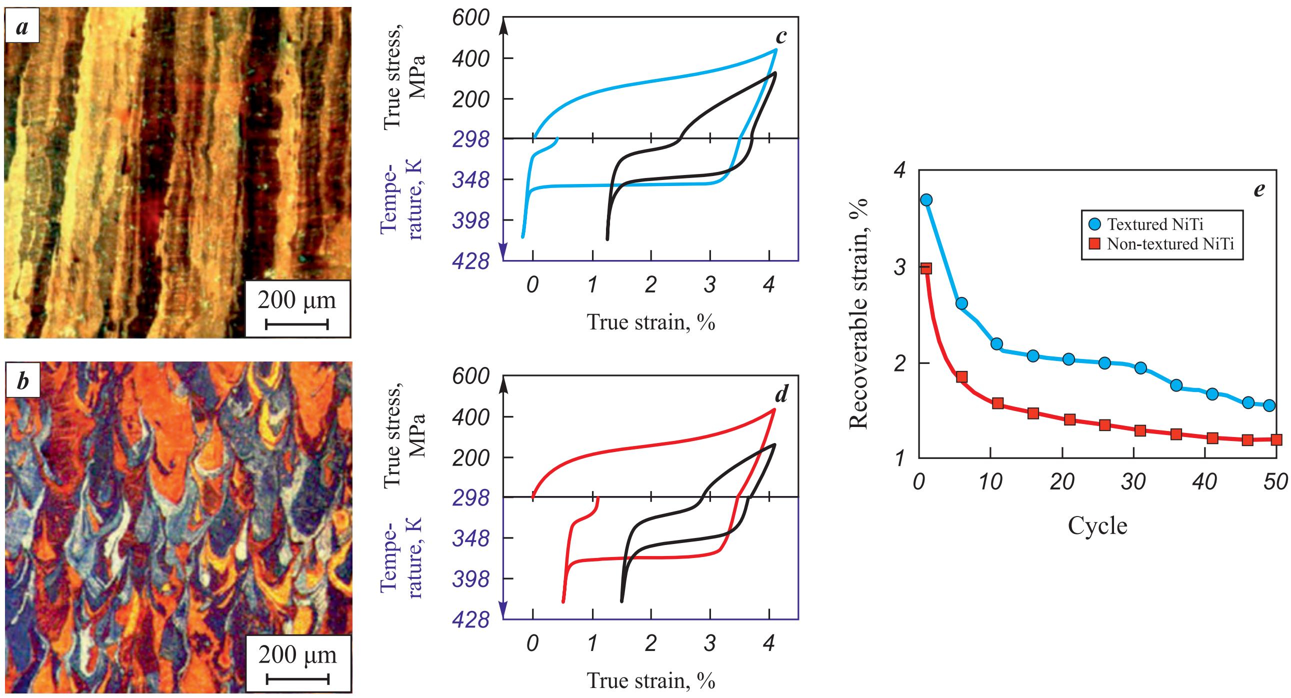

Fig. 5. Microstructure and strain curves of textured (***a***, ***c***), and non-textured (***b***, ***d***) NiTi alloys, and comparison of recoverable strain versus the number of cycles (***e***) [57]

Рис. 5. Структура и кривые деформаций текстурированного (***a***, ***c***) и нетекстурированного (***b***, ***d***) сплавов NiTi, а также сравнение восстановимой деформации в зависимости от количества циклов (***e***) [57]

Functionally graded metamaterials

Metamaterials are specially engineered materials with a unique internal architecture (geometry) that provides combinations of physical, mechanical, and functional properties distinct from those of the base material from which they are made. For example, auxetic meta-biomaterials with a negative Poisson's ratio and a low Young's modulus have been designed and modeled to closely replicate the properties of human trabecular bone [59], where the high stiffness of conventional materials often causes inflammation and implant rejection [60].

In energy absorption applications, metallic dampers with complex geometries frequently undergo permanent deformation due to local yielding. By contrast, nitinol (NiTi) provides recoverable deformation and effective energy dissipation through its unique superelasticity, offering new opportunities for the design and additive manufacturing of energy-absorbing architectural metamaterials [56]. Under uniaxial compression, lattice structures form superelastic hinges at their nodes, while the martensitic transformation gradually propagates from the nodes along the struts.

NiTi parts fabricated by SLM have also been shown to exhibit superelastic behavior under cyclic loading, with relatively low accumulation of irreversible strain (about 1.2 % after 11 cycles) [61], making them particularly suitable for applications requiring repeated shape recovery.

Modeling and design of functionally graded products

Digital design plays a crucial role in the development of functionally graded products. Because these products possess a heterogeneous internal structure, their design requires specially tailored methodologies. Traditional approaches have therefore been extended: today, not only the geometry of a single-material component is designed, but also its internal architecture, taking into account variable structures or the use of multiple materials. Finite element modeling has shown high accuracy in predicting the mechanical behavior of parts made from the heat-resistant alloy EI961, when combining SLM with direct laser deposition. Comparable results were obtained for the nickel alloy VZh159 in combination with the copper alloy CuCr1Zr. However, the authors [62; 63] highlighted the need for further refinement of models to more accurately account for the characteristics of interfacial zones in functionally graded materials. An innovative approach to predicting deformation and residual stresses in SLM-fabricated turbine blades was proposed in [64], showing how predeformed models can compensate for anticipated warping in the final parts. The inelastic behavior of functionally graded products was investigated in [65] by calibrating modeling parameters against experimental samples, which produced good agreement between predicted and measured mechanical properties. In [66], a methodology for modeling the mechanical properties of endoprostheses was developed by varying the topology of lattice structures, identifying optimal configurations for replacing both cortical and trabecular bone tissue (Fig. 6).

To minimize defects in multi-materials fabricated by SLM and to predict their resulting properties, computer simulations of both manufacturing and service processes are employed [67–70]. This is particularly important for parts made of alloys prone to defect formation, such as NiTi [53]. In both cases, the decisive factor is the interaction between two dissimilar materials. For example, in [71], thermo-mechanical models were used to simulate residual stresses in parts made of Inconel 625. In [72], a cellular automata model was developed to predict microstructure evolution during SLM of materials exposed to large temperature gradients and high cooling rates.

Artificial intelligence technologies in additive manufacturing

Modern software solutions based on artificial intelligence (AI) are increasingly being applied to the digital design of multi-materials produced by additive manufacturing [73]. Traditional design tools can no longer handle tasks of this complexity, whereas new approaches enable the full potential of multi-material products to be realized. For example, the company Leap 71 (United Arab Emirates) develops parts for SLM production using its proprietary AI-based software PicoGK (Fig. 7) [74].

Methods for designing smart multi-materials have also been proposed [75; 76]. In one study, an evolutionary algorithm was used for design [77]. This non-deterministic method relies on bio-inspired principles of natural selection and evolution, creating “more advanced individuals” across successive generations to represent candidate solutions. Alongside natural selection based on fitness – often referred to as “survival of the fittest” – concepts such as mutation, recombination, and populations containing “parents” and “children” are adapted to each design task. Using this digital design system, researchers demonstrated the feasibility of producing an active composite in the form of a simple cantilever beam with a multi-material structure that changed shape under thermal loading.

Machine learning methods can also be used to optimize processing parameters in the fabrication of multi-material products by SLM [78]. An algorithm based on a multidimensional Gaussian process was developed to predict part density and surface roughness as functions of parameters such as laser power, scan speed, and hatch spacing. Training data were collected using a high-throughput experimental approach. The resulting process maps provide clear visualization of the relationships between process parameters and the properties of interfacial zones in multi-material

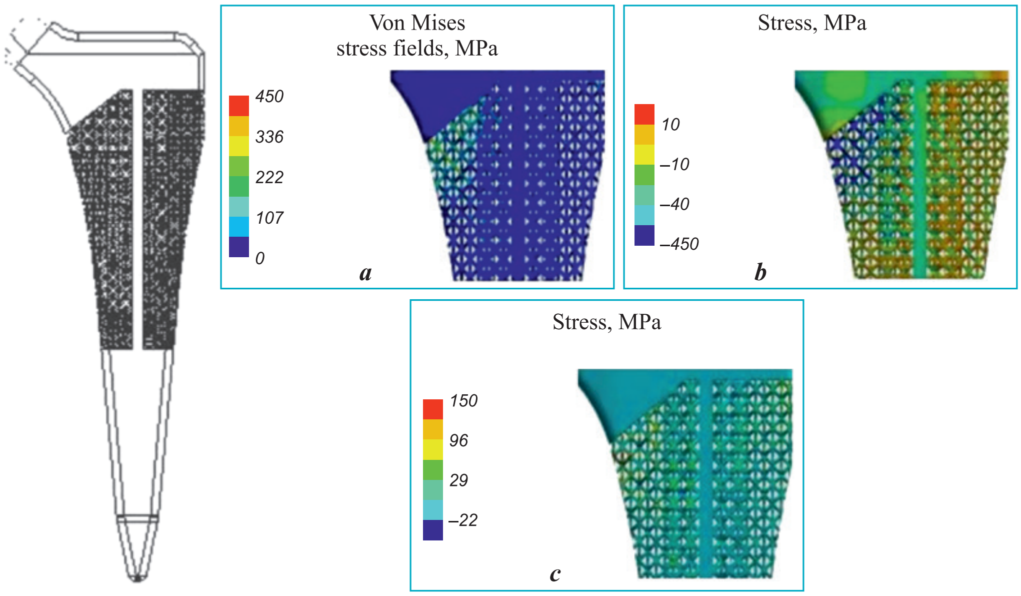

Fig. 6. Von Mises stress fields (***a***), maximum tensile stress fields (***b***), and maximum compressive stress fields (***c***) for an endoprosthesis with a graded structure under maximum load [67]

Рис. 6. Поля напряжений по фон Мизесу (***a***), поля максимальных растягивающих (***b***) и максимальных сжимающих (***c***) напряжений для эндопротеза с использованием градиентной структуры при наибольшей нагрузке [67]

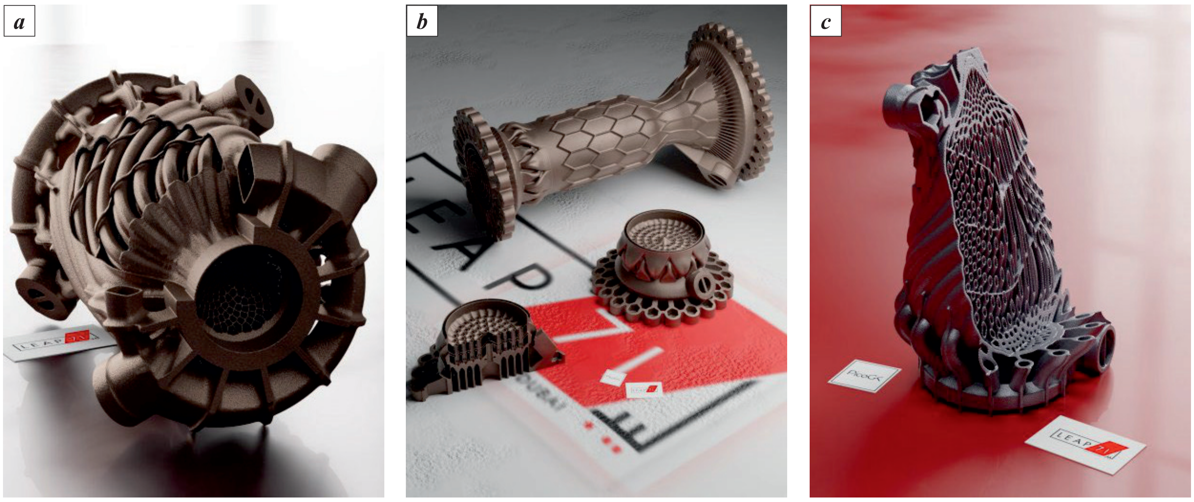

Fig. 7. Examples of parts designed using the PicoGK software developed by Leap 71 [74]
a – heat exchanger, ***b*** – rocket engine parts, ***c*** – tubular heat exchanger

Рис. 7. Примеры изделий, спроектированных в программном продукте PicoGK фирмы Leap 71 [74]
a – теплообменник, ***b*** – компоненты ракетного двигателя, ***c*** – трубчатый теплообменник

parts. Notably, process parameters exhibit a nonlinear dependence on composition, meaning that settings suitable for alloy *1* or alloy *2* cannot be directly applied to the interfacial zones.

To further improve the quality of multi-materials produced by SLM, real-time process monitoring can be implemented, with printing parameters adjusted based on data analysis [79; 80]. Advanced techniques such as high-speed and infrared imaging allow the collection of critical information on melt bath size and characteristics, while machine learning provides powerful tools for analyzing these data. In one study, acoustic and optical emission signals associated with the laser wavelength were monitored during the fabrication of multi-material copper parts [81]. A specialized signal monitoring and classification system based on contrastive deep learning was applied. The results revealed clear differences in energy levels for powders of different compositions, indicating variations in melt dynamics. The study also confirmed the effectiveness of combining contrastive learning with multi-sensor monitoring strategies for SLM processes in multi-material production.

Conclusion

Functionally graded products produced by SLM represent a promising direction in modern materials science. Multi-material systems with compositional gradients show substantial improvements in mechanical performance compared with single-material counterparts. Interfacial zones between different alloys play a crucial role in ensuring reliable bonding, while optimizing energy density significantly reduces porosity in these regions. The development of metamaterials with specially designed internal architectures imparts unique physical and mechanical properties, essential for applications such as biomechanically compatible implants and efficient energy-absorbing structures.

Functionally graded products with a shape memory effect, particularly NiTi alloys fabricated by SLM, exhibit enhanced functional performance. The formation of directional grain structures and textures extends the superelastic region and improves the stability of the shape memory effect. Advances in digital design and modeling now enable accurate prediction of properties and optimization of processing parameters, while the integration of artificial intelligence technologies opens new possibilities for design, real-time process monitoring, and process optimization.

Overall, functionally graded products produced by SLM hold great potential for aerospace, medicine, robotics, and other high-tech fields where unique combinations of properties are required.

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