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ADVANCED 3D PRINTING TECHNOLOGIES OF ALUMINOSILICATE CERAMICS FOR THE AEROSPACE AND DEFENSE INDUSTRIES

This article provides a comprehensive analysis of the current state and development prospects of additive manufacturing (AM) of aluminosilicate ceramics, specifically mullite and corundum, and their composites. It examines the fundamental limitations of traditional forming methods, such as high tooling costs (up to 80 % of the budget), significant raw material losses, and geometric determinism, which hinder the creation of complex internal cavities and lattice structures. Key methods for 3D printing of aluminosilicate ceramics are analyzed: in-line injection molding (DIW), vat photopolymerization (SLA/DLP/LCM), and powder technologies (Binder Jetting, SLS). Particular attention is paid to the rheological characteristics of pastes, the optical properties of suspensions, and the mechanisms of liquid-phase sintering, which are critical for minimizing porosity and ensuring the structural integrity of products. The influence of nanomodifiers and the use of secondary industrial raw materials in improving the physical and mechanical properties of products is studied. The role of mullitization and matrix reinforcement with acicular crystals in increasing fracture toughness was analyzed. The results confirm that the transition to hybrid additive manufacturing enables the creation of monolithic components for the aerospace industry (turbine blades, injectors), defense (ceramic armor with complex curvature), and energy. The transition to additive strategies ensures a material utilization ratio close to 1:1, guaranteeing exceptional thermal stability and resource efficiency under critical operating conditions.

Keywords: aluminosilicate ceramics; mullite; corundum; 3D printing of ceramics; additive manufacturing; paste rheology; microstructures.

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ПРОГРЕСИВНІ ТЕХНОЛОГІЇ 3D-ДРУКУ АЛЮМОСИЛІКАТНОЇ КЕРАМІКИ ДЛЯ АЕРОКОСМІЧНОЇ ТА ОБОРОННОЇ ПРОМИСЛОВОСТІ

У статті проведено комплексний аналіз сучасного стану та перспектив розвитку адитивного виробництва (АВ) алюмосилікатної кераміки, зокрема муліту та корунду, та їх композитів. Розглянуто фундаментальні обмеження традиційних методів формування, такі як висока вартість оснастки (до 80% бюджету), значні втрати сировини та «геометричний детермінізм», що стримує створення складних внутрішніх порожнин та решітчастих структур. Проаналізовано ключові методи 3D-друку алюмосилікатної кераміки: екструзійний друк (DIW), фотополімеризацію у ванні (SLA/DLP/LCM) та порошкові технології (Binder Jetting, SLS). Особливу увагу приділено реологічним характеристикам паст, оптичним властивостям суспензій та механізмам рідкофазного спікання, які є критичними для мінімізації пористості та забезпечення структурної цілісності виробів для мінімізації пористості. Досліджено вплив наномодифікаторів та використання вторинної промислової сировини у підвищенні фізико-механічних характеристик виробів. Проаналізовано роль муллітизації та армування матриці голчастими кристалами у підвищенні в'язкості руйнування. Результати аналізу підтверджують, що перехід до гібридних адитивних технологій дозволяє створювати монолітні вузли для авіакосмічної галузі (лопатки турбін, форсунки), оборонного сектору (керамічна броня складної кривизни) та енергетики. Перехід до адитивних стратегій забезпечує показник використання матеріалу, близьким до 1:1, гарантуючи виняткову термічну стабільність та ресурсну ефективність у критичних умовах експлуатації.

Ключові слова: алюмосилікатна кераміка; муліт; корунд; 3D-друк кераміки; адитивне виробництво; реологія паст; мікроструктура.

Introduction. Modern technological breakthroughs in strategically important industries are based on the use of aluminosilicate ceramics, the key components of which are corundum (α-Al_2O_3) and mullite ($3Al_2O_3{\cdot}2SiO_2$). The uniqueness of these materials lies in their ability to withstand critical temperatures (over 1800 °C), resistance to aggressive chemical environments, and an optimal balance of high strength and low weight.

In modern industry, these materials act as functionally critical elements, the integration of which is a prerequisite for the operation of high-tech components: in the aerospace industry, aluminosilicate materials are indispensable for the manufacture of heat shields, turbine blades, and combustion chambers, where metals reach their thermal endurance limits; in the defense industry, aluminum oxide is the only alternative for the production of ceramic armor (the share of the aerospace and defense sectors in the structure of global income from 3D printing, which in 2015 exceeded $4.9 billion, was about 16 %), where 3D printing allows the creation of personalized armor while maintaining high ballistic resistance (the ability to effectively absorb impact energy) [1,2]; in energy and ecology, aluminosilicates serve as the basis for the latest solid oxide fuel cells and highly efficient filtration membranes. In particular, 3D-printed biocarriers have a branched mesoporous structure and an ultra-high specific surface area-up to 711 m²/g – enabling precise control of porosity, maximizing the surface area for chemical reactions and active growth of bacterial biofilms during the purification of aggressive wastewater [3,4]; in microelectronics, aluminosilicate ceramics are gradually replacing silicon in high-temperature electronics (sensors operating at > 800 °C) due to their low coefficient of thermal expansion and excellent dielectric properties [5,6].

Traditional technologies for forming products from aluminosilicate ceramics (injection molding, slip casting, sol-gel casting, semi-dry (dry) pressing, plastic extrusion) have shaped the development of the refractory and insulation industries for decades, remaining the basic production methods.

However, at the present stage, especially in the aerospace and microsystems industries, these technologies reveal fundamental limitations that hinder scientific and technological progress [7–10].

Traditional methods do not allow for the implementation of the «free design» concept due to the need to manufacture expensive tooling (molds or dies), the cost of which can account for up to 60-80 % of the production preparation budget. This makes small-scale production or prototyping economically impractical [1] and also creates geometric determinism: the part must have a shape that can be removed from the mold without failure [10]. For example, the production of internal cavities with variable cross-sections or lattice structures to reduce the weight of aircraft parts is technologically impossible due to the impossibility of removing the punch or mold after pressing (the use of AM made it possible to reduce the weight of a highly loaded bracket for the aerospace industry by 18 % without losing its functionality) [1, 11]. In addition, traditional methods do not allow the creation of parts with negative angles, internal cooling channels of complex configurations, or cellular structures with controlled architecture, which is critical for modern heat exchangers and engine injectors [1, 12].

Traditional machining of ceramic blanks (CNC milling, grinding) in both the green and baked states has a number of critical drawbacks. First, it inevitably introduces surface microcracks and stress concentrators, which become failure points under high thermal loads, significantly limiting the reliability of precision parts (unlike modern methods achieving a resolution of 3 μm, traditional machining does not provide adequate control over cracks and structural defects) [13]. Second, uneven compaction during single-sided pressing creates a density gradient, leading to geometry distortion during long firing cycles [14, 15].

From an economic perspective, classical methods are extremely expensive: material utilization rates range from 10:1 to 20:1. This means that over 90 % of expensive raw materials are wasted, and in the manufacture of complex aerospace components, losses during machining amount to 80 % [11, 16, 17]. In contrast, additive manufacturing brings the Buy-to-Fly ratio (the ratio of raw material mass to product mass) closer to 1:1, dramatically reducing costs.

In addition, technological additives (plasticizers) introduced to improve the pressing of aluminosilicates often negatively affect refractoriness due to the formation of low-melting phases during sintering (if there are too many plasticizers, shrinkage (up to 40 %) occurs during sintering, which leads to deformation) [18, 19]. In combination with energy-intensive drying and firing cycles in large-scale furnaces, traditional approaches are inferior to additive technologies, which allow for localized heat treatment and comply with the principles of sustainable development [20, 21].

The transition to additive manufacturing (3D printing) enables the concept of «complexity for free». Instead of producing individual parts and then assembling them, additive manufacturing (AM) enables the printing of monolithic assemblies with integrated functions, radically increasing the reliability of systems in space or energy applications. Table 1 compares the characteristics of traditional and additive manufacturing methods for aluminosilicate ceramics.

Table 1 – Comparative characteristics of traditional and additive manufacturing methods

Comparison criterion	Traditional methods	Additive technologies
Use of raw materials	High losses (up to 70-80 %)	Minimal
Energy consumption	High (long sintering)	Possibility of reactive sintering (REAP)
Geometry	Simple, symmetrical	Complex, internal channels
Isotropy	High (properties are stable)	Low (pronounced anisotropy)
Speed of change	Slow (changing forms)	Instantaneous (changing the CAD model)
Economy	Mass production only	Prototypes/Series
The main challenge	Cost of molds	Rheology of pastes

The purpose of this review is to systematize modern technological approaches to aluminosilicate ceramics based on an analysis of the latest advances (2021–2026). The focus is on comparing 3D printing methods, rheology, and paste compositions, and analyzing the relationship between printing parameters and the microstructure, density, and functional characteristics of the finished product after sintering.

Analysis of research and publications. The development of additive manufacturing of ceramics has evolved from simple laboratory experiments to the creation of high-tech components for the aerospace industry. Analysis of sources [22–24] allows us to identify three key stages: the first stage (1980–1995) – concept formation – the first attempts to adapt stereolithography (SLA) to ceramics, the emergence of the first patents for SLA. In 1993, the foundation of Binder Jetting (BJ) was laid at MIT, opening the way to creating complex shapes without casting molds; the second stage – technological improvement (1996–2010). Development of selective laser sintering (SLS) methods for technical ceramics, but low product density and thermal stress remained the main barriers [25]; the advent of direct ink writing (DIW) methods, which made it possible to work with viscous clay masses [26]; the third stage – the era of functional ceramics (2011–present) – the transition from visual prototypes to functional products, the introduction of artificial intelligence (AI) for real-time defect monitoring [27], the creation of transparent ceramics [28] and microsensors for extreme temperatures [5, 6].

According to ISO/ASTM 52900:2021 [29], AM is defined as a process of joining materials to create objects from 3D model data, usually layer by layer. In the context of technical ceramics [6, 22], this classification distinguishes seven main categories, depending on the method of layer formation and the type of raw materials used: 1) Bath Photopolymerization (Stereolithography (SLA), Digital Light Processing (DLP), Liquid Crystal Display)); 2) Powder bed deposition (Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), Direct metal laser sintering (DMLS)); 3) Flow deposition (Continuous Flow (CS), Drop on Demand (DOD)); 4) Binder jet deposition (Binder Jet (BJ)); 5) Material Extrusion (Fused Filament Fabrication (FFF), Fused Deposition Modeling (FDM), Direct Ink Writing (DIW)); 6) Directed Energy Deposition (Laser Beam Metal Deposition (LBMD), Electron Beam Free-Form Fabrication (EBF3)); 7) Sheet Lamination (Laminated Object Manufacturing (LOM), Ultrasonic Additive Manufacturing (UAM)) [6].

The classification of additive technologies discussed above shows the versatility of 3D printing methods. However, the production of aluminosilicate ceramics (mulite, corundum) is one of the most complex areas due to the need for high-precision control of porosity and minimization of thermal stresses. Due to the high melting point and brittleness of these materials, modern research focuses on three main areas: Direct Ink Writing (DIW / FDM) – used for large-sized refractories and building elements [18, 30], the method is based on the extrusion of clay masses and aluminosilicate pastes; Vat Photopolymerization (SLA / DLP) – used to obtain high-precision parts of armor protection and microelectronics [2, 6], the suspension consists of finely dispersed powder of Al_2O_3 or mullite, distributed in a photopolymer resin; Binder Jetting (BJ) and SLS – the technology of jet application of a binding agent allows the creation of large-sized parts with complex topology, which are then impregnated with melts or suspensions to achieve functional density [3, 4, 12, 25].

Thus, the choice of a specific AM method for aluminosilicates is determined by the balance between the required precision, mechanical strength, and the functional purpose of the product.

Extrusion Printing (FDM/DIW). Direct Ink Writing (DIW) technology, also known as Robocasting, is currently one of the most flexible methods for producing aluminosilicate refractories and structural ceramics. Unlike powder or photopolymer methods, DIW is based on the layer-by-layer extrusion of a highly viscous paste through a precision nozzle, which places strict demands on the hydrodynamic and rheological properties of the working material.

A fundamental condition for a successful DIW process is the ability of the paste to behave as a liquid under pressure and as a solid after exiting the nozzle. According to studies of slurry hydrodynamics, the flow of paste in the confined space of a nozzle depends on the shear rate gradient (as the shear rate increases, the viscosity decreases by 2–3 orders of magnitude (e.g., from 1000 Pa·s to 1–10 Pa·s), which allows the paste to pass freely through the nozzle) [31, 32].

The key parameter of this method is the yield point. In [33, 34] it is justified that the paste should have sufficient viscoelasticity to easily pass through the nozzle at relatively low pressures and instantly restore structural rigidity (thixotropic recovery) to withstand the weight of the layers applied from above without deforming the lower part of the product (maintaining the yield point within 100–1000 Pa ensures instant structural stability of the paste after exiting the nozzle, allowing to achieve part accuracy up to 0.1 mm without deforming its base).

To achieve the required rheological profile in aluminosilicate systems, specific modifiers are used. In the study [35] it was shown that the combination of polyethylene glycol (PEG) and hydroxypropyl methylcellulose (HPMC) allows for precise adjustment of the yield point. PEG acts as a plasticizer and temporary binder, while HPMC forms a spatial network that prevents sedimentation of heavy corundum or chamotte particles, ensuring the stability of the geometry of the «green» body (the introduction of additives ensured the stability of pastes with a high solids content (up to 90 wt. %) and the preservation of their properties at extreme sintering temperatures of 1500 – 1600 °C.

In the source [36], formulations based on natural kaolin and technical alumina are considered in detail. It was found that the use of deflocculants (e.g., sodium silicate) allows to increase the solid phase content to 50–56 vol. %, while maintaining the fluidity of the paste. The use of biogenic nano-silica obtained from rice husk (RHA) deserves special attention [37]. Due to the amorphous state and ultra-high specific surface area of biogenic SiO_2, the reactivity of the system increases significantly. This allows to complete the synthesis of mullite at a temperature of 1400 °C, which is 200 °C lower than when using traditional quartz sand, while ensuring high stability of the geometry of the printed layers.

The most radical step in the development of DIW is the transition from organic bonding to chemical consolidation. A method for printing with alkali-activated pastes (geopolymers) based on waste chamotte and AZS ceramics is presented in the study [38]. The use of a solution of sodium hydroxide and silicate activates the surface of the waste particles, creating an aluminosilicate gel directly during or immediately after printing, which allows for the production of products with a compressive strength of up to 180 MPa at a firing temperature of 800 °C, which is significantly lower than traditional modes (1400 – 1600 °C). Furthermore, the addition of PMMA spheres as sacrificial templates allows for the creation of hierarchically cellular refractory structures.

Thus, the success of extrusion printing of aluminosilicates is determined not so much by the mechanical characteristics of the printer, but by the rheological design of the paste. The transition to the use of alkaline activation and biogenic nanoadditives opens the way to the creation of energy-efficient technologies for the production of highly loaded refractories using secondary industrial raw materials.

Stereolithography (SLA/DLP). Vat Photopolymerization technologies, which include stereoli-thography (SLA) and digital light processing (DLP), are currently the most advanced methods of additive manufacturing of ceramics in terms of resolution and surface quality of the product. The process is based on the selective curing of a photosensitive resin (monomer) filled with ceramic particles under the influence of a UV radiation source.

The method is based on the interaction of electromagnetic radiation with dielectric media [6, 26]. Unlike printing with pure polymers, the introduction of a ceramic filler radically alters the path of light through the suspension. The main technological barrier is the phenomenon of light scattering at the phase boundary between the ceramic particle and the polymer matrix (the criticality of the light scattering problem is explained by the high content of the hard phase (40–80 % by weight) in the composition of composite pastes for 3D printing) [39].

According to studies presented in the study [40], scattering critically affects two key parameters: the depth of cure – due to intense scattering of photons by ceramic particles, the beam energy quickly fades, which limits the thickness of the layer that can be polymerized in one exposure cycle, and the expansion of the polymerization zone – scattered light causes undesirable curing of the resin outside the given contour, which leads to a loss of geometric accuracy and «swimming» of small holes.

The authors [40] mathematically substantiated that the scattering intensity is proportional to the square of the difference in refractive indices (n) of the particles and the resin. For aluminosilicates ($n \approx 1.6–1.7$) and typical photopolymers ($n \approx 1.48$), this difference is significant, which requires careful selection of compositions to minimize optical distortions.

The role of nano-modifiers and surface quality. An innovative approach in DLP technology is the use of nano-sized additives. In [41] it was found that the introduction of nano-silica (SiO_2) into ceramic slurries can significantly improve the surface quality of printed parts. Nanoparticles act as optical stabilizers, leveling the distribution of light energy and reducing roughness. This allows overcoming the problem of anisotropy of mechanical properties typical for 3D printing, making the structure of the product more homogeneous (when reducing the particle size from 35 μm to 5 μm, the ratio of vertical strength to horizontal strength increased from 0.48 to 0.86; the ratio of strength in different directions at temperature reaches 0.88).

Requirements for suspension compositions and shrinkage parameters. To obtain functional ceramics after sintering, the slurry should have a high solids content (typically 45–60 vol. %), which ensures minimal porosity of the finished product [42]. However, a high particle concentration critically increases the viscosity of the slurry, which makes it difficult to apply new layers.

According to [43], the critical aspect is the control of linear shrinkage, which is about 12 %, and volumetric shrinkage, which occurs during pyrolysis of the bond. The discrepancy between these parameters affects the formation of porosity and can reduce the mechanical strength, which for mullite ceramics according to Weibull analysis is 94.96 MPa with an average yield of ceramic mass of 76 %.

Newer systems: LCM and CLIP. The development of photopolymerization methods has led to the emergence of LCM (Lithography-based Ceramic Manufacturing) and CLIP (Continuous Liquid Interface Production) technologies. Patent research [44] describes specialized photosensitive systems with a high content of ceramic precursor (from 25 % to 70 % by weight), which allow printing at high speed. The use of a mixture of nano- and micrometric powders ensures the production of dense structures that, after heat treatment, have an extremely low residual carbon content (less than 0.01 %), which guarantees the purity and strength of the oxide ceramics.

CLIP technology [45] provides a stable growth of the object at a speed of more than 0.5 mm/min. Due to precise control of polymerization (in particular, through the introduction of absorption modifiers at a concentration of 0.01–1 %), it is possible to obtain ceramic parts with a relative density of 98 % and higher. Such indicators make the mechanical characteristics of the products comparable to traditional isostatic pressing, which is critical for aluminosilicate components for aerospace purposes.

Thus, the development of SLA / DLP methods for ceramics is shifting from simple optimization of exposure time to deep control of the optical properties of suspensions using nanotechnology and the use of high-speed continuous molding methods. This allows to eliminate the fundamental limitations associated with light scattering and obtain ceramic products with submicron accuracy.

Powder methods (Binder Jetting, LCM). Powder additive manufacturing technologies, in particular binder jetting (BJ) and selective laser sintering (SLS), occupy a special place in the production of large-sized and complex ceramic products. Unlike extrusion or photopolymerization methods, these approaches are based on the formation of layers in a dry powder bed, which requires a deep understanding of the mechanisms of consolidation and microstructural evolution.

The fundamental basis for powder methods is the theory of solid-phase and liquid-phase sintering [46]. The process of transforming a powder bed into a monolithic body is accompanied by diffusion mass transfer, which for mullite systems becomes most active at temperatures of 1300–1700 °C. According to the source [47], the use of polydisperse mixtures (with an optimal ratio of Al_2O_3 and SiO_2 phases as 72:28) allows to achieve high packing density of the «green» body. This minimizes shrinkage and allows to maintain a low coefficient of thermal expansion ($4.5 \cdot 10^{-6}$/K), which ensures dimensional stability and the absence of microcracks in the final product.

In the Binder Jetting method, the object is formed by selective injection of a liquid binder into a powder substrate [48, 49]. The main scientific problem of this method is the high residual porosity (up to 40–50 %), caused by capillary effects during the interaction of the drop with the powder.

The study [50] presents an effective mechanism for overcoming this problem for aluminum oxide. The authors prove that the introduction of specific additives, such as $Ca(OH)_2$, MgO and SiO_2, allows initiating liquid-phase sintering. During heating, these components form a low-temperature eutectic melt, which, under the action of capillary forces, fills the intergranular pores and pulls the main Al_2O_3 particles together. This allows increasing the relative density of the products to 83.3 %, which is a high indicator for pressureless sintering in the BJ technology.

Selective Laser Sintering (SLS) and Hybrid Strengthening. SLS technology is based on localized melting or sintering of powder under the action of a laser beam. This method is challenging for ceramics due to their low thermal conductivity and high brittleness, which often leads to thermal cracking.

A hybrid approach, described in [51], for the fabrication of high-performance silica ceramic cores is of significant scientific interest.

The introduction of boron carbide (B_4C) into the SiO_2-based powder mixture improves laser energy absorption and controls phase transformations. To compensate for the porosity characteristic of the SLS process, vacuum infiltration (VI) with a $SiO_2 – Al_2O_3$ sol is used. This «sol-gel» step fills micro-cavities and provides additional chemical bonding of the particles.

Results [51] demonstrate a striking increase in mechanical properties: room-temperature flexural strength increases from 3.39 MPa (after SLS) to 27.35 MPa (after infiltration and firing), making these products suitable for casting hollow aircraft blades.

Powder-based AM ceramic methods are evolving toward hybridization. The primary focus is shifting from the printing parameters themselves to post-processing and the introduction of reactive additives. The use of liquid-phase sintering in Binder Jetting and vacuum infiltration in SLS eliminates the high porosity characteristic of these methods, providing mechanical strength sufficient for industrial use of aluminosilicates under challenging thermal conditions.

Ceramic 3D Printing Composites. The efficiency of additive manufacturing of ceramics is determined not only by equipment parameters but also by the chemical and mineralogical composition of the starting materials. The aluminosilicate group of materials, based on the $Al_2O_3 – SiO_2$ system, is most in demand for the creation of refractories, structural elements, and functional ceramics due to its ability to form a mullite phase ($3Al_2O_3{\cdot}2SiO_2$), which ensures high thermal and mechanical stability.

According to the classification of production cycles [52], the preparation of raw materials for 3D printing requires precise control of the solid phase content at 45–55 % vol. and precise dosing of Al_2O_3:SiO_2 oxides. Structure formation is based on phase transformations occurring at high temperatures. As indicated in [53], the mullitization process is a key stage of consolidation: the interaction between corundum (Al_2O_3) and silica (SiO_2) leads to the formation of acicular mullite crystals that reinforce the matrix, increasing fracture toughness and creep resistance.

Specialized warehouses for armor ceramics and aviation. Complex composite systems are being developed for extreme operating conditions:

– mullite-zirconium composites – a system based on a mixture of α-Al_2O_3 and zircon ($ZrSiO_4$) is critical for the production of armor ceramics. Reactive sintering occurs during printing and firing, resulting in the formation of a mullite matrix with uniformly distributed zirconium dioxide inclusions. This creates a transformational strengthening effect, necessary for absorbing high-velocity impact energy. Due to the lower specific gravity of mullite (3.2 g/cm³ versus 3.95 g/cm³ for corundum), the overall density of armor panels can be reduced to 3.74–3.76 g/cm³ without losing protective properties. The resulting ceramics can withstand hits from projectiles even with ultra-strong tungsten carbide cores, and its bending strength can reach 350 MPa;

– silica cores with added carbides [51] – laser sintering (SLS) composites use a mixture of fused silica with 0.5–1.5 % boron carbide (B_4C). Boron carbide plays a dual role: it acts as a laser radiation absorber and as a growth control agent for cristobalite grains, preventing excessive core brittleness.

Industrial waste management. Greening 3D printing is being achieved through the development of composites based on recycled materials. Reference [38] demonstrates the successful use of waste fireclay (CH) and aluminozirconium silicate (AZS) ceramics

The «ink» is based on ground refractory waste activated with alkaline sodium silicate solutions. The introduction of sacrificial templates in the form of PMMA spheres measuring 20–60 μm directly into the paste allows for the production of parts with controlled porosity, combining lightweight properties with high thermal conductivity (1800 °C).

Thus, an analysis of compositional solutions demonstrates a shift from the use of standard single-component powders to the design of complex multiphase systems. The use of reactive additives (zircon, carbides) and the shift to biogenic and recycled raw materials not only improves the printability of the pastes but also enables the creation of materials with new functional properties (increased fracture toughness, controlled porosity), which is critical for modern additive manufacturing.

Conclusions. Analysis of current trends in aluminosilicate ceramics reveals a fundamental technological shift from traditional forming methods to additive manufacturing, driven by the need to overcome geometric determinism and critical economic costs. Traditional approaches, despite their fundamental role, are ineffective when creating precision components with complex internal channels or lattice structures due to the high cost of tooling (accounting for 60-80 % of the budget) and significant waste of expensive raw materials, leading to a high Buy-to-Fly ratio. The transition to the concept of «complexity for free» through the introduction of 3D printing not only enables the integration of complex functions into monolithic parts but also radically changes the approach to materials design, bringing the raw material utilization ratio closer to the ideal 1:1 ratio.

At the current stage of technology maturity, precise rheological and phase design of the initial systems plays a crucial role. Technological breakthroughs in extrusion (DIW) and photopolymerization (DLP) methods have made it possible to achieve solids content in pastes at the level of 4.5–60 vol. % (up to 90 wt. %), which is critical for minimizing linear shrinkage, which is approximately 12–15 %. Successful implementation of this process is based on in-depth control of the viscoelastic parameters of the pastes and minimization of optical scattering in photopolymer systems. The use of nanomodifiers, such as biogenic nanosilica, not only improves structural homogeneity, increasing the strength isotropy coefficient from 0.48 to 0.88, but also ensures greener production by reducing the mullite synthesis temperature by 200 °C (to 1400 °C) while maintaining high performance characteristics.

Hybridization of consolidation methods is particularly important, particularly vacuum infiltration and alkaline activation, which provides a several-fold increase in flexural strength: from 3.39 MPa to 27.35 MPa for porous structures and up to 350 MPa for dense composites. The introduction of mullite-zirconium systems enables the realization of transformational strengthening, which is key to the creation of lightweight armor ceramics with reduced density (3.74–3.76 g/cm³) and the ability to absorb the impact energy of high-velocity projectiles.

Thus, the synergy of high-precision equipment and innovative chemical and mineralogical warehouse design transforms ceramic production into a process for the programmed creation of intelligent materials. This opens new horizons for energy-efficient and high-tech production in strategic industries, enabling the production of functional ceramics capable of operating under extreme thermal and mechanical conditions with maximum resource efficiency.

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