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Review

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ANALYSIS OF EXISTING METHODS AND ADDITIVE TECHNOLOGIES OF 3D PRINTING WITH POLYMER-CERAMIC MATERIALS

Abstract. This article presents a comprehensive analysis of additive 3D printing technologies using polymer-ceramic composites (PCCs). Particular attention is paid to the advantages, limitations, and prospects of these materials use in medicine, aerospace, and electronics. Additive manufacturing methods applicable to PCCs are systematized, including fused deposition modeling (FDM), stereolithography (SLA), and lithography-based ceramic molding (LCM). A detailed review of commercial and experimental compositions is presented, along with optimal filler content ranges, printing parameters, and post-processing modes. Comparative data demonstrate that the introduction of ceramic additives improves mechanical strength, thermal stability, and functional properties, but is accompanied by technological challenges such as increased material viscosity, abrasive nozzle wear, and shrinkage during sintering. An analysis of current industrial implementations confirms the growing potential of PCCs for biomedicine, energy, and high-tech industries. Polymer-ceramic composites produced using additive manufacturing methods offer a unique combination of polymer processability and ceramic performance. Despite technological challenges, advances in material formulation, equipment design, and digital integration are rapidly expanding the scope of PCC applications. Further optimization of formulations, printing parameters, and hybrid manufacturing methods will accelerate the transition of polymer-ceramic 3D printing from laboratory research to large-scale industrial use.

Keywords: additive manufacturing, 3D printing, polymer-ceramic materials, composites, FDM, SLA, LCM, ceramic-filled polymers

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АНАЛИЗ СУЩЕСТВУЮЩИХ МЕТОДОВ И АДДИТИВНЫХ ТЕХНОЛОГИЙ 3D-ПЕЧАТИ ПОЛИМЕРНО-КЕРАМИЧЕСКИМИ МАТЕРИАЛАМИ

Аннотация. Проведен всесторонний анализ аддитивных технологий 3D-печати полимерно-керамическими композитами (ПКК). Особое внимание уделено преимуществам данных материалов, ограничениям и перспективам их использования в медицине, авиационно-космической отрасли и электронике. Систематизированы методы аддитивного производства, применимые для ПКК, включая технологии моделирования методом послойного наплавления (FDM), стереолитографии (SLA) и литографического формирования керамики (LCM). Представлен детальный обзор коммерческих и экспериментальных композиций, показаны оптимальные диапазоны содержания наполнителя, параметры печати и режимы постобработки. Сравнительные данные демонстрируют, что введение керамических добавок повышает механическую прочность, термостойкость и функциональные характеристики, но сопровождается технологическими сложностями – ростом вязкости материала, абразивным износом сопел и усадкой при спекании. Анализ текущих промышленных внедрений подтверждает растущий потенциал ПКК для биомедицины, энергетики и высокотехнологичных отраслей. Полимерно-керамические композиты, полученные методами аддитивного производства, обеспечивают уникальное сочетание технологичности полимеров и эксплуатационных свойств керамики. Несмотря на технологические трудности, достижения в области разработки составов материалов, проектирования оборудования и цифровой интеграции стремительно расширяют сферу применения ПКК. Дальнейшая оптимизация составов, параметров печати и гибридных методов производства ускорит переход полимерно-керамической 3D-печати от лабораторных исследований к широкомасштабному промышленному использованию.

Ключевые слова: аддитивное производство, 3D-печать, полимерно-керамические композиты, FDM, SLA, LCM, полимеры с керамическим наполнителем

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Introduction. The transition to additive manufacturing (AM) technologies and, in particular, to 3D printing is one of the key areas of the fourth industrial revolution (Industry 4.0). These methods significantly expand design freedom, allow prototypes and small-scale production of products in short terms [1–6]. Unlike traditional methods such as injection molding, machining, stamping, etc., 3D printing forms a product "from the bottom up" by successively building up the material, which reduces the volume of waste and, in some cases, simplifies logistics and warehouse operations [1; 2; 6; 7].

In recent years, special attention has been paid to the use of composite materials in 3D printing. Among them, a special place is occupied by polymer-ceramic composites (PCC), which combine the advantages of a polymer matrix – manufacturability, relative low cost, ease of recycling – and the properties of ceramic fillers (high hardness, resistance to wear and aggressive environments, heat resistance) [8–12]. Such materials are in demand in the aerospace industry, medicine, electronics, power engineering and other areas where a combination of high-performance characteristics and a relatively small weight is required [13–16]. At the same time, the technology of additive manufacturing with polymer-ceramic materials requires solving a number of scientific and engineering problems. For example, it is necessary to ensure uniform distribution of the ceramic filler in the polymer matrix, optimal adhesion between the phases, and also to determine the optimal printing modes (temperature, extrusion speed, etc.) in order to avoid pore defects, delamination, microcracks [17–20]. The complexity of the process may increase with the desire to increase the proportion of ceramics, which often leads to an increase in the viscosity of the raw material, abrasive wear of the equipment and the complication of post-processing modes [12; 17; 20; 21]. This article is an overview of modern methods of additive manufacturing with polymer-ceramic materials, describes the key manufacturers and developers of such composites, considers examples of implemented polymer-ceramic compositions and products made from them, and compares the properties of the resulting materials. The problems and prospects for further research are considered [22].

Classification and advantages of additive technologies. Additive manufacturing in general includes more than a dozen different methods that can be systematized by a number of features. According to ASTM F2792-12a[1] [11; 23; 24], 3D printing technologies are divided into 7 large classes. The main ones are briefly presented below:

1. Extrusion (Material Extrusion). This class includes:

– Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) is the most common technology for extruding molten thermoplastic polymers;

– Paste Extrusion is the extrusion of viscous pastes containing ceramic powders and binders.

2. Photopolymerization (Vat Photopolymerization). This includes:

– Stereolithography (SLA) is the curing of a photopolymer with a laser in a bath;

– Digital Light Processing (DLP) – curing with light from a DLP projector;

– Continuous Liquid Interface Production (CLIP) – continuous curing of photopolymer.

3. Powder Bed Fusion:

– Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) – laser sintering/melting of powder.

4. Ink jet printing (Material Jetting, Binder Jetting):

– Binder Jetting – drop-by-drop application of a binder onto a powder layer;

– Material Jetting – forming a product from a photopolymer using drops.

5. Lamination (Sheet Lamination):

– Laminated Object Manufacturing (LOM) – layer-by-layer gluing of sheet materials (paper, polymers, metals).

6. Directed Energy Deposition (DED) – feeding metal powder or wire into the laser or electron beam zone, more often used for metals.

7. Hybrid Approaches – a combination of different methods (e.g. powder feed + extrusion).

Of all the diversity in the context of polymer-ceramic composites (PCC), the most widely used technologies are FDM (FFF) and photopolymerization (SLA/DLP), as well as stereolithographic approaches

[1] ASTM F2792 12a. Standard Terminology for Additive Manufacturing Technologies. ASTM International, West Conshohocken, PA, 2012. URL: https://www.astm.org/f2792-12a.html (date of access 02.09.2025).

to creating purely ceramic products (LCM), which can also be adapted for PCC. The reason is that these methods are most convenient for introducing a ceramic phase in the form of microparticles/nanoparticles [25–29].

The main advantages of additive manufacturing using PCC [1; 2; 4; 10; 11; 22; 28; 31] are:

– the ability to create products of complex shapes with internal channels, porous structures, etc.;

– reducing waste during production and simplifying design;

– a wide range of product properties due to variation in the fractional composition and concentration of the ceramic filler;

– potentially lower cost of small-scale batches compared to traditional casting and pressing methods.

The main limitations associated with the use of PCC [11; 19; 20; 22; 25; 28; 29] in 3D printing are:

– the need to select a recipe (polymer + ceramics + binders and plasticizers) to ensure good processing during printing;

– the effect of a high ceramic content on the viscosity of the melt, equipment wear;

– post-processing (burning out the binder, sintering) can lead to significant shrinkage and the appearance of defects if the modes are not debugged.

In addition, the number of ready-made filaments or suspensions with a high ceramic content is still limited, which complicates the mass implementation of the technology. However, the growing number of studies and implementations of PCC in industry (aviation, medicine, energy) allows us to predict the rapid development of this area [17; 28; 33; 34].

Polymer-ceramic materials for 3D printing. These materials are multiphase systems in which the continuous phase (matrix) is a thermoplastic or thermosetting polymer, and the dispersed phase is a ceramic powder. Such powders can be single-phase (for example, aluminum oxide Al_2O_3, zirconium oxide ZrO_2) or complex (mixtures of several oxides, nitrides or carbides) [8; 10; 19]. Most often, the polymer matrix consists of common thermoplastics: ABS (acrylonitrile-butadiene-styrene), PLA (polylactic acid), PETG (polyethylene terephthalate glycol), PA (polyamide), PEEK (polyether ether ketone), PEI (polyetherimide), etc., which determine the range of printing temperatures and the main mechanical properties [8; 10; 11]. The addition of ceramics improves rigidity, heat resistance, wear resistance and other characteristics. However, these fillers increase the material density and viscosity, complicating processing and often reducing impact strength and ductility [9; 12; 17; 20].

The main requirements for the feedstock are:

1) optimum particle size of the ceramics (usually 1–10 μm, or < 1 μm). Particles that are too large may cause nozzle blockages and structural inhomogeneity, while particles that are too small may cause increased viscosity and agglomeration [19; 20; 28];

2) compatibility. Chemical inertness of the polymer to the ceramics, no reactions at elevated temperatures [10; 11; 22];

3) uniform mixing. Mixers such as twin-screw extruders or planetary mixers are used to ensure homogenization of the composition [17; 22; 37; 38];

4) stability of the filament (or suspension) during storage: delamination, precipitation of the ceramics, thickening, etc. [19; 25; 39].

If these conditions are met, it is possible to obtain high-quality ceramic-filled filaments for FDM (FFF) 3D printing, pastes or photopolymer resins for SLA/LCM [17; 25; 29].

Currently, the most well-known manufacturers of polymer-ceramic materials are the following companies:

– Lithoz (Austria) – LCM technology and LithaCore photopolymer suspensions based on Al_2O_3, ZrO_2 and Si_3N_4. Contain up to 50 vol.% ceramic powder and require multi-stage binder burnout (up to 800 °C) followed by sintering at 1500–1600 °C [25; 29];

– 3DCeram (France) and other SLA/LCM manufacturers – photopolymer suspensions for printing technical ceramics (alumina, zirconia, hydroxyapatite) are used for medical and aerospace applications [25; 28];

– Admatec[1] (Admaflex, Netherlands) – line of equipment and suspensions based on Al_2O_3 and ZrO_2 for DLP/LCM. Contains 40–50 vol.% powder, burns out the binder and sinters at 1500–1600 °C [25];

[1] ADMAFLEX Technology: [overview] // VoxelMatters. 2023. URL: https://www.voxelmatters.com/additive-manufacturing/am-technologies/what-is-admaflex/ (date of access 02.09.2025).

– Nanoe/Zetamix[1] (France) – a series of filaments based on PLA or PA12 with zirconium oxide (ZrO_2), aluminum oxide (Al_2O_3) or hydroxyapatite. The materials are designed for FDM printing; after binder burning at ~ 500 °C and sintering at 1300–1500 °C, dense ceramics are obtained [34];

– Tethon 3D[2] (USA) – the porcelite resin combines a photopolymer binder with porcelain powder; after curing and sintering (1200–1300 °C) shrinkage is below 20 %;

– Nanovia[3] (France) – high-temperature PA12-based filaments with 30–35 vol.% SiC or other ceramic fillers are extruded at 240–260 °C and sintered at 1600–1750 °C [51].

Research institutions (MIT, Fraunhofer Institute, Tomsk Polytechnic University, etc.) are also conducting research on creating new formulations, improving processing and mechanical properties of PCC [28; 29; 33; 34].

Table 1 provides examples of commercially available and experimental polymer-ceramic compositions used in FDM and SLA/LCM, along with their fabrication methods and recommended heat treatment regimes.

T a b l e 1. **Examples of polymer-ceramic compositions for 3D printing**

Manufacturer	Material/Composition	Technology	Ceramic content, vol.%	Printing temperature, °C	Production method / Heat treatment	References
Admatec Admaflex 130	Al_2O_3 + photopolymer	DLP	–	–	Photopolymer suspension / photopolymer burnout 200–600 °C; pre-annealing at 500 °C (1–2 h); intermediate heating 600–1400 °C; sintering 1500–1600 °C; shrinkage: 15–25 %	[25]
Nanoe (Zetamix)	ZrO_2 + polymer	FDM	50	180–200	Filament extrusion / thermal debinding up to 500 °C; sintering 1400–1500 °C; shrinkage: 20–25 %	[11; 17; 28; 34]
Lithoz	LithaCon (Al_2O_3/ZrO_2)	LCM	Up to 60	–	Photopolymer suspension / bond burnout 200–600 °C; pre-annealing at 500–800 °C to prevent defects; sintering 1500–1600 °C; shrinkage: 15–25 %	[19; 25; 29; 47]
Tethon 3D	Porcelite (porcelaincompound)	DLP	~ 55	–	Photopolymer resin / photopolymer burnout 200–600 °C; intermediate heating 500–1100 °C; sintering ~ 1200–1300 °C; shrinkage: 15–20 %	[25]
Nanovia	HTPA12 + SiC	FDM/ FFF	30–35	200–220	Filament extrusion / polymer burnout 200–425 °C; holding at 425 °C for 240 min; sintering 425–2050 °C; (Ar/N_2) shrinkage: 10–15 %	[47; 51]
Own research*	PLA + SiC	FDM	~ 30	210–220	Filament extrusion / additional grinding; polymer burning-out 200–500 °C; sintering 1800–2100 °C; (argon or nitrogen) shrinkage: 15–25 %	[18; 33; 42; 51]

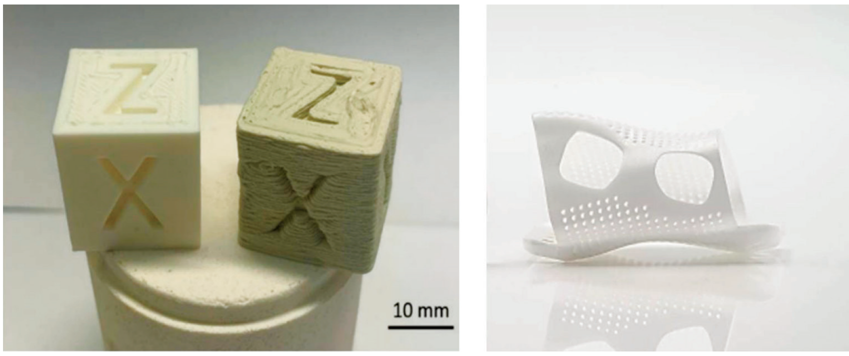
* Example of experimental compositions developed in research laboratories.

The analysis of the presented data shows that for each type of polymer-ceramic material, the method of mixture preparation and the uniformity of filler particle distribution are of key importance [10; 11; 22; 28]. The particle size of the ceramics has a significant effect on adhesion to the polymer matrix: smaller particles (< 10 μm) provide a larger contact area and better adhesion, but increase the viscosity of the melt

[1] Zetamix White Zirconia datasheet // Zetamix. 2020. URL: https://zetamix.fr/wp-content/uploads/2026/01/Datasheet-Zetamix-White-Zirconia.pdf (date of access 02.09.2025).

[2] Tethon 3D. Porcelite 3D printing resin datasheet. 2019. URL: https://www.tethon3d.com/porcelite (date of access 02.09.2025).

[3] Nanovia. SiC – Silicon carbide (FFF filament) datasheet // Nanovia.tech. 2023. URL: https://nanovia.tech/en/ref/nanovia-cr-sic/#:~:text=Nanovia%20SiC%20%3A%20Silicon%20carbide (date of access 02.09.2025).



a *b*

Examples of printed samples: *a* – samples produced by FDM from PLA + Al_2O_3;
b – samples produced by LCM from a ZrO_2 suspension

[19–21]. The use of preliminary drying of granules and powders before extrusion helps to avoid defects associated with the presence of moisture [19; 20; 32; 39; 43–46]. As can be seen from the presented data, with an increase in the mass fraction of the filler, the modulus of elasticity and the operating temperature increase, but at the same time shrinkage during sintering increases [9; 17; 20; 25; 28; 29]. Experimental work shows that the optimal ratio of ceramics to polymer depends on the printing technology: for FDM, 20–35 vol.% of filler is usually used [9; 17; 22; 38; 39], and for SLA/LCM – up to 50 vol.% [25; 28; 29]. Increasing the ceramic content above 40 vol.% requires careful optimization of the composition and the use of additives to improve adhesion [19; 25; 28]. Figure *a* shows test samples for mechanical testing printed via FDM method from pure PLA and ceramic-filled PLA + Al_2O_3 [9; 17]. Figure *b* shows complex geometric parts for medical prostheses manufactured using LCM technology from a zirconium oxide suspension (Lithoz materials) [13; 25; 29].

As demonstrated in [9; 17] the addition of ceramic fillers to polymer matrices leads to a noticeable improvement in flexural strength and stiffness already at moderate filler contents of approximately 20–30 wt.%, which corresponds to roughly 7–12 vol.% depending on the densities of the components. These values therefore describe the initial strengthening region of polymer–ceramic composites rather than the concentration range typical for highly filled feedstocks used in additive manufacturing. However, it is important to maintain a balance between the filler content and the technological efficiency of the printing process. Below, we will consider the main technologies and manufacturers of polymer-ceramic materials for 3D printing, which have become widespread at the time of writing this paper.

Fused deposition modeling (FDM) technology. In FDM 3D printing with polymer-ceramic filament [17; 37–39; 43–45], it is important to consider the following:

– elasticity of the filament – threads that are too fragile or overloaded with ceramics break during feeding;

– melting/glass transition temperature – should match the selected polymer matrix (PLA, ABS, PA12, etc.);

– printing speed and layer height – have a strong effect on interlayer adhesion and strength of the finished product;

– nozzle wear resistance – ceramics (Al_2O_3, SiC) have an abrasive effect, it is recommended to use hardened or carbide nozzles.

All these factors determine the quality of the resulting products. Subsequent removal of the polymer bond "debinding" and sintering (1200–1600 °C) of the ceramic framework allows obtaining virtually pure ceramic products [17; 29; 34].

Table 2 summarizes typical FDM printing parameters for ceramic-filled filaments (various materials). The table shows that operating temperatures are usually 10–30 °C higher than for "pure" polymers due to the increased viscosity of the ceramic-filled melt. Increasing the temperature ensures smoother extrusion, but can accelerate matrix degradation [38; 39; 44–46].

It is also important to consider nozzle wear: ceramic particles (Al_2O_3, SiC) have high hardness and can quickly destroy brass or steel nozzles, so nozzles made of hardened materials (coated steel, tungsten carbide) are recommended [38; 39].

T a b l e 2. **Parameters of FDM printing with ceramic-filled filaments**

Filament composition	Print temperature, °C	Speed, mm/s	Infill, %	References
PLA + Al_2O_3	180–210	20–40	40–80	[9; 17]
PLA + SiC	220–240	20–40	40–80	[18; 42]
PLA + Si_3N_4	220–230	30–50	50–80	[7]
ABS + Al_2O_2	230–250	30–50	40–80	[10; 38]
ABS + Montmorillonite	230–240	25–40	50–70	[36; 38]
PA12 + SiC	200–220	20–35	60–80	[36], footnote 3 on p. 11
PEEK + Hydroxyapatite (HAP)	230–240	25–40	50–90	[48; 49]

Research presented in [9; 17; 20; 39; 42; 47] shows that bending strength can increase by 30–50 % compared to the original polymer with the introduction of 20–30 wt.% (7–12 vol.%) Al_2O_3, ZrO_2 or SiC, but this reduces impact toughness. Further increase in filler loading results in a sharp rise in melt viscosity, reduced impact toughness, and deterioration of extrusion processability. The experimental data of the presented works show that the optimal printing speed is in the range of 20–40 mm/s, and the layer height of 0.15–0.30 mm provides better interlayer adhesion and product density [44–46]. Additional optimization of 3D printing parameters allows reducing defects, increasing mechanical strength and ensur uniform distribution of ceramic particles in the product structure [35; 37; 39].

Stereolithography (SLA) technology. This technology is based on point (or line-by-line) curing of a layer of liquid photopolymer with a laser beam [27; 41]. To create polymer-ceramic materials, ceramic nanoparticles or microparticles are added to the resin, and the resin itself is modified with surface-active and photoinitiating additives, which ensure stable distribution of the filler [19; 25; 28; 29]. To obtain a ceramic product, the part successively undergoes the process of burning out the polymer bond and sintering the ceramic frame. It is important to take into account shrinkage, which reaches 15–25 % depending on the ceramic content [25; 28; 29].

Advantages of SLA [25; 28; 41]:

– highest precision: the layer thickness can reach 25–50 µm, and in some cases – up to 10 µm;

– high surface quality;

– possibility of creating complex geometry and hollow structures.

Limitations of SLA [19; 25; 28; 29]:

– high cost of photopolymers and equipment;

– requires protection from UV radiation and safety precautions when working with toxic components;

– the viscosity of the suspension increases sharply when filling above 40 %, which complicates curing.

After printing, the product goes through the following stages [25; 28; 29]:

– cleaning from uncured resin;

– thermal removal of the polymer binder (debinding);

– sintering of the ceramic frame at temperatures up to 1500–1600 °C.

Despite its limitations, SLA technology remains one of the leading ones for precision 3D printing of PCC in medicine (dentures, ceramic crowns, bridges), electronics (housings, substrates), manufacturing of jewelry molds, complex prostheses, etc.

Lithography-based Ceramic Manufacturing (LCM) technology. LCM is a further development of SLA/DLP technologies, specially adapted for ceramic compositions. The difference is in the use of a DLP projector or LED sources in the blue range (about 460 nm) and more advanced exposure systems (step-and-repeat or scrolling), which allows for uniform curing of highly filled materials [25; 28; 29; 41].

The main stages of LCM printing with polymer-ceramic materials [25; 28; 29]:

1. The platform is immersed in a bath with a photosensitive suspension containing ceramic particles.
2. The projector (or LED module) exposes the layer.
3. The platform is lifted, a new layer is applied.
4. After construction, the entire 3D part is cleaned of unwashed suspension.
5. Next, the polymer binder is burned out, followed by sintering (1400–1600 °C) of the ceramic framework [28–29].

The main advantages of the technology [25; 28; 29] are:
– high precision – resolution down to the micron level is possible;
– homogeneity of the structure due to thorough dispersion and the ability to cure thin layers;
– suitable for refractory technical ceramics (Al_2O_3, ZrO_2, Si_3N_4, HAP, etc.);
– possibility of obtaining virtually pure ceramics by burning out the binder;
– integration into the industrial cycle, especially for small batches.
The limitations of this technology [25; 28; 29] are similar to those of SLA:
– high cost of equipment and consumables;
– sensitivity to dispersion disturbances – can lead to defects during sintering;
– step-by-step heat treatment is required, often in several stages: binder burning out (200–600 °C), preheating (600–900 °C), sintering (1400–1600 °C).

Lithography-based Ceramic Manufacturing occupies an important place among the technologies of 3D printing of PCC, especially in the production of products with precision geometry and high density. Systems from Lithoz and Admatec are successfully used for the production of bone implants, dental structures (crowns, bridges), substrates in microelectronics and parts of gas turbine engines. Thus, LCM technology is one of the most promising for the creation of high-precision ceramic products, but requires careful preparation of the suspension and strict adherence to all stages of curing and heat treatment [13; 25; 28; 29].

Table 3 presents generalized data on the properties of polymers with various ceramic fillers.

T a b l e 3. **Comparison of properties of polymers with different ceramic fillers**

Matrix + Filler	Filler content, wt.% / vol. %	Flexural strength, MPa	Elastic modulus, GPa	Production/ Processing methods	Peculiarities	References
PLA + Al_2O_3	~ 20–30 wt.%	50–70	3.5–4.5	Extrusion (FDM), post-bake 600–800 °C (opt.)	Moderate biocompatibility, relatively easy to print	[9; 17; 20; 34]
ABS + Al_2O_2	~ 25–30 wt.%	40–60	4.0–5.0	Extrusion (FDM), post-bake 700–900 °C	Increased stiffness (E), improved heat resistance; possible drop in impact strength; higher printing temperature; more difficult extrusion	[10; 22; 36; 38; 39]
PA12 + SiC	~ 20 vol.%	60–80	5.0–6.0	Extrusion (FDM), sintering up to ~1200 °C (experimental)	Good wear resistance, more difficult extrusion	[42; 47; 51]
Photopolymer+ Al_2O_3	~ 25–30 vol.%	70–90	5.5–7.0	SLA photopolymer resin, photopolymer burnout, sintering 1400–1500 °C	High precision, full transition to ceramics possible	[19; 25; 29; 28]
Photopolymer ZrO_2 + HAP	50–60 vol.%	80–100	7.0–10.0	LCM photopolymer suspension, LED curing, firing, sintering 1500–1600 °C	Properties close to pure ceramics are achieved	[13; 24; 25; 28]
HTPA + Al_2O_3	25–30 vol.%	45–65	4.5–5.5	FDM extrusion, thermally stable matrix, post-fire 600–800 °C	Improved heat resistance, experimental formulations	[20; 34]
Porcelite (SLA)	~ 40 (vol.% not specified)	50–60	4.0–6.0	SLA, photopolymer resin + porcelain powder, sintering ~ 1300 °C	Smooth surface, suitable for prototyping	[25; 28; 29]

Comparison of the properties of various combinations of polymers and fillers shows that for composites based on PLA + Al_2O_3, ABS + Al_2O_3/TiO_2, PA12 + SiC, photopolymers with Al_2O_3 and ZrO_2 (Lithoz, Admatec), as well as HTPA + Al_2O_3 filaments, an increase in the ceramic content (20–50 vol.%) increases the flexural strength and elastic modulus [9; 17; 20; 22; 25; 29; 34; 47]. At the same time, the operating temperature of the materials increases, which makes them promising for high-temperature applications [9; 36; 47]. However, excessive filler content (> 40–50 vol.%) reduces impact strength and complicates the extrusion process. Twin-screw extruders and surface-active additives are used to improve particle dispersion, which reduces agglomeration and increases structural homogeneity (for PLA + Al_2O_3, for PA12 + SiC) [17; 22; 47]. Experiments also show that Lithoz and Admatec photopolymer resins make it possible to achieve high precision of products with 50 vol.% ceramics while maintaining strength properties, but require multi-stage heat treatment (burning, heating, sintering) [25; 28; 29; 19].

Development prospects and trends. From all of the above, the following can be noted: 3D printing of PCCs opens up wide opportunities in various industries, but requires further research and optimization. The most relevant areas are:

1. Optimization of filament and resin compositions. Development of new binders and dispersion media for higher ceramic filling, improved adhesion and minimization of agglomerates [19; 20; 25; 33; 34].

2. Increasing the filler share. Achieving 50–60 % in FDM remains a complex task requiring special additives and high temperatures [17; 22; 37; 38; 39].

3. Equipment improvement. Development of extruders with ceramic nozzles, real-time viscosity and temperature monitoring systems [32; 35; 40; 46].

4. Integration into smart factories (Industry 4.0). Digital twins, automated quality control and fast adjustment of printing parameters [5; 30; 35].

5. Expansion of application areas [11; 13; 15; 16; 28; 29; 30]:
– medicine: individual ceramic bone and dental implants;
– energy: parts for fuel cells, heat exchangers;
– electronics: sensor housings, microcircuit substrates;
– robotics: hinge parts, protective shells.

6. Multi-material printing. Simultaneous printing with polymer-ceramics and metal, creation of gradient structures (Functionally Graded Materials) [22; 24; 49].

7. Environmental aspects. Use of biodegradable matrices (PLA, PHA) with ceramics, recycling of waste, secondary resources [8; 14; 50].

Thus, the synergy of progress in materials, equipment and digital technologies will make it possible in the coming years to eliminate many technological limitations and expand the use of polymer-ceramic composites in additive manufacturing.

Conclusion. Polymer-ceramic composites obtained by additive manufacturing methods represent a significant step forward in materials science and technology. They allow combining the mechanical, thermal and chemical resistance of ceramics with the ease of molding polymers, as well as obtaining parts of complex shapes and internal structures, which was difficult or impossible using traditional casting and pressing methods.

The most popular technologies for printing PCCs are FDM (for the manufacture of filaments with 20–40 % filling) and SLA/LCM (for high concentrations of ceramics and products with precision geometry). In both cases, it is extremely important:

1. Carefully select the composition, ensuring dispersion of particles.

2. Control the printing parameters (temperature, speed, post-processing).

3. If necessary, carry out debinding (burning out the binder) and sintering to obtain “clean” ceramics.

Given the rapid improvement of equipment and the emergence of new formulations, it is expected that in the coming years even more companies will enter the market with finished products for polymer-ceramic printing. This will allow for a wider application of these materials in medicine (for example, individual crowns, bone implants), aircraft manufacturing (turbine blades, wear-resistant components), electronics (substrates, antenna components) and other high-tech industries.

Thus, additive technologies of 3D printing with polymer-ceramic composite materials can radically change the approach to the creation of high-strength, durable and at the same time relatively lightweight products of complex shape, providing new opportunities for designers and engineers.

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