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The history of the development of 3D printing technologies and their use in world artistic ceramics

***Abstract**. The article is devoted to the study of the history of the emergence and development of additive technologies in world artistic ceramics. The article analyzes information on the history of the emergence of additive technologies. The principle of operation of 3D printing equipment, features of its use, the most common areas of use and materials used in 3D printing have been considered. An analysis of the specifics of the technical characteristics of 3D printers and technologies for 3D printing with ceramic masses has been shown that the use of ceramic materials as raw materials for 3D printing is a progressive trend due to the emergence of the possibility of forming ceramic objects and products that are practically indestructible reproduction and replication using traditional methods. In this article, the authors have been analyzed the advantages and disadvantages of manufacturing ceramic products by 3D printing. It has been established that the main difference between the production of three-dimensional plastic or metal elements and ceramic elements is the main feature of the ceramic manufacturing technology, namely that the printout is not a ceramic product before firing in the oven, that is, without firing, it is simply an element printed from* *clay materials (that is, such a printout before firing is called the "green part" – an unprocessed element). Currently, there are no 3D printers that can immediately produce ready-made ceramic products, all elements printed from ceramic materials require drying and firing. But, despite this nuance, printers that print with clay materials are called ceramic 3D printers. As 3D printing can accurately realize the creative thinking of artists and designers, 3D printing technology is increasingly used in the creation of ceramic products and contemporary ceramic works. The authors of the article emphasize that three-dimensional printing with clay provides ceramists with completely new opportunities for creating ceramic products with a complex configuration, texture, etc. Ceramic artists from all over the world are already actively using this technology in their work. Therefore, part of the study is devoted to examples of the use of 3D printing technology in world artistic ceramics, as well as to the description and analysis of the most interesting achievements in this direction of creativity, according to the authors.*

***Keywords**: 3D printing; additive manufacturing; clay; decorative and applied art; technology and equipment for 3D printing; artistic ceramics*

Introduction.

The development of modern technologies makes it possible to involve new technical and production possibilities in artistic practice, in particular computer technologies, which gives artists the opportunity to expand the arsenal of their creative pursuits. All over the world, in recent years, one can trace the growing interest in the production of ceramic products using additive technologies, i.e. 3D printing of products with ceramic materials (Baltazar, Dias-de-Oliveira, Pinho-da-Cruz, Gouveia, & Olhero, 2021; de Abreu et al., 2023; Pires, Luís, Fernandes, & Oliveira, 2023). Research laboratories, institutes, firms and individual artists have appeared, developing new methods of making ceramic products and equipment for this process.

It is well known (Valera-Jiménez, Marín-Rueda, Pérez-Flores, Castro-García, & Canales-Vázquez, 2021; Hu, X., Lai, Hu, Y., Li, Zhao, & Tong, 2022; Lamnini et al., 2022) that 3D printing ceramic materials presents significant challenges due to several unresolved issues, including excessive surface roughness, suboptimal mechanical properties, high porosity, and low precision of parts. Additionally, adapting ceramic 3D printing technology to different materials is challenging, often necessitating the development of specific 3D printing techniques for particular properties, which increases costs. However, with ongoing advancements in technology and theory, ceramic 3D printing has made substantial progress and remains a major research focus. While traditional ceramics benefit from high-temperature sintering, which is difficult to replicate in ceramic 3D printing, the latter can produce complex 3D structures that are impossible to achieve with traditional ceramic processes.

The aim of the article is to research the history of the development of 3D printing technologies and their use in world artistic ceramics.

Research Methods.

This study is devoted to the study of the history of the emergence and development of additive technologies. Information on the history of the emergence of additive technologies was analyzed, namely, the principle of operation of 3D printing equipment, features of its use, and materials used in 3D printing were considered.

Three-dimensional printing with clay provides ceramists with completely new ways of creating ceramic products of complex configuration, texture, etc. Ceramic artists from all over the world are already actively using this technology in their work. Therefore, part of the study was devoted to examples of the use of 3D printing technology in world artistic ceramics, as well as to the description and analysis of the most interesting achievements in this direction of creativity, according to the authors.

Results and Discussion.

Review of the history of the emergence of additive technologies.

The earliest technologies of modern 3D printing first began to appear in the late 1980s, at that time they were called rapid prototyping technologies – RapydPrototype (RP). This is because the processes were originally conceived as a quick and cost-effective way to create prototypes for industrial product development.

The emergence of the first devices, which can be attributed to the predecessors of 3D printers, dates back to the early 1980s, when Dr. Hideo Kodama developed the first rapid prototyping system using photopolymers. The operation principle of this device consisted in the layer-by-layer reproduction of objects according to the given model. Actually, most modern 3D printers work according to this principle.

The next stage in the field of 3D printing was the invention of stereolithography (SLA) by the American Charles Hull in 1984, a patent for this technology was issued in 1986. Thanks to this technology, it became possible to produce on 3D printers objects that were modeled on a computer by the method of 3D modeling, that is, according to computer digital models. A liquid substance based on acrylic – a photopolymer that solidified under the action of an ultraviolet laser, turning into a plastic product – also served as a material for printing.

In the early 1990s, Charles Hull's company 3D Systems Corporation (which is still one of the leaders in the industry) established the production of printers based on the technology of laser stereolithography from photopolymers (SLA). 3D Systems built its first commercial rapid prototyping system, the SLA-1, in 1987 and after extensive testing sold it in 1988. However, even though SLA technology may claim the top spot in the history of 3D printing, it was not the only rapid prototyping technology at this time.

In 1987, Carl Deckard, who worked at the University of Texas, applied for a patent in the US for selective laser sintering (SLS-Selective Laser Sintering). This patent was issued in 1989, and SLS was later licensed to DTM Inc. and later acquired by 3D Systems.

Also, in 1989, Scott Crump, co-founder of Stratasys Inc. applied for a patent for FDM-Fused Deposition Modeling (FDM) technology, which the company still owns, the technology used today by many entry-level, open-source RepRap (Replicating Rapid Prototyper) printers. The FDM patent was issued to Stratasys in 1992 in Europe.

In 1989, Hans Langer founded EOS GmbH in Germany. After playing around with SL technology, EOS shifted its focus to SLS technology. Today, EOS is recognized worldwide for the quality of its products for industrial prototyping. In 1990, EOS sold its first Direct Metal Laser Sintering (DMLS) stereo system in collaboration with the Electrolux division in Finland, which was later acquired by EOS.

Other 3D printing technologies emerging in these years include the production of ballistic particles (BPM - Ballistic Particle Manufacturing), originally patented by William Masters, the production of objects by the method of lamination (LOM – Laminated Object Manufacturing), patented by Mykhailo Feigin, mask stereolithography (SGC – Solid Ground Curing), patented by Yitzhak Pomerantz and three-dimensional printing (3DP), patented by Emmanuel Sachs. Thus, in the early nineties, there was an increase in the number of competing companies in the rapid prototyping market, but only three of them have survived to this day – 3D Systems, EOS and Stratasys.

It should be noted that the term "3D printing" was first used only in 1995 at the Massachusetts Institute of Technology, and the term "3D printer" was officially used only in 1996, when the Actua 2100 device from 3D Systems was created. The first 3D printers were low-power, worked slowly, and when trying to speed up the production process, products came out with large errors. Only since 2005 have 3D printers appeared with high print quality.

Until 2008, 3D printers could only work with one type of material – ABC plastic. Later, with the development of the 3D printing industry, the number of materials with which printers can work gradually increased. At the moment, there are more than a hundred of these materials. Among them: acrylic, concrete, hydrogel, paper, gypsum, wood fiber, ice, metal powder, nylon, polycaprolactone (PCL), polylactide (PLA), polypropylene (PP), low-pressure polyethylene (HDPE), clay, chocolate, and even human cells.

Fields of Application, Principles of Operation of 3D Printers and Features of 3D Printing Technologies.

The main feature of modern 3D printers is that all models are printed layer by layer, layer by layer. Almost any thing can be created on a 3D printer – from children's toys, souvenirs, dishes, fabrics for sewing clothes, to implants for use in medicine, as well as things with a large number of details – cars, planes, and even houses.

Industries where 3D printing can be used:

- Construction. There is an assumption that in the future the process of constructing buildings will be much faster thanks to 3D printing.

- Medicine. Thanks to 3D printing, doctors have been able to create copies of the human skeleton, blood vessels, etc. 3D printers are widely used in dental prosthetics.
- Architecture and design. Creation of mock-ups of interior elements, buildings and areas allows to evaluate the ergonomics, functionality and appearance of the prototype.
- Education. 3D models are excellent visual materials for learning at all levels of education.
- Automotive industry. Such a method as 3D modeling allows to test the car at the development stage.
- Modeling. Production of packaging materials, toys and souvenir products.
- Light industry. Production of various elements of consumer goods. Manufacturing of clothes and shoes. Currently, similar clothes and shoes are used only at shows. The material here is polyurethane, rubber and plastic.
- Jewelry business. 3D modeling technologies allow to create full-fledged products from metal powder.
- History and anthropology. Models are created on the basis of archaeological finds and allow to assess the reliability of the scientists' assumptions.
- In all other areas not mentioned above, 3D modeling is gradually finding its application.

Thanks to the advent of 3D printing technologies, it has become possible to mechanize and, to some extent, simplify many complex technological processes (Shelyagin, et al., 2005; Strelko et al., 2019). Currently, 3D printing technologies are actively developing and improving all over the world. Each company that develops and manufactures 3D printers seeks to cover as many areas of application of 3D technologies and 3D printing as possible. The variety of 3D printers and consumables for 3D printing is increasing every day.

The principle of forming products by three-dimensional printing is called additive (from the word Add (English). The work of all 3D printers is related to computer design. First, it is necessary to create a computer model of the future object. This can be done with the help of a three-dimensional graphic editor of the CAD system (3D StudioMax, SolidWorks, AutoCAD), or by previously scanning the ready-made object in 3D. Then, with the help of a special software product, the designed or scanned object is divided into layers and a set of commands is generated, which determines the sequence of applying layers of material during printing. Information about any material object to be printed is loaded into the memory of the 3D printer. Similar to a regular paper printer, it creates, that is, reproduces, exclusively on the basis of downloaded data, a material object. The only difference from 2D printers is that objects are reproduced in three-dimensional space. Next, the 3D printer forms the object layer by layer, gradually applying portions of the material (Figure 1).

Placing the print head in the system of two coordinates X and Y, the printer applies the material layer by layer according to the modeled (given) electronic circuit. When moving the platform one step along the Z axis, the construction (drawing) of a new level of the object begins.

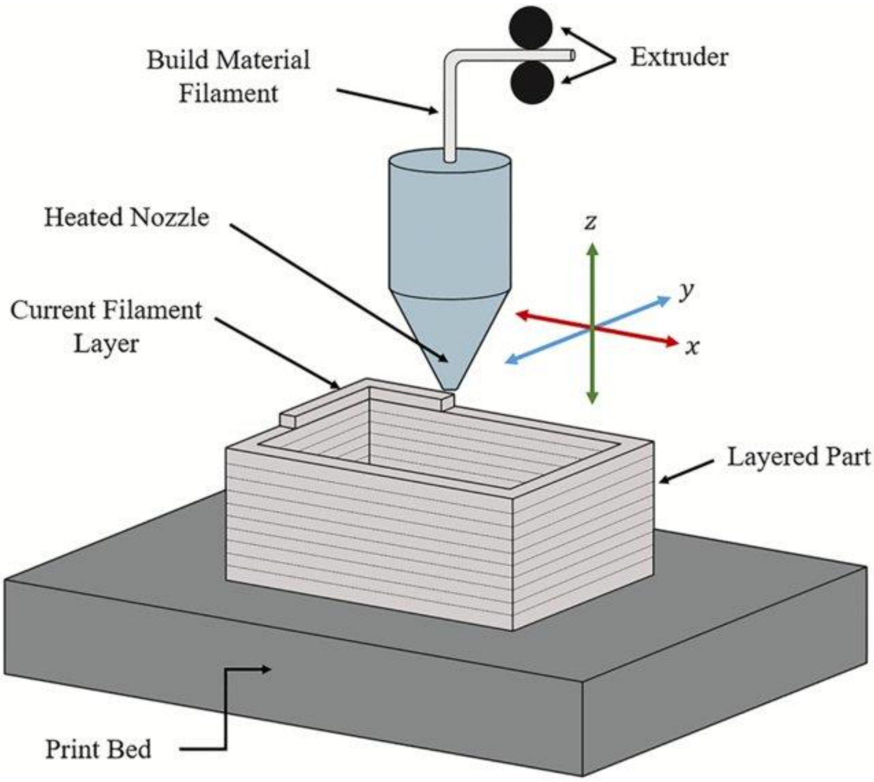

Figure 1. Basic working principle of material extrusion printing (Shah et al., 2019).

Professional 3D printers use different properties of the materials from which they print. As mentioned above, many materials can be used for printing in additive manufacturing (plastic, metal, glass, ceramic, wood, sand, and even human tissue). Some types of printers are able to simultaneously work with different materials, both in terms of properties and color.

Printing on 3D printers can be done in different ways, depending on the material used. There are quite a lot of three-dimensional printing technologies (Bernatskyi & Khaskin, 2021; Strelko, Pylypchuk, & Berdnychenko, 2019). They differ in the principle of formation of layers and their connection. The main technologies are SLA, SLS, DLP, EBM, HPM, FDM.

SLA (**Stereolithography**) technology: (laser) stereolithography (Sokolovskyi & Bernatskyi, 2023). Thanks to this technology, it is possible to build printed objects the fastest. The technology uses a photopolymer on which a laser beam is directed, thanks to which the material hardens. After hardening, the product can be easily processed (glued, painted, etc.).

SLS (**Selective laser sintering**) technology: selective laser sintering is the sintering of powder reagents under the influence of a laser beam (Berdnikova et al., 2021). This is one of the technologies that allows the production of molds for metal and plastic casting.

DLP technology (**Digital light processing**): digital light processing. This is a relatively new technology, for the implementation of which stereolithographic printing devices are used. Printers of this type use digital light processing. This technology uses photopolymer resins and a DLP projector to create three-dimensional figures.

EBM (**Electron Beam Melting**) technology: electron beam melting. This technology uses electron beam melting to create three-dimensional objects. A special material – metal clay – was developed for layer-by-layer surfacing of high-precision parts. This material is made from a mixture of organic glue, metal shavings and water.

HPM, FDM (**Fused Deposition Modeling**) technology: modeling by the method of thread deposition. The object is formed by layer-by-layer application of threads of molten thermoplastic. The material solidifies immediately after exiting the nozzle, which moves in three planes. In some models of 3D printers, a second thread from a different, soluble material is used to build support structures. This technology makes it possible to obtain final models from structural and high-performance thermoplastics. This is currently the only technology that provides mechanical, thermal and chemical strength of parts. An interesting device has appeared these days that is used for manual printing on the basis of FDM technology – pens for drawing 3D objects. Pens are made according to the same scheme as printers. The plastic thread is fed into the handle, where it melts to the desired temperature and is squeezed out through a small nozzle. The last device is especially interesting for use by artists. It allows to create three-dimensional objects actually using lines.

Features of Printers and Technologies for 3D Printing with Ceramic Masses.

Currently, it is obvious that with the development of new technologies, the question arises as to where exactly it is appropriate to use them, because along with a large number of really useful products, 3D printers create a lot of unnecessary things. Special concerns arise regarding ecology and the environment, because currently most products are printed from plastic or other material that is not disposed of. A great alternative was the use of clay as a printing material. Nowadays, certain products are printed from ceramics for medicine, aerospace, design, etc. The use of ceramic materials as raw materials for 3D printing is a progressive trend due to the emergence of the possibility of forming ceramic objects and products that are practically impossible to reproduce and replicate using traditional methods.

Over the past few years, interest in the production of ceramic products with the help of 3D printing has significantly increased throughout the world. It should be noted that the first prototypes of printers that used ceramic powder masses for printing were developed in the 1990s by Emmanuel Sachs and his colleagues from MIT (Massachusetts Institute of Technology). At that time, the first Binder Jetting printers were developed and successfully used to print raw ceramic elements.

The Binder Jetting method (technology of inkjet printing with the help of applying powder and gluing it with a binder) is still used by many manufacturers of 3D printers. In general, Binder Jetting can be used to 3D print ceramic materials such as ExOne or

Voxeljet. Voxeljet devices are used by the British chemical concern Johnson Matthey, whose special research and development department developed in 2017 a pilot unit for printing large elements (on the scale of hundreds of kilograms) and is looking for new applications for printed ceramics (for example, as a substrate for catalysts for the chemical industry).

One of the first 3D printers that prints directly with clay (clay mass) was produced in 2013 by students of the University of Bristol (England) under the leadership of Stephen Hoskins (Hoskins & Huson, 2014; Huson & Hoskins, 2014). This 3D printer created a complete ceramic product, fully ready for heat treatment.

Actually, it should be noted that all currently known 3D printers that print using clay raw materials create only "semi-finished products", i.e. "raw" products, which can be called ceramic only after drying and full firing at a temperature suitable for the clay used. In the terminology of 3D printing, such unfinished products are called "green object", apparently by analogy with fruits or fruits.

In the same year, 2013, the Israeli research and design studio Studio Under announced the development of a 3D printer, which claimed the title of the largest device for printing ceramics in the world at that time. Studio Under, founded in 2012 by designers Eran Gal-Or and Omer Merzel, designs and prints ceramic products, which it distributes worldwide. In 2013, the studio presented the technology of color 3D printing from ceramic materials, which allows the production of colored products. Studio Under developed a fast 3D printer that could print products from ceramic materials (as well as from almost all types of paste-like materials - metal paste, plastic resins, concrete, etc.) in large sizes. The printing area of the printer was 800×800×850 mm, and its speed was equal to 450 mm/h. The device had a special extruder, as well as a cartridge with a capacity of 20 liters, which allowed printing large-sized products. Studio Under used Autodesk Shapeshifter software for work.

Information about similar developments in the following years came from several more countries, in particular from the Netherlands, the United States of America, etc.

At the beginning of 2018, the Ukrainian-American startup Kwambio presented the first industrial printer designed for precise ceramic printing using Binder Jetting technology (Pei, Kabir, & Leutenecker-Twelsiek, 2023; Tabard et al., 2021; Zgalat-Lozynskyy et al., 2021).

In turn, JetX® has proposed Nano Particle Jetting printers, which are equipped with a head that injects resin droplets containing an appropriate amount of ceramic or metal powder particles (Lyu, Yang, Li, Tan, & Liu, 2023; Oh et al., 2019; Zhong et al., 2022).

Another technology widely used for the production of ceramic components is robocasting (Peng, Zhang, & Ding, 2018; Zhang et al., 2020; de Abreu et al., 2023). Extruding ceramic paste from an extruder may seem primitive compared to other methods, but it is much cheaper and works great for printing large parts. Researchers liked the technique, resulting in a large number of amateur designs for printing ceramic materials using the DIW technique. Some of them have spawned companies that sell all-ceramic printers and/or offer custom printing services. One of them is Vorm Vrij, which offers Lutum printers for printing clay as well as other thick paste materials (Lamnini, et al., 2022; Pei, Kabir, Leutenecker-Twelsiek, 2023).

Manufacturers of ceramic printers often emphasize that their products do not harm the ecological balance of the planet. For example, the Vorm Vrij company emphasizes that clay is a more environmentally friendly material, especially compared to plastic. The Italian company WASP very clearly emphasizes its "sustainability" (its full name is "Complex Peacekeeping Project"). This company makes ceramic printers that work in the delta system, and has also become famous in recent years for the development of a large-sized printing device that can print houses. Other DIY ceramics printers include the Potter Bot (cartesian head movement). The GAIA Multitool (delta system) series of Polish universal printers is also known.

The next significant technologies in ceramic 3D printing are SLA and DLP. The use of stereolithography in 3D printing with ceramic materials, as mentioned above, has been known since the 90s of the last century, in particular at the University of Michigan (USA). The company that commercialized the technology was Austrian Lithoz, founded in 2011 as a branch of the Technical University of Vienna. Lithoz now sells advanced LCM (lithography ceramic manufacturing) or DLP printing systems with ceramic particles dissolved in resin. The company also offers some ceramic materials for its printers: aluminum and zirconium oxides, SiAlON, a calcium phosphate-based material (derived from calcium phosphate certified for use in implants), and other custom-made compositions as well.

Printers for printing with ceramic materials based on SLA technology are offered by the French company 3DCeram (Charbonnier, Laurent, Blanc, Valfort, & Marchat, 2016; Nakai et al., 2021; Fournier et al., 2023). In addition to printers, the manufacturer sells ceramic pastes (their range is very similar to Lithoz's offer), as well as additional devices for cleaning prints of raw pastes and kilns for firing ceramics.

Of course, there are still many companies on the market that offer printers and printing materials for ceramics based on photopolymerization. Ceramic printers working on DLP technology are sold by the Dutch company Admatec, the company Formlabs recently introduced its own ceramic resins (they belong to the Form X platform, that is, a number of experimental products). Ceramic resins for SLA / DLP printers, as well as ceramic powders for Binder Jetting printing are also available from the American company Tethon 3D.

Italian 3D printer manufacturer WASP has developed LDM (Liquid Deposition Modeling) technology. Printing with clay on a 3D printer with its help is very simple. The method of liquid application of clay solves many technical problems associated with printing from clay materials. However, some difficulties have yet to be overcome. The firm has high hopes for a collaboration with artist and ceramic 3D printing teacher Francesco Pacelli, through which they plan to find out why some of the finished models are subject to damage or deformation and how this can be prevented. For some time, it has been testing the capabilities of the WASP Delta Style 3D printer equipped with their LDM extruder and demonstrating some of the ceramic designs he modeled. According to Pacelli, it is the clay substance and the way it is processed and mixed that is the key to developing the right printing technology using such materials. 3D printing with clay using LDM technology allows to tightly control the flow of clay material fed to the extruder. The process is strictly synchronized with a stepper motor, which guarantees a consistent supply of material. This prevents the formation of air bubbles, deformations and other defects that can ultimately cause the destruction of ceramic products. Of course, not every material is suitable for such a case. 3D printing with clay is an unusual business. Accordingly, clay for a 3D printer should be unusual. The artist is exploring different types of ceramics to expand the amount of raw clay available for 3D printing. He also experimented with different blends, textures and printing parameters for LDM technology and found some successful solutions to many of the most common problems. Among other things, he found that covering freshly printed objects with plastic bags will help maintain the correct humidity level necessary to prevent drying and cracking during preparation for firing. The collaboration between Pacelli and WASP is an ongoing project that will continue to develop new materials for 3D printing and determine the optimal printing parameters for different types of ceramics.

The technology of 3D printing with ceramic materials is now actively interested all over the world. It is good that Ukraine is not an exception. So, the Odesa startup Kwambio, which was founded back in 2015 by Volodymyr Usov, developed its version of a 3D printer with ceramic materials, which was named "Ceramo One". In addition, the people of Odessa also opened the first factory for 3D printing of ceramic products in Ukraine and Europe. According to the developers, the main difference between the Ukrainian Kwambio printer and its analogues in the world is high speed (160 mm/s) and printing accuracy (20 μm), as well as a wide selection of materials of its own development, which allows printing both design objects and industrial samples. The maximum size of the product that "Ceramo One" can print at one time is 35×35×38 cm. Larger products can be printed in parts. The new printer prints using special clay-based powders, which were also developed at the factory. Thanks to its own production, Kwambio has expanded the range of color solutions: now there are about 100 colors of ceramic powders in the assortment.

In a fairly short period of development of 3D printing technologies with ceramic materials, companies have appeared in the world that have established the production of industrial samples of 3D printers and offer to purchase them. Let's try to make an overview of the main proposals in this field (Table 1).

Table 1 provides an overview of the ceramic 3D printer market. 3D printers are listed in alphabetical order. If necessary, such printers can be purchased on the manufacturer's websites. Let’s note that most of the prices in the table are price ranges, that is, indicative.

Table 1.
List of 3D printers that print with ceramic materials as of 2024.

No.	Printer	Technology	Print volume, mm	Country	Estimated cost, $
1	3d-figo — FFD 150H	FFF/FDM	150×150×120	Germany	50000–100000
2	3DCeram Ceramaker	resin	300×300×110	France	250000
3	3D Systems ProX DMP 200 Dental	powder	140×140×100	USA	250000
4	Admatec ADMAFLEX 130	resin	96×54×120	Netherlands	€125000
5	AIM3D ExAM **255**	FFF/FDM	255×255×255	Germany	50000–100000
6	DDM Systems LAMP	resin	no data available	USA	250000
7	ExOne Innovent	Jetting	160×65×65	Germany	100000–250000
8	HP Jet Fusion 3D 4210	Jetting	406×305×406	USA	100000–250000
9	Kwambio Ceramo One	Jetting	350×350×380	Ukraine/USA	25000
10	Lithoz CeraFab 7500	resin	76×43×150	Austria	250000
11	nScrypt 3Dn 450HP	FFF/FDM	no data available	USA	250000
12	Prodways ProMaker V6000	resin	120×500×150	France	250000
13	Voxeljet VX4000	Jetting	4000×2000×1000	Germany	250000
14	XJet Carmel 1400	Jetting	500×280×200	Israel	250000

Analysis of the advantages and disadvantages of manufacturing ceramic products by 3D printing.

The main difference between the production of three-dimensional plastic or metal elements and ceramic elements is the main feature of the ceramic manufacturing technology: the printout is not a ceramic product before firing in the oven, that is, without firing, it is simply an element printed from clay materials (as previously noted, such a printout before firing is called the green part - an unprocessed element). Currently, there are no 3D printers that can immediately produce ready-made ceramic products, all elements printed from ceramic materials require drying and firing. But, despite this nuance, printers that print with clay materials are called ceramic 3D printers.

In general, ceramic materials provide a number of properties: high strength and dimensional stability; low density; chemical stability; high electrical insulation capacity; high resistance to abrasion and corrosion. Thanks to these properties, 3D printing with ceramic materials is suitable for an extremely diverse range of applications.

Since the authors were interested in the use of 3D printing in artistic practice, the biggest advantage of this technology for use in the production of works of art is the possibility of multiplying (replicating) the same elements, which is a rather monotonous job and, of course, a machine can handle it better. The next advantage is the possibility of manufacturing extremely complex products in terms of design and configuration. The variety of possibilities and the large space for experiments will also, probably, allow the wider use of 3D printers as another tool in the arsenal of the modern ceramic artist.

But, unfortunately, 3D printing with clay is not yet a perfect process. It presents some of the risks, problems and limitations that can be encountered in the most used manufacturing technologies. The reason for this is the peculiar characteristics of the clay material, such as excessive softness and the amount of time required for drying. Many objects are at risk of shrinkage or cracking before they can be fired. Also, 3D printing with clay involves significant limitations in geometry. The reason is the use of auxiliary materials unsuitable for clay raw materials. And this can cause the destruction of printed objects.

One of the main problems that can be encountered in the process of 3D printing is the coefficient of reduction (shrinkage) of clay. Depending on the process used for printing, drying, firing or hot pressing a ceramic object can cause shrinkage of up to 20 percent. Such shrinkage can be a significant problem if the nature of the ceramic product requires precise dimensional control.

Various researchers have found that some components that are successfully used in 3D printing technologies with other components are practically not acceptable at all, or create certain problems when printing with clay materials. Thus, organic ingredients such as cellulose in the ceramic powder used as a binder cause an increase in clay shrinkage. In addition, due to the combustible nature of these organic binders, the products received a too porous structure, which sometimes caused their destruction or significant deformations under the influence of high temperatures during the firing process.

Quite often there are problems with the composition of the mass required for printing for powder printing methods. Preferably, the powder together with the clay materials should additionally contain at least one silicate, usually sodium silicate. Also, the powder should have the plasticity that clay gives, which will ensure the preservation of the shape of the product and the possibility of its preservation during the firing process. It is important that the materials used for 3D printing are adapted to receive and hold the glaze. The best powder formula for printing ceramics:

(a) about 50% to about 80% clay;
(b) from about 5% to about 20% feldspar;
(c) from about 2% to about 10% refractory cement;
(d) from about 2% to about 10% frit;
(e) from about 0.5% to about 4% sodium silicate.

It should be noted that among all 3D printing technologies, only two can print ceramic products from clay materials. Both technologies were discussed in more detail in the previous paragraph, so let’s only note that this is the "Binder Jetting" technology (Baltazar, Dias-de-Oliveira, Pinho-da-Cruz, Gouveia, & Olhero, 2021; Marques, Miranda, Silva, Pinto, & Carvalho, 2021; Valera-Jiménez, Marín-Rueda, Pérez-Flores, Castro-García, & Canales-Vázquez, 2021) working with powder masses and the technology of "direct ink writing" or "robocasting" – extrusion of ceramic paste from an extruder , that is, a technology that works with pasty (plastic) ceramic masses (Malik, Selvakannan, Mazur, Li, & Bhargava, 2022; Monfared et al., 2022; Pires, Luís, Fernandes, & Oliveira, 2023).

Examples of the use of 3D printing technology in world artistic ceramics.

During the last century, the definitions and boundaries of art have changed radically, as have the technologies and methods of artistic practices. One of the most noticeable trends is that the latest techniques and technologies are more often penetrating the field of art. Artists are increasingly actively using new materials and technologies that facilitate certain processes or realize complex creative ideas.

Thanks to the development of computer technologies, it is now possible to free artists from tedious mechanical work, to speed up the manufacturing of certain elements or the execution of certain processes, and in some cases to improve their quality. If a few years ago 3D printing with ceramic materials was of interest mainly to 3D printer developers, programmers and people connected with new technologies, now more and more artists are becoming interested in this technology to create their own creative works. Often, artists begin to create their own 3D printer samples adapted to their needs.

An integral part of the creative process is computer 3D modeling and visualization, which is an integral part of product development and is used for several purposes: to create product prototypes; for preparation for direct production using a 3D printer; for a preliminary assessment of the physical and technical characteristics of the designed objects. To reproduce a three-dimensional object in reality, of course, it is necessary to design a 3D model in digital format. Such a model is created using graphic 3D programs.

One of the artists who uses modern technologies in his work is Anton Alverez's, a Swedish artist of Chilean origin who graduated from the Royal College of Art (London, Great Britain) in 2012. In his creative pursuits, he tries to combine technological innovations with traditional craftsmanship (Figure 2, Figure 3). His practice is focused on designing systems and creating tools and processes for the production of sculptural objects and architecture. The technological equipment developed by the artist to assist in the creation of works is an integral part of the artist's creativity and even himself (Figure 4). With his creativity, he demonstrates that an artist can become both a craftsman and an engineer, and there is no boundary between these roles. Alvarez continues, as if playing, to expand the boundaries of art, creating works that are rich in tradition and at the same time extremely unconventional squeeze plastic clay mass of various configurations.

Figure 2. The Project of Anton Alverez's "Alphabet Aerobics". National Centre for Craft and Design Sleaford, UK (2016). (Thisner, 2016).

Figure 3. The Project of Anton Alverez's "Alphabet Aerobics". National Centre for Craft and Design Sleaford, UK (2016). (Thisner & Bodiam, 2016).

Figure 4. The Extruder of Anton Alverez's. Project “Alphabet Aerobics”. National Centre for Craft and Design Sleaford, UK (2016). (Thisner, 2016).

Alvarez usually works with quite large volumes. The artist is not limited to simply squeezing the clay through the extruder, he controls the process, cooperates with the machine, allowing the clay to sag under its own weight, or to bend in the direction he needs. Such technological development allows the artist to create complex plastic and geometric forms.

The creative possibilities of 3D printing technology are explored by the Emerging Objects studio from the United States of America in its project "GCODE. Clay" presented at the creative studio "Space 2214" in Berkeley as part of the open exhibition "Pattern, Predictability and Repetition" in 2016. The design studio Emerging Objects was founded by Ronald Rael, a professor of architecture at the University of California, Berkeley, and Virginia San Fratello, an associate professor at California State University, San Jose. Rael's work is aimed at researching actionism through art and architecture, through the land art of the 1960s. San Fratello is interested in finding digital, ecological and building design elements in architecture. Given the similarity of their interests, it is only natural that they turned to 3D printing technology in their creative pursuits. As part of the project, a series of objects from various clay materials, including porcelain, potter's clay and fireclay, were printed. Authors of "GCODE. Clay" aimed not only to explore the potential of digital control of the creative process, but also to explore the plasticity of various ceramic materials, the limitations caused by gravity and the behavior of hardware. Describing their project, the artists noted that they forced the 3D printer to go beyond its usual limits and create a series of controlled errors. As a result of the experiment, various 3D-printed vases, bottles, pots and other objects were obtained (Figure 5).

Figure 5. The project "GCODE. Clay" of design studio Emerging Objects (Rael, San Fratello, Wilson, & Schofield, 2016).

The smallest details are made extremely carefully and form various textures imitating knots and weaving (Figure 6).

Figure 6. The project "GCODE. Clay" of design studio Emerging Objects (Rael, San Fratello, Wilson, & Schofield, 2016).

In 2016, the German designer Steffen Hartwig, as part of his master's thesis, produced a series of 3D-printed ceramic products using a 3D printer of his own development (Figure 7).

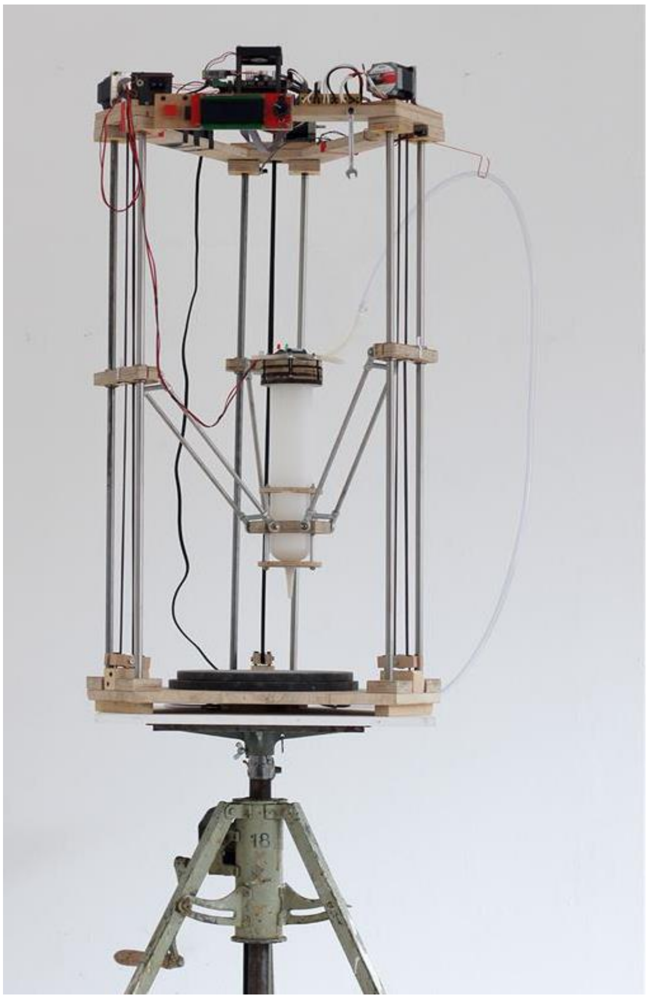

Figure 7. 3D printer of his own development of German designer Steffen Hartwig (Fioretti, 2016).

The artist is extremely interested in ceramics and pottery, as one of the oldest types of human creativity. He is passionate about this topic and collects original pottery items, so he had the idea of merging innovative techniques and traditional types of creativity. The young designer began to explore the boundaries between man and machine, trying to find a way to express traditional craftsmanship through digital technology. Obviously, because of this, his collection is dominated by, at first glance, very simple objects, practically standard ceramic products such as vases and bowls, but in many works, there are some imperfections that the author created on purpose. Such bright, unusual, but programmed details add originality and a certain "handicraft" to his machine-printed products. (Figure 8).

Figure 8. The experimental 3D printing of stoneware clay by of German designer Steffen Hartwig. “Early vase with big loops” (a) and “Breakfast arrangement” (Hartwig, n. d.).

Olivier van Herpt has been dealing with the problems of 3D printing from ceramic materials since 2014, starting with the period of study at the Eindhoven Design Academy. For him, 3D printing of ceramic products is a paradox: on the one hand, it allows a person to create incredibly complex shapes, on the other hand, it completely excludes a person from the process. Olivier built a machine with a piston extruder, which is capable of building clay products up to 90 cm high and 60 cm in diameter, using plastic clay (rather than a slime-like mass, like most machines) (Figure 9).

Figure 9. 3D Printed Ceramics of Olivier van Herpt (van Herpt, 2014).

By changing the settings on the 3D printer, the artist can experiment and give the works different shapes and looks. Van Herpt actively exhibits his works in the most prestigious galleries and museums in the world: the Stedelijk Museum in Amsterdam, the Cooper Hewitt in New York, the London Design Museum, and the Pompidou Center in Paris. In his work, the artist refers to the traditions of ceramic production. In the "Adaptive Manufacturing" series of works, he designs vase-like objects with a variety of interlaced patterns (Figure 10), reminiscent, according to the artist, of artisans' products, when each object was made by hand, so they were individual and unique. But now there is a machine that makes a product from start to finish. Each unique vase from this collection demonstrates the potential of cutting-edge technology while harkening back to a bygone era (Figure 10).

Figure 10. The "Adaptive Manufacturing" series of works of Olivier van Herpt (Smits, 2014).

In 2017, Olivier was offered to make a modern porcelain product (Figure 11) for the art museum Den Haag (Kunstmuseum Den Haag). For this project, the artist developed the first large-scale porcelain 3D printing equipment. The project is called "Arcanum" and consists of fourteen porcelain pieces standing on top of each other and based on an original 17th-century Delft faience pyramid base. Just as Delft faience once arose from the attempts of Dutch artisans to unlock the secret and reproduce Chinese porcelain, Olivier also had to overcome certain difficulties and unravel the secrets. He had to come up with a printing technology with two-color porcelain that would imitate ancient products. The artist managed to develop porcelain 3D printing with cobalt oxide pigment. The idea of supplementing the ancient flower pyramid with individual cup-shaped elements – modern and quietly beautiful – turned out to be successful. Taking the old and creating the new with respect for it is truly a challenge.

Figure 11. The project “Arcanum”. Porcelain flower pyramid (Schreurs, 2017).

During 2014–2023, Olivier van Herpt also created many impressive unique interior items in the form of floor-standing vases of asymmetrical shape, complemented by a play of fastidious textures. These objects open a new world of digital technologies. The small stripes remind that the object was 3D printed, but only when viewed from a close distance. Among van Herpt's recent projects is "Blue and White" (2018) – thin-walled vases, the color of which is reminiscent of Delft faience. Each object is one meter high.

The Dutch company "VormVrij 3D" deals with 3D printing technologies, manufacture and sale of equipment for printing with clay materials. The company was founded by designers Marlike Venacker and Jao van den Herik, graduates of the Design Academy in Eindhoven. The founders of the company have diverse interests in the fields of design, art, culture, and are also activists in organizations that help women and children in West Africa and in environmental organizations. The special attention of artists to 3D printing with clay materials is dictated, in fact, by the struggle to reduce the use of plastic and return to environmentally friendly materials, one of which is clay.

Figure 12. The project “Blue and White”. Porcelain (van Herpt, 2018).

The VormVrij 3D team hopes that combining materials from the past with modern technologies will change the perception of household ceramics. The 3D printer of the "LUTUM 4" company is able to print products of quite significant sizes: up to 85 cm in height and with a base area of up to 58×79 cm. The base of the printer is heavier, adapted to work with clay, which is much heavier than other materials used for 3D printing. The base withstands the weight of the clay when making large products and prevents their possible deformation. The printer is built on the Arduino platform with Ramps 1.4 shill (add-on board), three 2A type stepper motors and "air" print heads. 3D printing of products takes from fifteen minutes, which significantly exceeds the speed of most existing 3D printers. Of course, the exact printing time depends on the size of the product and the humidity of the clay used. The company not only manufactures equipment and printers for 3D printing, but also prints ceramic products itself, cooperating with various artists and designers, conducts master classes, actively popularizes 3D printing methods, etc. Quite often, "VormVrij 3D" ceramic products are traditional basic ceramics, jugs, vases, baskets (Figure 13). More modern models are also presented, such as complex-shaped vases (Figure 14), as well as sculptural compositions depicting various anthropomorphic elements (Figure 15).

Figure 13. Products of VormVrij 3D (n .d.).

Figure 14. Products of complex configuration VormVrij 3D (n .d.).

Figure 15. Products of sculptural compositions depicting various anthropomorphic elements of VormVrij 3D (n .d.).

Noticeable improvement in print quality and significant increase in product size of VormVrij 3D (Figure 16).

Figure 16. "VormVrij 3D. Printing with clay materials (n .d.).

Turkish ceramist Fatih Aslan, who works at the Department of Ceramics and Glass at Dokuz Eylul University in Izmir, Turkey, is engaged in research in the field of industrial design, 3D printing with clay materials. The artist designs porcelain lamps of quite large sizes and complex shapes (Figure 17), and prints sculptural ceramic objects in the form of female portraits (Figure 18).

Figure 17. Fatih Aslan. Lamps, porcelain. 3D printing (Aslan, n .d.).

Figure 18. Fatih Aslan. Sculptural portraits. 3D printing (Aslan, n .d.).

As 3D printing can accurately realize the creative thinking of artists and designers, 3D printing technology is increasingly used in the creation of ceramic products and contemporary ceramic works (Hu, X., Lai, Hu, Y., Li, Zhao, & Tong, 2022).

Handcrafting ceramic pottery in the traditional method or virtual reality (VR) with intricate surface details is still challenging for the ceramic and graphic artist (Dashti, Prakash, Navarro-Newball, Hussain, & Carroll, 2022). Free-form pottery modeling can be efficiently geometrically modeled with the right tools with detailed 3D print outputs, yet challenging to be manufactured using traditional art. The new advanced pottery VR simulation is a promising method to recreate the traditional pottery simulation for a better experience with some barriers. The challenges that arise from surface detail in pottery are a tedious task accomplished by mesh blending and retopology.

Conclusions.

The article examines the history of the development of 3D printing technologies and their use in world artistic ceramics.

An analysis of the specifics of the technical characteristics of 3D printers and technologies for 3D printing with ceramic masses has been shown that the use of ceramic materials as raw materials for 3D printing is a progressive trend due to the emergence of the possibility of forming ceramic objects and products that are practically indestructible reproduction and replication using traditional methods.

It has been established that the main difference between the production of three-dimensional plastic or metal elements and ceramic elements is the main feature of the ceramic manufacturing technology, namely that the printout is not a ceramic product before firing in the oven, that is, without firing, it is simply an element printed from clay materials (that is, such a printout before firing is called the "green part" – an unprocessed element). An analysis of various technologies for 3D printing of ceramic products in art has been shown that currently there are no 3D printers that can immediately produce ready-made ceramic products, all elements printed from ceramic materials require drying and firing. But, despite this nuance, printers that print with clay materials are called ceramic 3D printers.

At the same time, three-dimensional printing with clay already today provides ceramic artists with completely new opportunities for creating ceramic products of complex configuration, texture, etc.

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Історія розвитку технологій 3D друку та їх використання у світовій художній кераміці

Анотація. *Стаття присвячена вивченню історії виникнення та розвитку адитивних технологій, що застосовуються у світовій художній кераміці. Авторами проведено аналіз інформації стосовно способів отримання виробів шляхом пошарового нарощування матеріалу, розглянуто принцип дії обладнання для 3D-друку, визначено особливості його використання, перераховано найпоширеніші галузі, в яких застосовуються ці технології та матеріали. Здійснений аналіз технічних характеристик 3D-принтерів та технологій друку керамічними масами, показав, що використання цих матеріалів в якості сировини для 3D-друку є прогресивною тенденцією, яка надає можливість формувати керамічні об'єкти та вироби, які практично не піддаються відтворенню та тиражуванню за допомогою традиційних методів. У дослідженні зосереджено увагу на перевагах та недоліках виготовлення керамічних виробів способом 3D-друку, а також встановлено факт відмінності між виробництвом тривимірних пластикових або металевих елементів і керамічних об'єктів. Ця відмінність зумовлена особливістю технології виготовлення кераміки, оскільки роздрукований предмет не є керамічним продуктом до випалу в печі, тобто без випалу – це просто елемент, надрукований із глиняних матеріалів (така роздруківка до випалу називається «зеленою частиною» – необробленим елементом). Наразі не існує 3D-принтерів, які могли б одразу продукувати готові керамічні вироби – всі елементи, надруковані з керамічних матеріалів, потребують сушіння та випалу, не зважаючи на це, принтери, які друкують глиняними матеріалами називають керамічними 3D-принтерами. Оскільки 3D-друк може точно реалізувати творчий задум художників і дизайнерів, технологія такого друку все частіше використовується у створенні керамічних виробів і сучасних керамічних арт-об'єктів. Автори статті наголошують на тому, що тривимірний друк глиною надає художникам-керамістам абсолютно нові необмежені можливості створення керамічних виробів складної конфігурації, з різноманітною фактурою* *та тональними розтяжками, тож наразі керамісти усього світу почали активно застосовувати цю технологію у своїх творчих практиках. Значну частину дослідження присвячено прикладам використання технології 3D-друку провідними фахівцями світової художньої кераміки, а також фіксації та аналізу найбільш цікавих, на думку авторів, здобутків цього сучасного та інноваційного творчого напрямку.*

Ключові слова: *3D-друк; адитивне виробництво; глина; декоративне та прикладне мистецтво; технологія та обладнання для 3D-друку; художня кераміка*

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