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THEORY AND TECHNOLOGY OF FORMING PROCESSES

MATERIALS AND TECHNIQUES FOR 3D PRINTING IN UKRAINE (OVERVIEW)

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An overview of additive manufacturing techniques in Ukraine from the end of the last century to 2021 is presented. The current state of 3D printing in Ukraine was analyzed in terms of new developments (startups), research areas, and direct implementation of additive manufacturing techniques. The main scientific and research teams that were actively engaged in the development and implementation of additive manufacturing techniques in Ukraine since the end of the 1990s were addressed. They include those involved in research of selective laser sintering for ceramic powders produced from refractory ZrO_2*–*TiO_2 *and* TiN*–*TiB_2 *compounds conducted at the Frantsevich Institute for Problems of Materials Science, National Academy of Sciences of Ukraine, and research intended to produce 3D parts by fused deposition of metals or alloys called xBeam 3D Metal Printing conducted at the Paton Electric Welding Institute, National Academy of Sciences of Ukraine. This technique found its commercial implementation in the Chervona Hvilya PJSC startup. The paper discusses the main trends in the development of new equipment for 3D printing with ceramics, polymer/ceramic materials, and metals and alloys, as well as experiments combining different materials to achieve new properties. The latest experiments on the shape of materials are presented. They involve the formation of lattice structures that not only reduce the weight of parts but also impart properties that are comparable to those of dense materials. The main attention is paid to the overview of up-to-date capabilities and prospects for the use of additive manufacturing techniques and materials in national materials science. Attention is also focused on prospects for producing parts of complex shape for various functional purposes from ceramics, metals, and associated composites.*

Keywords: *additive manufacturing techniques, 3D printing, materials science, ceramics, metals, polymers.*

INTRODUCTION

We are well familiar with the prospects of using 3D printing in various areas of our lives. The world is undergoing virtually revolutionary changes in the development and implementation of additive manufacturing techniques in both everyday life and industry. Ukraine is implementing additive manufacturing techniques with

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high-technology countries. The use of a construction 3D printer produced domestically and provided by Mellivora LLC for a research project on the construction of a 6 m × 8 m concrete house in the village of Nedrigailiv, Sumy region, was announced recently [1]. A fairly wide variety of 3D printers designed for fused deposition modeling (FDM) is offered for domestic consumers in Ukraine at prices ranging from several thousand hryvnias for home use to expensive professional models. A fairly wide range of filaments (thermoplastic threads with a 1.75 or 3 mm diameter) is proposed for such printers. The filaments are conventionally produced from thermoplastics (ABS, PLA, polycarbonates, polyamides, polystyrene, lignin, etc.), but there are also thermoplastic-based composites reinforced with carbon fibers, wood, and ceramic particles. In addition to the FDM technique, being currently the most widespread because of low cost and general availability, there are a number of other additive manufacturing techniques that have been implemented in aerospace engineering, metallurgy, medicine, design, and other industries, considering their complexity and cost of process equipment and consumables.

Since the 3D printing methods are quite widely covered in scientific reviews and papers, our overview will mainly focus on the introduction of additive manufacturing techniques and materials in Ukraine as of 2021 and on the prospects for development of 3D printing in our country.

CLASSIFICATION OF ADDITIVE MANUFACTURING TECHNIQUES

All current additive manufacturing (AM) techniques can be grouped into the following categories: vat photopolymerization (VP), material jetting (MJ), binder jetting (BJ), powder bed fusion (PBF), material extrusion (ME), directed energy deposition (DED), and sheet lamination (SL) [2].

Vat Photopolymerization (VP) is an AM technique in which a liquid photopolymer is selectively hardened under the action of ultraviolet radiation.

Material Jetting (MJ) is a technique of making a part by applying droplets of the material onto the build platform.

Binder Jetting (BJ) is a technique of producing plaster, sand, metal, and ceramic parts. A powder layer is applied first onto the build platform and then a head (as in an inkjet printer) injects a liquid binder into the powder material, selectively joining its particles together.

Powder Bed Fusion (PBF) is an AM technique that selectively applies thermal energy to melt the surface of a preliminarily deposited powder layer.

Material Extrusion (ME) is the most common and easy-to-implement AM technique. The material is selectively fed through a nozzle or jet to build up a part layer by layer. Printers employing plastic filament extrusion or fused deposition modeling (FDM) are most widespread and suitable for home and office use.

Directed Energy Deposition (DED) is a technique of making parts from metals and alloys in which thermal energy is applied to join the material by layer-by-layer fusion. The heat source can be a laser, an electron beam, or a plasma arc. The starting material is metal powder or wire.

Sheet Lamination (SL) is an AM technique in which a part is build up from sheets of the material that are joined with each other.

REVISITING THE HISTORY OF ADDITIVE MANUFACTURING DEVELOPMENT IN UKRAINE

Although additive manufacturing techniques found worldwide application in the twenty-first century, 3D printing was introduced into Ukrainian materials science in the second half of the 1990s. A scientific team from the Frantsevich Institute for Problems of Materials Science (IPMS) led by A.V. Ragulya (now Academician of the National Academy of Sciences of Ukraine, IPMS Deputy Director) conducted research on selective laser sintering (SLS) of ceramic powders produced from refractory compounds [3, 4]. The researchers used an SLS machine that had the following components: an LTN-103 YAG laser with a maximum laser power of 250 W and an output laser beam diameter of 6 mm, a target movement control system (including a computer, a coordinate unit, and *X* and *Y* mechanical drives), and a target with a system for depositing powder layers. The design of this SLS machine differs from other devices in that the laser beam is focused at one point of the target, and target movement is controlled by electromechanical drives (Fig. 1). In the SLS process, as suggested by the name of this technique, a powerful laser

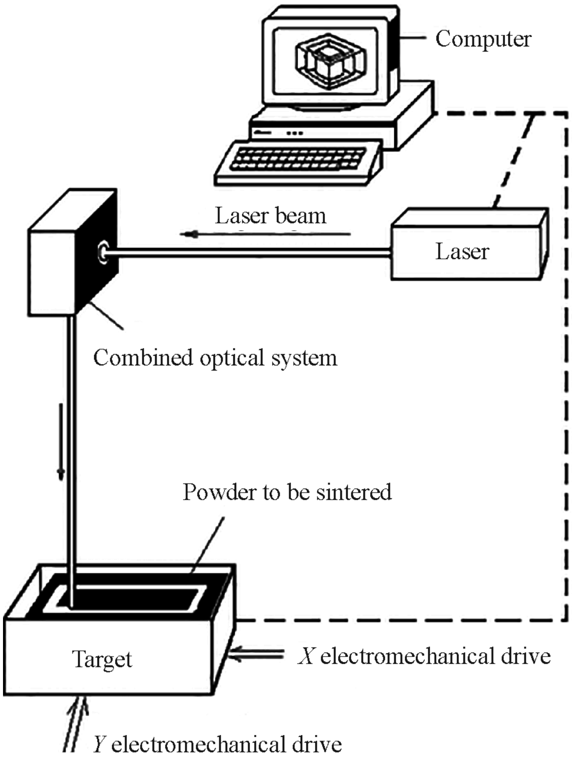


Fig. 1. Selective laser sintering machine

beam selectively irradiates the powder layer surface along a given pathway. The powder is heated and thus sintered (partially fused) to bind the material together to build a three-dimensional structure. Then a new powder layer is applied to the layer already sintered to be subsequently heated and bound. The process is repeated layer by layer until a three-dimensional part is build up. Unlike FDM, the SLS process does not require that additional support structures are arranged for overhanging areas because they remain surrounded by the loose powder. A low-melting component (commonly nylon or polyamide) is currently used in SLS to bind together more refractory particles in a layer, while the buildup of 3D parts examined in [3, 4] is called SLM (selective laser melting) or LPBF (laser powder bed fusion).

Important characteristics of laser sintering machines include the laser power range, target (or laser beam) movement speed, and laser beam diameter. The processing area can be changed by increasing (or decreasing) the laser beam diameter and powder layer thickness.

To study the structurization in a single sintered layer, ZrO_2–TiO_2 and TiN–TiB_2 eutectic materials were subjected to laser sintering. Single-layer and multi-layer rectangular samples were made. The samples were laser sintered by varying the laser power and laser beam scanning speed to assess the quality of layer overlapping (joining) in the buildup of complex parts (Fig. 2).

Both loose ZrO_2–TiO_2 or TiN–TiB_2 powder mixtures and sintered cylindrical samples of specific composition were subjected to laser sintering. The loose mixtures were used to make multilayer parts and the cylindrical samples to study how the material acquires its structure under the action of laser radiation on the powder mixture in both one and several layers.

Note that this effort was innovative at that time, and the developers even now focus their main attention on the production of parts from metal powders by SLS/SLM. Nevertheless, the idea of building up parts from eutectic ceramic materials by 3D printing remains relevant, is still to be studied, and is awaiting implementation.

The Paton Electric Welding Institute (National Academy of Sciences of Ukraine) also worked on the introduction of additive manufacturing techniques for the rapid production of metal and alloy parts. The research was conducted in the conventional area for this scientific team: production of three-dimensional parts by fused

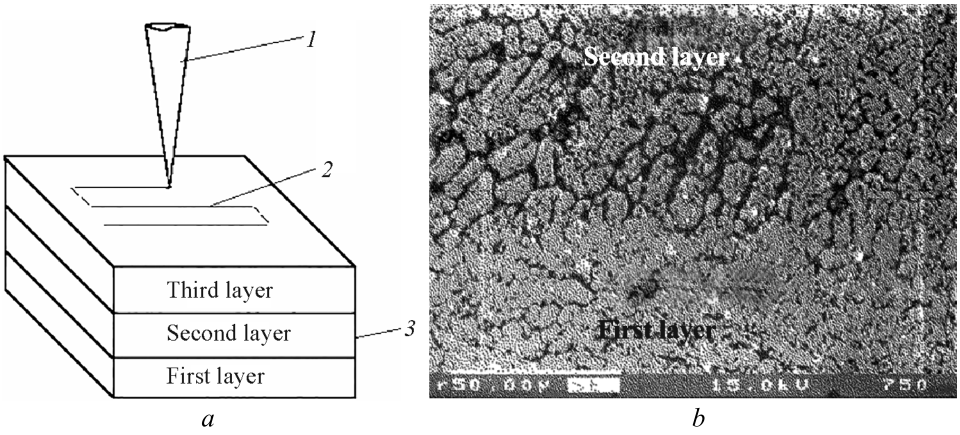


Fig. 2. Selective laser sintering of a multilayer sample: *a*) general scheme (*1*—laser beam; *2*—sintered material; *3*—powder layers); *b*) boundary between two sintered layers of the ZrO_2–TiO_2 powder mixture

deposition and development of electron-beam equipment. This initiated the development of equipment for electron-beam 3D printing with the use of metal powder materials to make parts of any shape [5]. The layer-by-layer fused metal deposition technique to make 3D parts was also commercialized, but we will consider it further as a project implemented successfully in modern conditions.

The overview of publications through the history of additive manufacturing development in Ukraine starting from the nineties of the last century to the beginning of the twenty-first century presented in this paper did not find other stable research teams whose scientific interests would involve the elaboration of 3D printing methods with ceramic materials, metals, or alloys with the purpose of their subsequent implementation. We will further address current trends in the development of additive manufacturing techniques in the world and Ukraine.

CURRENT STATE OF ADDITIVE MANUFACTURING TECHNIQUES IN UKRAINE (MATERIALS SCIENCE ASPECTS)

3D printing techniques have long gone beyond the research laboratories and are now at the stage of commercial use. Besides a fairly large number of commercial projects for the development of equipment and materials for printing with thermoplastics employing the FDM technique, there are several successful startups in Ukraine for the design of 3D printers for ceramic and metal materials. The Ukrainian–US Kwambio Company (Odesa) and Chervona Hvilya PJSC (Kyiv) are most famous among them.

The production of three-dimensional parts by fused deposition of metals or alloys called xBeam 3D Metal Printing found its commercial implementation in the Chervona Hvilya PJSC startup [6]. The Chervona Hvilya Company first built a pilot printing system employing the xBeam 3D Metal Printing technique. The experimental 3D printer began making a wide range of articles from ordinary industrial wire, simplifying the production of parts. The Company now offers a range of printers for both laboratory use (xBeamLab) and industrial printing of large products (xBeamWorks, xBeamGrand) [7].

According to the classification of additive manufacturing techniques, xBeam 3D Metal Printing belongs to directed energy deposition (DED) processes. The technique is implemented as an electron beam gun and a wire feed system (Fig. 3*a*). This method is similar to FDM, where the thread filament is deposited layer by layer to build up a part. Such setup and 3D printing process are illustrated in Fig. 3.

The Kwambio startup is another example of additive manufacturing techniques successfully implemented in our country. The 3D printing solutions based on the binder jetting (BJ) method allowed the development of a 3D printer to start making ceramic parts at a plant in Odesa (Fig. 4). The main advantage of this printer is its price, constituting about 25,000 US dollars and being an order of magnitude lower than that of the competitors. The binder jetting printing allows a part to be reproduced accurately in accordance with the generated 3D model, opening up prospects for the printing of bioceramics for prosthetics [8].

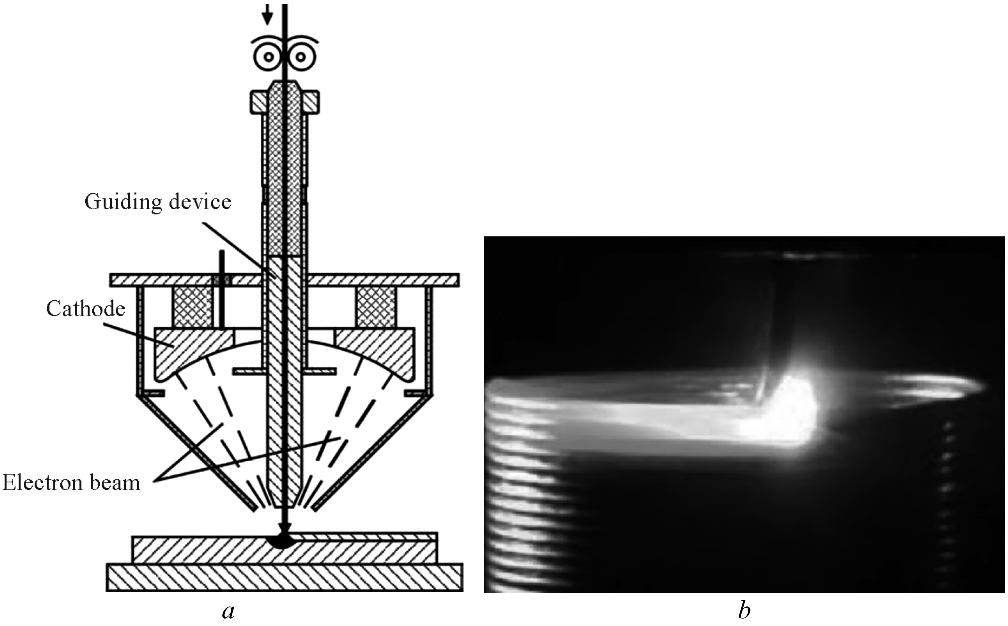


Fig. 3. xBeam 3D Metal Printing: *a*) schematic of fused deposition; *b*) photograph of layer-by-layer printing process [7]

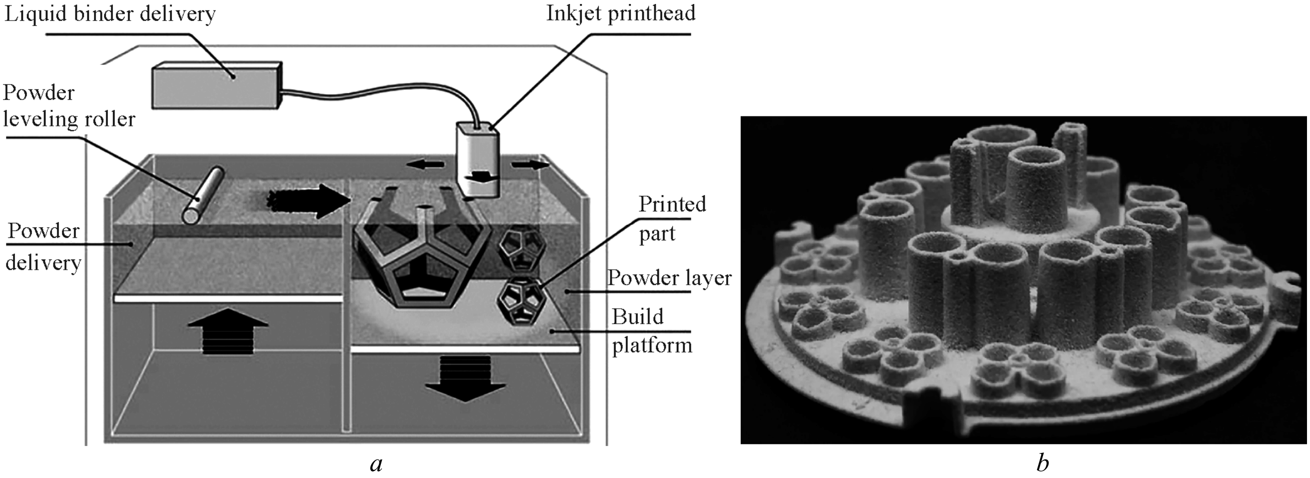


Fig. 4. Binder jetting technique: *a*) general printing schematic [9], *b*) examples of ceramic parts produced with the Kwambio printer [8]

Unfortunately, the metal or ceramic printing techniques discussed are rather expensive and difficult to implement. Moreover, they require specific equipment, qualified personnel, and consumables. Another restraining factor for the introduction of the above-mentioned additive manufacturing techniques is the equipment price and the net cost of printed parts. Depending on the printing technique and the size of printed parts, the price for some 3D printers can reach several million US dollars. Hence, only large high-technology companies whose activities are not associated with mass production can afford such 3D printers. The net cost of parts built up with the techniques concerned increases accordingly.

Nevertheless, there are successful examples of using AM techniques in Ukraine. The Ukrainian state enterprise 'Yangel Pivdenne Design Office', known for advanced developments in aerospace engineering, actively implements additive manufacturing techniques for building up parts in complex shapes and structures from metal powders. The enterprise uses a 3D metal printing technique that should replace classical production processes such as casting, stamping, welding, cutting, etc. [9]. The Pivdenne Design Office employs selective laser melting to make unique parts of complex profile for rocket and space vehicles without the use of mechanical processing and expensive equipment [10].

The introduction of additive manufacturing techniques at an enterprise such as the Pivdenne Design Office is economically feasible and innovative because the main advantages of selective laser melting pointed out by Pivdenne experts include, in particular, the high accuracy and reproducibility of parts, the similarity between the mechanical properties of the 3D printed parts and cast products, the ability to design and make geometrically complex products and parts with a complex profile without scaffolding, a shorter research and development cycle, and lower weight of the parts because of internal cavities [11].

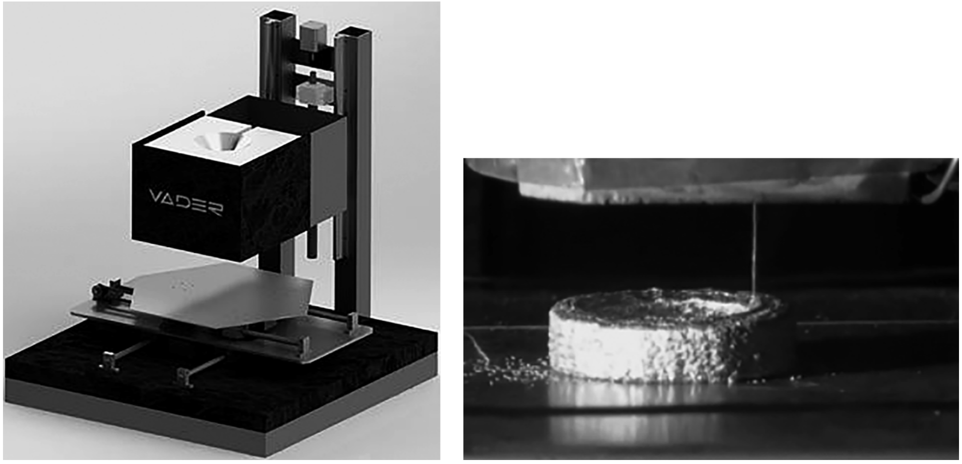
DEVELOPMENT OF NEW 3D METAL PRINTING TECHNIQUES AND MATERIALS

There are a number of restrictions associated with 3D printing in terms of new materials developed for additive manufacturing processes that would allow the production of metal parts. For example, the 3D printer described in the publication on additive manufacturing techniques at the Pivdenne Design Office, specifically the SLM Solutions SLM 280 HL printer, costs more than 250,000 US dollars. There is clearly no possibility for third-party research groups to perform experiments with new powder materials using this printer.

A number of companies have purchased similar equipment and offer metal printing services. For comparison, metal (cobalt–chromium alloy) printing using a Sisma SLM printer (maximum part sizes are 100 mm in diameter, 100 mm in height, and 20 μm in layer thickness) proposed in Ukraine costs from 1.5 euro per gram [12]. However, expensive equipment should be not be exposed to experimental materials in this case either. To solve this issue, the developers of materials for additive manufacturing techniques may directly contact equipment manufacturers interested in expanding the range of materials for their equipment or cooperate with counterparts abroad having 3D printers to perform experiments with materials and participate in projects that would allow them to purchase this equipment for the development of their own materials.

Considering that the offer of equipment is quite extensive, the first-priority task is to develop new materials for various additive manufacturing techniques whose demand would be only increasing. Hence, at the beginning of 2019, Smartech Publishing presented a report on the evolution of 3D printing. The document emphasized that this industry would generate up to 3.6 billion US dollars worldwide in 2028. According to the report, ceramic 3D printing would come to maturity in 2025 and would find application as a manufacturing technique across various industries.

On the other hand, the demand for metal printing machines is quite high, encouraging small companies to develop their own low-cost 3D printers. For example, Scott Vader and Zack Vader from Vader Systems developed a 3D printer called Vader 3D to print three-dimensional parts from molten metals (Fig. 5) [13]. Vader 3D uses



a *b*

Fig. 5. Vader 3D printer: *a*) experimental model [13], *b*) liquid metal printing process [14]

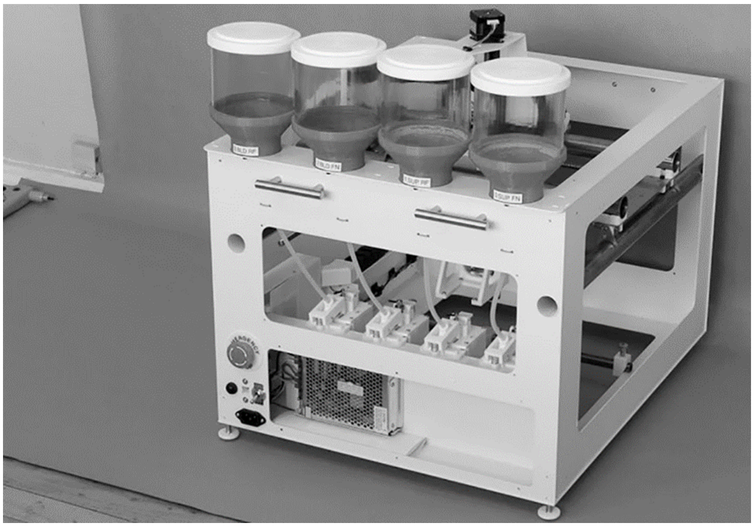


Fig. 6. Iro3d 3D metal printer [15]

liquid metal for printing, resulting in dense solid-metal products. The ultimate strength of finished products printed with Vader 3D is 30% higher than the ultimate strength of the same parts produced by casting [14]. The Vader 3D printer operates by spraying a jet of molten metal that is pushed out of the thermal chamber at a rate of up to 2,000 drops per second, falls onto the part surface where it joins with the previous metal layer, and then cools and hardens to form a model with smooth and even surface.

Vader 3D currently costs between 10,000 and 15,000 US dollars and can use only aluminum, but the developers are examining the printing with other materials and the reduction in price to less than 10,000 US dollars.

The US iro3d startup provided another opportunity to produce metal parts without significant financial costs [15]. This startup began supply of its first affordable 3D printers for making metal products. Moreover, their printers are now available at prices starting at 5,000 US dollars, which is comparable to the price of professional FDM printers. This price is relatively low on the market of AM metal parts compared to the solutions offered by 3D Systems or EOS. Even newcomers such as Desktop Metal and Markforged, desiring to reduce the cost of technology, offer printers whose price approaches 100,000 euros. Early in 2018, the iro3d manufacturer presented its first version of a 3D printer (Fig. 6). A few months later, after being tested by US dealers, iro3d printers were supplied to several US companies, and plans of supplies to Asia and Canada are being considered.

The new iro3d printer employs indirect production process. Instead of printing a finished 3D metal part, iro3d selectively deposits sand and metal powder inside a crucible printed to the desired shape. After the sintering stage, the crucible is removed to leave only the metal part. Depending on the metal, the sintering temperature and length are varied. The manufacturer states that a copper–iron part would be sintered at 1184°C for about 2 h.

The iro3d printer is now compatible with high-carbon steels, copper alloys, and nickel. Examples of iro3d-printed parts are shown in Fig. 7.

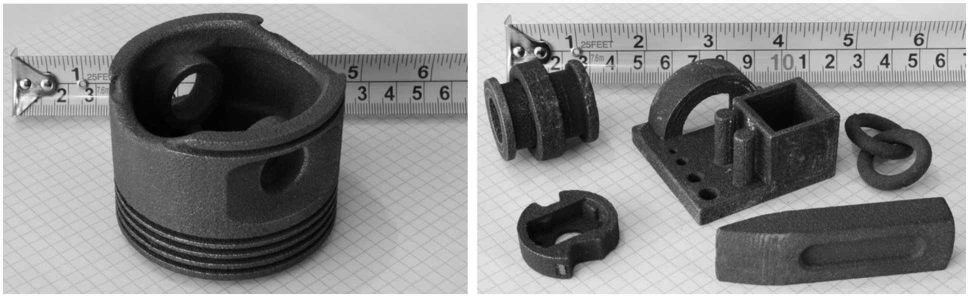


Fig. 7. Parts produced with an iro3d printer [15]

Additional studies conducted by the manufacturer are intended to optimize the printing system for the production of aluminum, stainless steel, or titanium parts that are widely used in industry.

In terms of performances, the iro3d printer offers a 300 mm × 300 mm × 100 mm printing volume and a 0.3 mm minimum layer thickness. The time for printing a standard part will depend on its size and may be reduced through adjustment of the printing parameters. Iro3d also states that printing with its equipment does not result in any shrinkage compared to other solutions that involve the use of metal-filled plastic pellets.

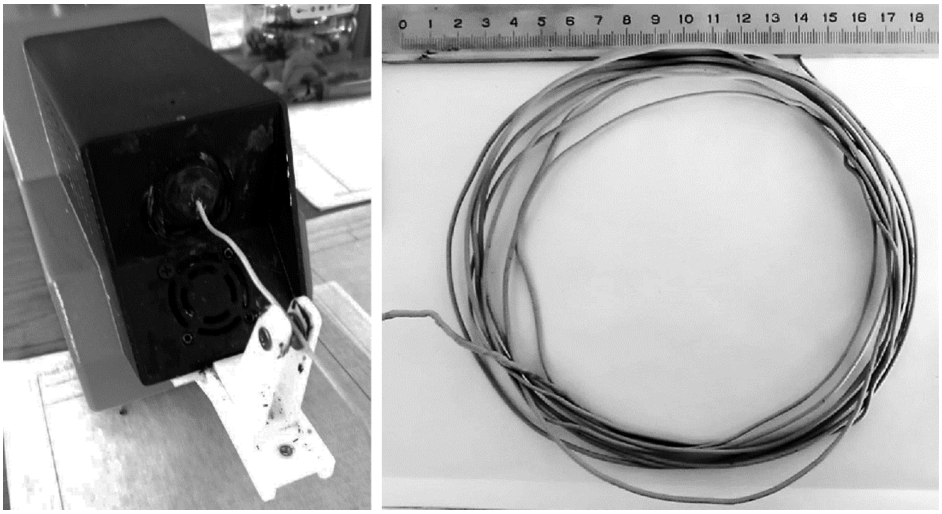
GENERALLY ACCESSIBLE 3D PRINTING

Material extrusion is most popular 3D printing process as it is adapted to both low-cost desktop systems and large frame industrial machines. Fused deposition modeling is currently most common and affordable 3D printing technique for making plastic parts. Nevertheless, material extrusion can also be used for 3D printing of ceramic, metal, glass, biocomposite, clay, and other parts. This printing method is called robocasting or direct ink writing (DIW).

As already noted, 3D printing with polymer materials by fused deposition modeling (FDM) found the wideset application among the additive manufacturing techniques. This method involves layer-by-layer buildup of a part by fused deposition of a special polymer thread called a filament. The market now offers a wide selection of filaments made of plastics such as ABC, PLA, POM, PETG, PP, PE, and other polymers. In addition, numerous manufacturers of 3D printing materials recently started the mass production of filaments from metal/polymer and ceramic/polymer composites. Such composite filaments impart the mechanical properties (high hardness, wear resistance, electrical conductivity, etc.) to the printed parts that cannot be achieved with the use of conventional plastic filaments. Ready-made filaments filled with bronze (Bronzefill), copper (Copperfill), aluminum-based alloy 6061, SiO_2 and ZrO_2 ceramic particles, 316L stainless-steel particles, and carbon particles and fibers can be purchased today. These filaments are intended for mass consumers and thus the proposed filament fillers (ceramic, metal, carbon) perform mostly a decorative function, imparting the desired color or texture and sometimes even specific scent (for example, scent of wood) to the printed part.

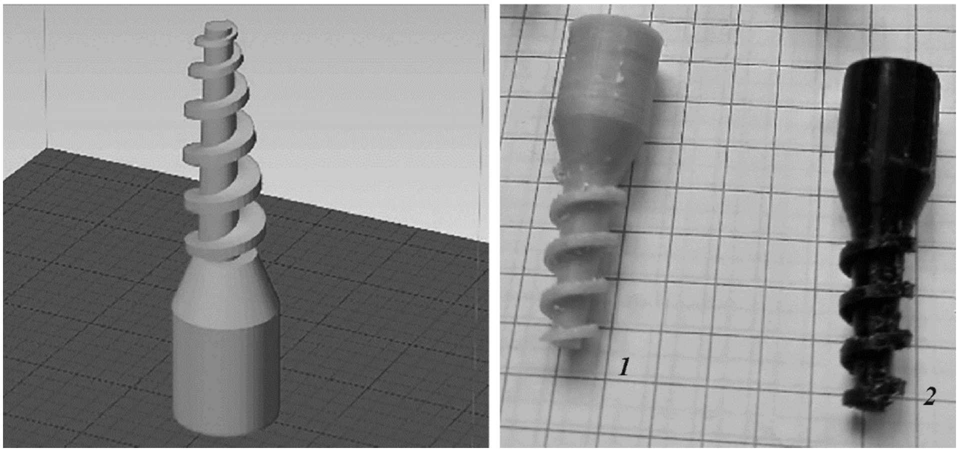
Such composite filaments can be easily produced not only on an industrial scale and in laboratory conditions but also by individual researchers. This significantly promotes the development of new FDM materials.

For example, there are desktop extruders that are not only imported but also produced in Ukraine and cost 24,000 to 28,000 UAH (as of 2021). These extruders allow the production of filaments from polymer materials but require experiments with the formation of composites. Figure 8*a* illustrates the extrusion of a ceramic/polymer



a *b*

Fig. 8. Extrusion of a polymer/ceramic filament (*a*) and a filament (*b*) produced from polypropylene reinforced with 5 vol.% Si_3N_4 [16]



a *b*

Fig. 9. 3D auger model (*a*) and printed parts (*b*) from filaments reinforced with ceramic particles (*1*) and from PLA plastic (*2*) [16]

filament using a Wellzoom desktop extruder. Filaments of desired diameter with different metal, ceramic, and other fillers can be produced (Fig. 8*b*) [16].

To design and 3D print models by FDM, open source 3D software, such as Blender, Ultimaker Cura, etc., can be applied. The composite filaments can be used in any FDM 3D printer with an accuracy of 0.1 mm. Figure 9 illustrates modeling of an auger with the Blender software and shows examples of parts printed with an Ultimaker+ 3D printer from a polymer material and a composite containing silicon nitride particles.

Studies on the printing of polymer-based composites using the FDM technique in Ukraine are conducted at the Paton Electric Welding Institute, Frantsevich Institute for Problems of Materials Science, Bakul Institute for Superhard Materials, National University of Technologies and Design (NUTD), and other scientific institutions. The Ukrainian researchers mainly focus on the development of new composite filaments to impart new useful properties to 3D printed parts. Employees of NUTD together with the Galkin Donetsk Institute for Physics and Engineering (National Academy of Sciences of Ukraine, Kyiv) produced 3D printing filaments based on zirconium oxide nanoparticles by extracting the matrix polymer from the microfiber composite and developed fine-fiber filter materials from them [17]. There is also active research in the production of effective antiviral and antimicrobial polymer biomaterials and wear-resistant polymer/metal and polymer/ceramic materials [16–20].

Direct ink writing (DIW) or robocasting is another extrusion technique for making 3D printed parts from ceramics, metals, and other fine materials that is under intensive development. Robocasting (also robotic material extrusion) is an additive technique for layer-by-layer 3D printing of a part by extruding the ink (paste) through the 3D printer head. Equipment for DIW is in the affordable price category (starting at 3,000 US dollars). This technique became most popular among the designers because it allows original clay models to be printed directly from the computer (Fig. 10) [21–23].

Noteworthy is that robocasting is promising for 3D printing of workpieces from ceramic and metal materials [23]. Moreover, the acceptability of this technique for printing organic and inorganic bioimplants is being extensively studied [23–26].

Robocasting is also under active development in Ukraine. Figure 11 shows equipment for 3D printing of ceramic workpieces used at the Frantsevich Institute for Problems of Materials Science. A Zmorph 2.0 3D printer using ceramic pastes (Zmorph, Poland) (Fig. 11*a*) is equipped with a 100 ml extruder (Fig. 11*b*) designed as a catheter-type syringe. Special extruder nozzles (of different diameter) are used to control the extruded thread size [16, 27].

It should be noted, however, that the FDM printing technique mostly involves the production of ready-made parts suitable for use, while the DIW technique offers workpieces to be further heat treated to acquire necessary mechanical properties.


a *b*

Fig. 10. 3D printers for robocasting: *a*) 3D PotterBot 10 XL [21], *b*) StoneFlower 3.1 Multimaterial 3D printer [22]

Another way of developing additive manufacturing techniques is to print parts whose shape (structure) determines their properties. For example, scientists from the University of Singapore and the California Institute of Technology (USA) developed a new type of lightweight chainmail fabric, which is flexible like fabric in starting state but can stiffen on demand (Fig. 12) [27].

The material consists of nylon octahedrons that interlock with each other. When vacuum-packed, this fabric becomes much more rigid and can hold up much more than its own weight. The idea of such material is that it is allowed to be flexible in a plastic bag until increased stiffness is required, which is reached by air removal. The fabric undergoes a transition under which the particles transform from a fluid-like state to stiff shapes. In addition, hollow 3D printed structures are much lighter than dense materials. Besides nylon, the researchers also experimented with aluminum fabric, and it showed similar results. Of course, many issues may occur in practice with such material (for example, if a bag with this fabric loses its tightness, the material would not stiffen successfully). It is also rather difficult to remove the air from the bag quickly to produce something like light armor. Nevertheless, the material is promising for space applications.

Researchers from the Rice University's George R. Brown School of Engineering (USA) and their colleagues developed polymers based on tubulanes, theoretical structures of cross-linked carbon nanotubes predicted to have extraordinary strength [29]. 3D-printed polymer blocks were successfully tested to withstand a gunshot, a new step toward 3 printing of light armor (Fig. 13). The bullet stopped approximately in the second layer of the tubular structures, and no significant structural damage was found beyond this layer, while bullets fired at the same speed caused cracks throughout the reference cube. Tubulane-type polymer structures created at the Rice University were better able to handle the impact of a bullet than the reference polymer cube (Fig. 13).

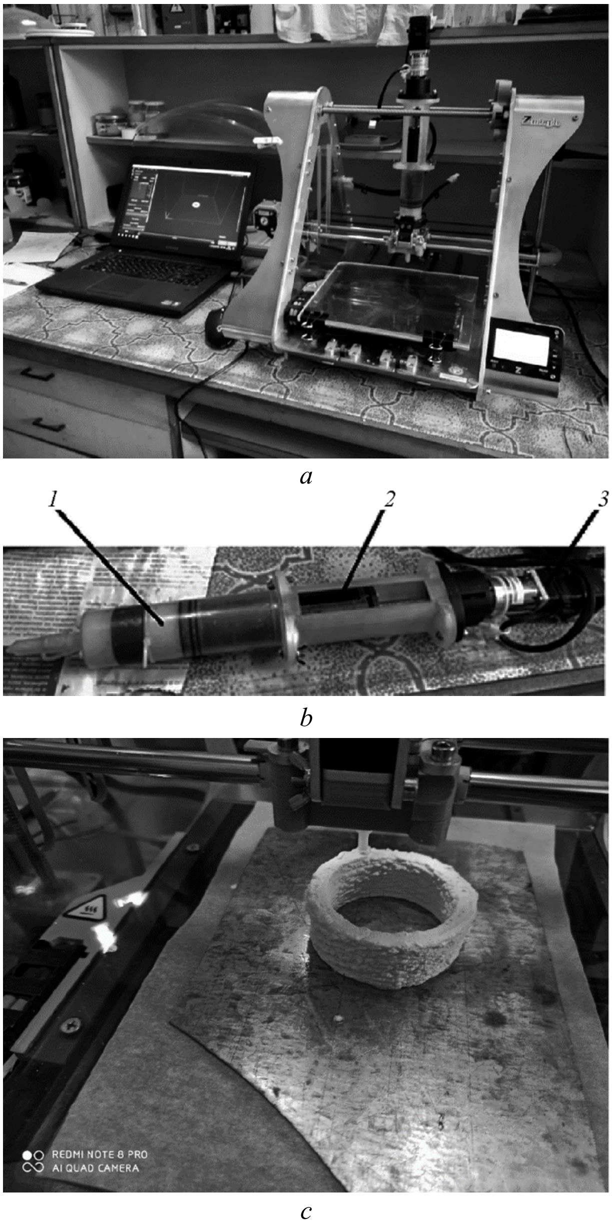


Fig. 11. Robocasting 3D printing: *a)* Zmorph 2.0 3D printer using ceramic pastes; *b)* extruder for printing with ceramic pastes (*1*—extruder filled with ceramic paste, *2*—piston, *3*—engine); *c*) aluminum nitride paste printing [27]

Fig. 12. 3D printed nylon fabric changing its mechanical properties [28]

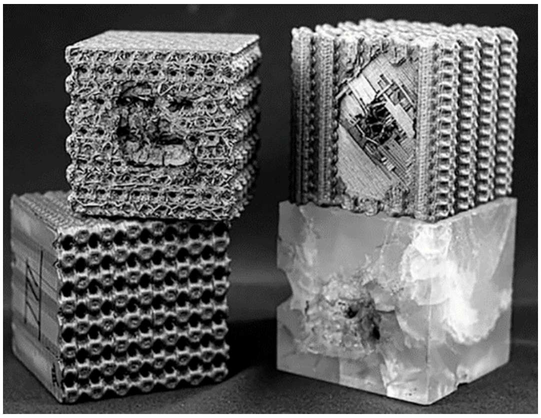


Fig. 13. Tubulane polymer structures developed at the Rice University and reference polymer cube (bottom right) [29]

3D printing provided a new level of accessibility for the development of lattice structures. 3D printing makes it much easier to create lattice structures and design the internal geometry of various structures because it includes not only hardware but also software for optimizing the topology of materials (Fig. 14).

The balance between the weight and shape adjustment can be crucial for modern sports equipment. In this context, 3D printing has a significant advantage over conventional production methods. 3D printing is very effective in creating optimized internal structures for better aerodynamics, weight balance, and increased strength. Lattice structures have already been actively used to produce sports equipment. For example, printed helmets with a lattice structure produced from carbon fibers can already be found on sale (Fig. 15) [30].

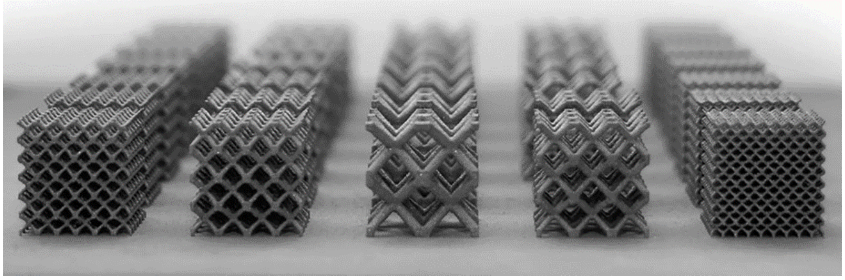


Fig. 14. Lattice test structures built on Renishaw AM250 metal AM system at the University of Nottingham (Great Britain), as part of the Aluminum Lightweight Structures via Additive Manufacturing (ALSAM) project [30]

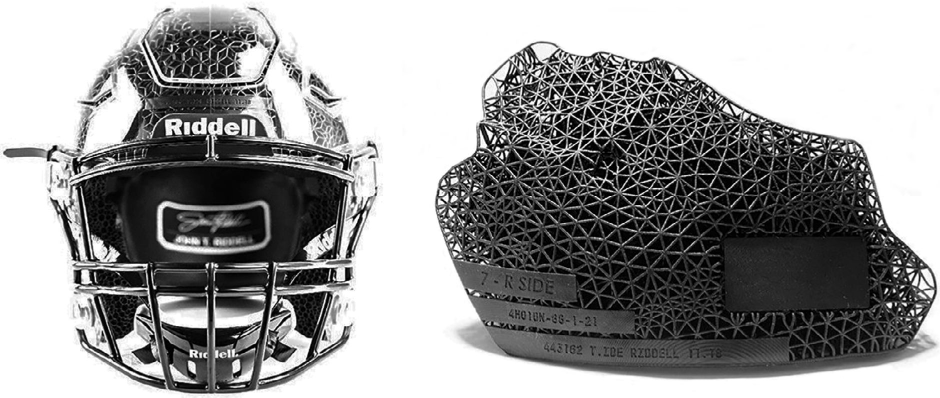


Fig. 15. 3D printed carbon-fiber reinforced helmet liner [30]

Fig. 16. Structural material based on 3D printed lattice structures [34]

In addition, companies dealing with construction perform experiments with 3D printing and lattice elements in architecture [31–33]. For example, Branch Technology invented a 3D-printed lattice made of ABS plastic reinforced with carbon fibers. Such a lattice can serve as the core for a modular wall system that combines common building materials such as foam insulation, sprayed concrete, and cladding [34]. According to the experiments, this material is light and long-living (Fig. 16).

PROSPECTS FOR DEVELOPING ADDITIVE MANUFACTURING TECHNIQUES AND MATERIALS IN UKRAINE (CONCLUSIONS)

The modern world is becoming more personalized, and additive manufacturing techniques naturally fit into the trends that determine the future path of human development. Noteworthy is that the Ford company, being the first to introduce a conveyor for the mass production of unified cars, was among the first to start 3D printing in the production of brackets for the Ford Mustang Shelby GT500 braking system with DLS [35]. The COVID-19 pandemic also somewhat altered the development of new technologies and the overall vision of human development. When the pandemic began in 2019–2020, we saw many examples of using 3D printers for the rapid production of components for medical equipment and medical staff. At the same time, architects proposed an individual approach to the design of an autonomous house employing additive manufacturing techniques with minimized contact with the environment and projects of closed autonomous apartment buildings equipped with 3D printers for printing the necessary parts without contact with other people [31, 32].

The implementation of additive manufacturing techniques in medicine requires special attention. The capabilities of an individual approach in 3D printing of parts can be fully favored. There are systems that allow the production of bone bioprostheses: from preliminary scanning of the patient's injury using X-ray 3D analysis to computer processing and printing of the necessary part [36, 37]. Moreover, there is research into 3D bioprinting of human organs, and a model of the human heart has already been printed. This all inspires the development of an area such as 3D bioengineering [38].

As the above information shows, both commercial projects for the implementation of 3D printing techniques and research efforts to study materials and identify promising areas for the use of parts produced with additive manufacturing are under intensive development in Ukraine. The overview of Internet resources and communication with experts in various fields indicate that there is quite strong interest in additive manufacturing techniques. There are a number of courses at higher and secondary educational institutions that focus on the fundamentals of additive manufacturing. Such courses will significantly contribute to further popularization of 3D printing, especially of FDM as an affordable technique. Most research institutions have departments that conduct research in the use and implementation of 3D printing materials and techniques. Moreover, the need for the development of the Ukrainian defense industry calls for the production of high-precision ceramic parts with appropriate physicochemical properties and for import phaseout of spare parts for military equipment. The introduction of additive manufacturing techniques allows the set objectives to be reached and national production to be brought to the world level. A series of economic surveys indicate that increase in the share of additive manufacturing techniques on the national market is a prerequisite for economic growth and will promote future technological leadership in the country, which will stimulate the development of this area at legislative and economic levels [39–41].

However, there is an unfortunate gap in the national 3D printing field, which is rather a small scope of information in English on the Internet and scientific papers in specialized journals; this does not permit the dissemination of information on national developments in this area.

In conclusion, it should be noted that new information on the development of additive manufacturing techniques in Ukraine was continuously emerging when this paper was being written. This demonstrates that we are keeping pace with the global trends in research and implementation of 3D printing techniques. The variety of additive manufacturing techniques allows all interested researchers to choose the most suitable 3D printing method and test their ideas by developing new materials and structures.

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