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COMPARATIVE ANALYSIS OF MODERN TECHNOLOGIES OF ADDITIVE PRODUCTION

Abstract. *In today's conditions, 3D printing is used to create unique models, prototypes, and equipment necessary for conducting experiments and studying various phenomena and processes, for the rapid prototyping of various parts and devices in scientific and engineering research. 3D printing technologies are actively used to create individual medical implants, prostheses, and organ models for training and planning operations, which significantly improves the quality of medical care. In the aerospace and automotive industries, additive manufacturing is used to create lightweight and durable parts helping to reduce weight and improve vehicle efficiency. The use of additive manufacturing methods, technologies, and tools allows you to check and test designs and concepts before mass production. In this work, a detailed analysis of various existing 3D printers is carried out depending on the tasks, and modern technologies of additive manufacturing are investigated depending on the set goals and scientific and applied tasks. Such technologies include Fused Deposition Modeling, Stereolithography, Selective Laser Sintering, Direct Metal Laser Sintering, and Digital Light Processing. In the work, a comparative analysis of these technologies was carried out according to various criteria, such as principle of operation, materials, resolution, surface finish, accuracy, speed, strength, application, cost, complexity of parts, and post-processing. For each technology, the advantages and disadvantages of its use are determined depending on the goals and objectives. It should be noted that some materials may not be suitable for printing complex parts or require additional support during the printing process. This can lead to complexity in the processing of products and increase the time and costs of printing. Improper selection of materials for 3D printing can be harmful to the environment or human health when used incorrectly. For example, some plastic materials may emit toxic elements or have low biodegradability. Also, using excess expensive material unnecessarily can increase the cost of the project.*

Keywords: additive manufacturing, 3D printing, additive manufacturing technologies, Fused Deposition Modeling, Stereolithography, Selective Laser Sintering, Direct Metal Laser Sintering, Digital Light Processing.

1. Introduction

3D printing is used in a variety of fields, from engineering to manufacturing, dentistry, healthcare, jewelry, and other industries. 3D printing technology has a variety of applications, from making visual and functional prototypes to manufacturing end-use parts. Each of the 3D printing technologies available on the market has its own advantages and limitations, so each of them is better suited for certain purposes than others. When choosing a 3D printer, it's important to consider the technology that best suits your needs and requirements [1–3].

Choosing 3D printing technology and material with the right functional properties is crucial to ensure that parts work correctly.

1) *The dimensions of the construction field and the accuracy of the reproduction of the part (tolerances).* The most common printers offer a print volume with a cube side of about 200 mm, while large format options reach a size of 300x300x600 mm. Professional desktop printers can be supplied in standard or large format models. Moreover, most of the standard sizes are a cube with a side size of 200 mm. Larger models may offer a print area 5 to 10 times larger.

The next thing to consider when it comes to functional properties is tolerances. Different technologies have different tolerances. They use high-precision lasers to shape each layer of material with reliable and reproducible results.

2) *Choice of 3D printing technology. Properties of materials.* First of all, you need to consider the types of plastic for a 3D printer. Plastic for 3D printing, or filament, is made in the form of a thin thread, with a diameter of 1.75 mm and 3 mm. Most often, threads with a thickness of 1.75 mm are used in the basic configuration, but some manufacturers of 3D printers provide the opportunity to install a three-millimeter plastic feeding system. Plastic for 3D printing has many varieties, among which the most common are ABS and PLA plastic. In addition, desktop 3D printers can be used to create metal parts by casting 3D printed templates out of plastic [2, 4, 5].

The wrong choice of materials in 3D printing can lead to various problems:

– If the chosen material is not strong enough for your needs, printing parts may lead to brittleness or deformation;

– If the material cannot withstand high or low temperatures, it can lead to a loss of shape or properties of the part during operation;

– Some materials may have different properties than those specified in the specifications, resulting in unexpected printing results.

– some materials may not adhere well to the substrate or have problems with adhesion, leading to defects on the print surface;

– Other problems may include dimensional changes during cooling, large deviations in geometry, or improper surface texture.

Given the challenges above, it is important to carefully examine the properties of each material and its suitability for a specific application before embarking on 3D printing.

2. Methods and materials

2.1. Classification of Modern 3D Printers

3D printing technology began to gain popularity in the 1980s, starting as a rapid prototyping method [1, 6, 7]. The main goal of this technology was to help manufacturers create models of their products quickly and economically. In 1983, Chuck Hull invented the first technique, called stereolithography, which used ultraviolet light to cure resin into precise shapes. In the years that followed, various approaches emerged, such as modeling deposited deposition, which melts plastic to form layers. Initially, such printers were large and expensive, which limited their use in industrial settings. However, over time, they have been improved, with more compact and affordable models appearing, making the technology accessible to hobbyists, schools, and small businesses, radically changing the way we create and think about manufacturing objects [5, 8].

3D printers are advanced devices that convert digital drawings into physical objects through additive manufacturing. This process involves applying materials layer by layer based on precise geometric data from CAD. There are different types of 3D printers. All 3D printers are distinguished by their ability to produce complex designs with high precision and minimal material waste. They have found applications in a variety of industries, enabling rapid prototyping, custom manufacturing, and the production of complex components.

Modern 3D printers allow you to quickly create various products with variable geometry without the need to create new molds or tools. They allow the creation of products with a high degree of complexity, including internal cavities and complex structures. These types of printers reduce the cost of producing tools and molds because the process is based on adding material rather than cutting from a block.

It is also worth mentioning the shortcomings that can appear during the printing process on modern 3D printers. Although the range of materials available has expanded, the choice is still limited compared to traditional production methods. Printing speeds with modern 3D printers are often slower than traditional manufacturing methods, especially when creating large parts. Also, products created using 3D printing may have less smooth surfaces, which requires additional processing to achieve the required quality. Some 3D printers may have limited accuracy and repeatability when creating parts, especially when working with large objects. An important factor is that investments in 3D printers and materials can be high, especially for more advanced models and specialized materials.

Depending on their size, 3D printers can be classified into different categories. Here is a general classification of 3D printers by size, as shown in Figure 1 below.

Desktop 3D printers:

- intended for use on a desk or table;
- compact, light and suitable for home use, small business and hobbyists;
- usually have dimensions from 100x100x100 mm to 300x300x300 mm (or similar dimensions).

Medium-sized 3D printers:

- larger than desktop printers but still suitable for most workplaces;
- offer greater build volume compared to desktop printers, making them suitable for prototyping, small-scale production, and educational purposes;
- dimensions can vary from 300x300x300 mm to 600x600x600 mm or more.

Industrial 3D printers:

- designed for high-volume production, rapid prototyping and production applications;
- have a significantly larger volume of assembly compared to desktop printers and medium-sized printers, which allows for the manufacture of larger parts and components;
- dimensions can vary widely, starting from approximately 600x600x600 mm and reaching the size of several meters.

Large-scale and serial 3D printers:

- have an extremely high production volume, capable of producing full-scale prototypes, architectural models, furniture and even entire building components.
- the volume of the assembly can vary from a few meters to tens of meters, depending on the specific application and industry;
- 3D printer size classification may vary by manufacturer and model. Some manufacturers may use different terminology or size ranges to classify their printers;
- in addition, advances in technology may lead to the development of printers with different sizes and capabilities that exceed traditional classifications.

Figure 1. General classification of 3D printers depending on the goals and applied design tasks

2.2. Modern Technologies of Additive Manufacturing

The choice of 3D printing technology depends on the goals you set for the project [8–10]. In order to rationally choose one or more 3D printing technologies, you need to take into account such factors as: printing accuracy; the strength of the parts that will be obtained after printing; print speed; Materials; size and scope, financial budget.

To date, there are only 5 additive manufacturing technologies. All of them are shown in Figure 2 below [8].

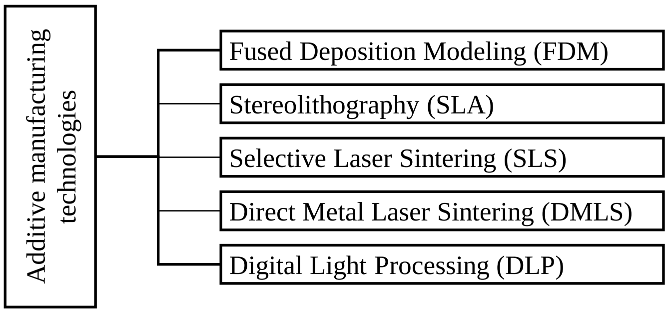


Figure 2. Classification of modern additive manufacturing technologies

A detailed description of each of the technologies in order to understand and choose the most optimal of them is given below. It should be noted that the choice of the optimal technology is key for mass production in general.

2.2.1. Fused Deposition Modeling

Fused Deposition Modeling (FDM) technology, also known as Fused Filament Fabrication (FFF), is a 3D printing method that is known for its speed, accuracy, and affordable cost. In FDM, molten plastic is precisely applied by a parts creation machine, allowing parts to be produced in as little as one day [9–11].

The FDM 3D printing service makes it possible to create large parts on platforms up to 60 cm, x92 cm, x92 cm. FDM also offers a wide variety of industrial-quality colors and thermoplastics, including ABS plastic, ASA, polycarbonate, and ULTEM, making this method the most diverse of all 3D printing processes. The FDM method is one of the most common 3D printing methods, which involves melting, extrusion, and applying thermoplastic filament to a printing platform to create objects step by step. Widely used for rapid prototyping, FDM can also be applied to create customized production aids and small parts. This method allows you to print large objects [11, 12]. FDM offers a large selection of industrial-quality thermoplastics and a variety of colors, making it the most diverse of all 3D printing technologies. The most commonly chosen FDM materials are engineering-grade such as PLA+, ABS, ASA, PETG, PC, and TPU, as well as premium materials with high strength and thermal stability for use in advanced automotive, aerospace, and medical industries such as PEEK and ULTEM®. For complex geometric shapes, when using FDM, support structures are required, which increases the consumption of materials, time and requires further processing. FDM technology is used for the manufacture of various products, some of them are shown in the figure 3.

(a) b) c)

Figure 3. Practical application of FDM in the modern world: a) production of individual products; b) production in the industry; c) production of functional parts

2.2.2. Stereolithography

Stereolithography belongs to a group of additive manufacturing technologies known as bath photopolymerization. All of these methods are based on the same principle where a light source – a laser or projector – is used to solidify the liquid resin into a solid plastic. The main difference between the two is the location of the main elements, such as the light source, the construction platform, and the resin tank.

SLA is one of the three main technologies in 3D printing, along with FDM and SLS. It belongs to the category of printing on resin. Another approach that is often compared to SLA is digital light processing (DLP), which is an evolution of the SLA process by using a projector screen instead of a laser.

Although SLA technology is not as common as FDM, it is actually the oldest of the additive manufacturing technologies. The SLA process itself was first developed in the early 1970s by Japanese researcher Dr. Hideo Kodama, who created a modern method of stereolithography using ultraviolet light to solidify photosensitive polymers. The term "SLA" was coined by Chuck Hull, the founder of 3D Systems, in 1986 when he patented the technology. According to his definition, SLA is the process of creating three-dimensional objects by sequentially superimposing layers of photosensitive material. However, SLA 3D printing technology was not the first to become widespread. When patents expired in the late 2000s, small-format desktop 3D printers expanded access to additive manufacturing, and FDM became popular on desktop platforms. Although FDM was available and attracted a lot of attention in the early days of 3D printing, high-precision results and biocompatible materials, which are essential for professional applications, were important factors in the development of SLAs. Small SLA 3D printers have brought high resolution and greater access to a variety of materials that were previously only available on industrial systems. This has significantly expanded the possibilities of using 3D printing in various industries, including engineering, design, dentistry, jewelry, and other industries.

The SLA allows you to produce customized products such as personalized gifts, promotional items, and specialized components tailored to individual requirements. It offers flexibility in design and customization options. Examples of the application of the technology are shown in Figure 4.

(a) b) c)

Figure 4. Practical application of SLA in the modern world: a) aerospace and automotive industries; b) jewelry and fashion; c) dental and medical models

2.2.3. Selective Laser Sintering

This method is also known as Selective *Laser Sintering (SLS*). It is one of the variants of 3D printing technology widely used in industry. SLS is available only on expensive professional 3D printers and is distinguished by the high quality of manufactured products. With its help, it is possible to achieve results close to the reproduction of products by injection molding.

Selective laser sintering, like many other additive manufacturing methods in industry, uses powders and powder mixtures as the material. This method allows you to create all-metal objects in just a few hours. The ability to manufacture products with complex shapes explains its popularity among industrial organizations in the world.

As with any other 3D printing technology, the main requirement is to have a ready-made 3D model that meets certain criteria. This model is the basis for creating a product. The process of technology is quite simple: a special compartment of the 3D printer is filled with material, then the printing process begins. Interestingly, before playing begins, the material is heated to its melting point.

When using a laser rig and a scanning mirror, the laser beam is directed at the desired areas of the powder, sintering them together, creating layer by layer. After the first layer is sintered, the surface leveling mechanism adds a thin layer of powder on top, and the process is repeated until the object is fully constructed. This means that the object is created from the bottom up, and due to the continuous filling of the chamber with powder, there is no need for supporting structures.

Overall, selective laser sintering (SLS) is valued for its ability to produce functional parts with high strength, precision, and complexity, making it a versatile technology suitable for a wide range of applications in various industries. Figure 5 shows the main applications of SLS 3D printing technology.

(a) b) c)

Figure 5. Practical application of SLS in the modern world: a) medicine; b) automotive prototyping; c) aerospace components

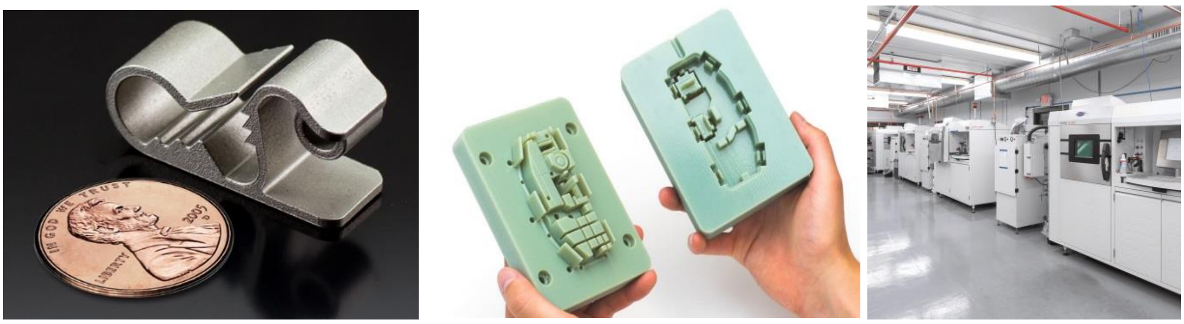
2.2.4. Direct Metal Laser Sintering

Direct Metal Laser Sintering (DMLS) technology is widely used in industry and is represented by a variety of professional equipment for 3D printing. It consists in creating products according to specified 3D models from a special metal powder using a laser. The technique of direct laser sintering of metals is in many ways similar to the technologies of selective laser sintering (SLS) and selective laser melting of metals (SLM).

However, these techniques have their own unique characteristics and advantages. Direct laser sintering of metals is used for additive manufacturing of metal products of almost any complexity. The high accuracy of the equipment for such 3D printing minimizes errors during reproduction. The features of this technique provide the products with high strength.

The basic principle of direct laser sintering of metals is similar to other 3D printing techniques. The basis for creating a physical object is its three-dimensional model in the appropriate format for a 3D printer. With the help of special software, the model is prepared for printing, all the necessary options for playback are installed. Then the prepared file is transferred to a 3D printer, where the process of direct laser sintering of metals begins.

At this stage, the key components are a metal powder chamber, a material, a special leveling roller and one or more lasers. First, a certain amount of material is loaded into the chamber, sufficient to create one layer. This powder is leveled with a special device, the excess is removed. Then the process of building the model begins: the powder is sintered with a laser in the form of the first layer. Then a new layer of material is added, leveling and the laser sinters the second layer of the 3D model. This procedure is repeated until a complete reproduction of the product has been created. DMLS is a versatile additive manufacturing technology used in a variety of industries (Figure 6) that require metal parts with complex geometries, high strength, and precision.



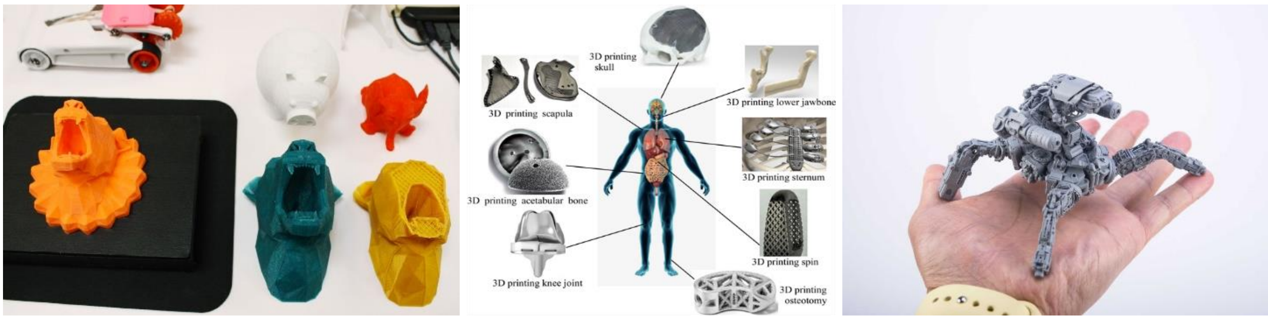
(a) b) c)

Figure 6. Practical application of DMLS in the modern world: a) metal parts and their structures; b) production of tools and molds; c) industry

2.2.5. Digital Light Processing

Resin has been used in the field of 3D printing for a long time. The first patent for this technology was granted in 1986 by Charles Hall, who developed stereolithography (SLA) technology. Over time, new technologies have emerged that have improved the 3D printing process. With the expiry of patents, new developers have appeared in the market. Currently, resin-based 3D printers are represented by various categories from hobbyists to industrial professional units. With the variety of devices, many resin technologies have emerged, such as LCD, mSLA, DLP, SLA, and others.

ISO standards apply to all areas of activity in various fields. This is especially important in industries where efficiency is ensured by the use of homogeneous expectations and terminology. In the context of 3D printing, there is some confusion about using the term "stereolithography" to describe the entire resin printing process. But stereolithography is only a primitive technology. In the ISO/ASTM 52900:2015 standard, users can find a clear definition of this technology. All resin 3D printing technologies refer to bath polymerization, because the photopolymer resin is in a special tank. For example, in inkjet printing, the process is carried out through a nozzle. On the Figure 7 shows the various applications of this 3D printing technology.



(a) b) c)

Figure 7. Practical application of DLP in the modern world: a) studying materials and conducting experiments; b) medicine; c) miniature objects

2.3. Analysis of Technologies, Materials and Methods of Additive Manufacturing

2.3.1. Technologies of Additive Manufacturing

FDM is one of the most widely used additive manufacturing technologies. It works by squeezing molten material (usually plastic filament) through a heated nozzle onto a printing platform, where the material solidifies and forms a layer. After that, the next layer is printed and the process is repeated until the final part is created. The main components of the FDM system include a molten material extruder, a movable printing platform, and printing process control software. FDM allows you to create medium to high precision parts and can be used for a wide range of applications from prototyping to the production of functional parts. The advantages of FDM include relatively low hardware and material costs, a wide variety of materials available (e.g., ABS, PLA, PETG), the ability to create large parts, and relatively fast print speeds for some applications. However, FDM also has disadvantages, such as limitations in accuracy and detail compared to some other technologies, visible layers on the surface of parts (requiring post-printing processing to obtain a smooth surface), and some material limitations compared to more modern methods such as DMLS (direct laser sintering of metals).

SLA, due to its ability to produce high-resolution parts and detailed parts, has several applications in various industries, for example, the technology is widely used for rapid prototyping in product development and design. This allows designers and engineers to quickly create accurate prototypes to test shape, fit, and function before mass production. Taking into account the principles of SLA, this technology is actively used in the production of dental models, surgical guides, prostheses and anatomical models for medical education and planning of surgical operations. The high precision of the technology makes it suitable for creating complex dental and medical devices. SLA is also used in the aerospace and automotive industries to prototype components, create tools and fixtures, and produce functional prototypes of parts with complex geometries. It helps to test and inspect designs before manufacturing.

SLS uses a high-power laser to selectively fuse powdered materials, typically plastics or metals, to create solid objects. This technology has several applications in various industries due to its ability to produce complex parts with high strength and precision. Applications include widely used to create functional prototypes of parts and components in product development and design. This allows designers to test and validate designs before mass production, especially for parts with complex geometries. The technology is also suitable for the production of end-use parts and components, especially in industries such as aerospace, automotive, and consumer goods. Parts manufactured with SLS can have high mechanical strength and withstand demanding application conditions. Another of the practical applications of SLS is to use it to make tools, fixtures, fixtures and molds for various manufacturing processes. The ability to create complex and durable tools makes SLS valuable in industries that require rapid tooling solutions.

DMLS uses a high-power laser to fuse metal powders layer by layer to create solid metal parts. This process is also known as direct laser metal melting (DMLM) or powder bed laser melting. DMLS can handle a variety of metal materials, including stainless steel, aluminum, titanium, cobalt-chromium, and nickel alloys. This makes the technology suitable for the manufacture of parts with specific mechanical, thermal or chemical properties. DMLS is capable of producing parts with complex geometries, internal cavities, and complex structures that would be difficult or impossible to achieve with traditional manufacturing methods. Data technology provides high dimensional accuracy and surface finishes, making it suitable for applications where tight tolerances and smooth surfaces are required. With this technology, parts are built layer by layer, allowing for design freedom and integration of features such as internal channels, lattice structures, and conformal cooling channels. DMLS is widely used in the aerospace industry to produce lightweight yet durable components such as turbine blades, brackets, structural parts, and engine components. The ability to create complex geometries and lightweight structures is critical in aerospace applications. DMLS technology is also used in medicine and dentistry for the manufacture of implants, prostheses, orthopedic devices and dental restorations. The biocompatibility of certain metals used in DMLS makes the technology suitable for medical implants.

DLP uses a digital light projector to cure the photopolymer resin layer by layer, creating solid objects. Printers that use this technology can produce high-resolution prints with fine detail and a smooth surface, making them suitable for applications that require complex designs. DLP printing is typically faster compared to other resin-based 3D printing technologies, such as SLA (stereolithography), making it effective for rapid prototyping and small-scale production. DLP printers provide high precision and dimensional accuracy, ensuring that the printed parts meet the intended design specifications. DLP technology supports a variety of photopolymer resins, including standard resins, engineer-grade resins, flexible resins, and dental-grade resins, ensuring the versatility of material properties. DLP technology is actively used in dental laboratories for the manufacture of dental models, crowns, bridges, orthodontic devices and surgical guides. This allows dental professionals to receive precise and customized dental solutions. DLP is also suitable for creating miniature models, figurines, architectural models and scale copies with intricate details. It is popular among hobbyists, fashion designers, and artists to create detailed miniatures.

Brief characteristics for each type of modern additive manufacturing can be presented in Table 1.

Table 1. Additive Manufacturing Technologies Analysis

Technology	FDM	SLA	SLS	DMLS	DLP
Principle of operation	Extrusion of thermoplastic filaments	Laser Curing of Liquid Resin	Laser Sintering of Powder Materials	Laser Melting of Metal Powders	Light Curing of Photopolymer Resins
Materials	Wide range of thermoplastics	Photopolymer resins	Various plastics, metals, ceramics	Metals (e.g. stainless steel, titanium)	Photopolymer resins
Resolution	Average	High	High	High	High
Surface Finishing	Satisfactory	Excellent	Excellent	Excellent	Excellent
Accuracy	Average	High	High	High	High
Speed	Medium to High	Medium to High	Average	Medium to High	Medium to High
Strength	Average	Average	High	High	Medium to High
Application	Prototyping, training, custom parts	Prototyping, Dentistry, Jewelry	Aerospace, Automotive, Medical	Aerospace, Automotive, Medical	Jewelry, dental, prototyping
Cost	Low to medium	Low to medium	High	High	Low to medium
Complexity of details	Limited complexity	High Complexity	High Complexity	High Complexity	High Complexity
Post-processing	Minimum	Average	Average	Medium to High	Average

Based on the above characteristics of each of the known technologies, the corresponding advantages and disadvantages can be recorded. They are listed in Table 2.

Table 2. Advantages and disadvantages of additive manufacturing technologies

Technology	Advantages	Disadvantages
FDM	Low cost of equipment and materials	Limited resolution and surface finish
	A wide range of thermoplastic materials are available	Limited precision for complex geometries
	Suitable for rapid prototyping and simple parts	Layer Lines and Visible Stepping
	Easy post-processing and support removal	Not ideal for highly detailed or complex designs
SLA	High Resolution and Excellent Surface Finish	Relatively higher cost of equipment and materials
	High Precision for Complex Designs	Limited build capacity for some machines
	Wide range of resin materials available	Resin processing and post-processing can be messy
	Suitable for dental, medical and jewelry work	The resin can be sensitive to environmental factors
SLS	High strength and durability of parts	Higher cost compared to FDM and SLA
	Ability to use a variety of materials, including plastics, metals, ceramics	Limited resolution compared to SLAs
	Complex geometry and internal structure possible	Powder handling and recycling can be challenging
	Suitable for functional prototypes and end-use parts	Post-processing may be required to remove excess powder
DMLS	High precision and accuracy of metal parts	High cost of equipment and materials
	Wide range of metal materials available	Limited build capacity for some machines
	Complex geometries and lightweight designs are possible	Some metals may require post-processing, such as heat treatment
	Suitable for aerospace, automotive, and medical applications	Limited to metals and high-temperature materials
DLP	High-resolution printing with fine details	Limited material capabilities compared to other technologies
	Excellent surface finish and smoothness	Resin processing and subsequent curing process required
	Printing speed compared to some other resin-based methods	Limited build capacity for some machines
	Suitable for jewelry, dental, and highly detailed prototypes	The resin can be sensitive to environmental factors

2.3.2. Analysis of Technologies, Materials and Methods of Additive Manufacturing

Based on an overview of the materials used in additive manufacturing using FDM, it is possible to identify the advantages and disadvantages of each of these materials. The main summary data of the comparison are shown in Table 3.

Table 3. Comparative Analysis of 3D Printing Materials Using Fused Deposition Modeling (FDM)

Material	Advantages	Disadvantages	Application
ABS Plastic	Durable and impact-resistant	May decrease in size when cooled	Prototyping, high-strength parts
PLA Plastic	Biologically	Stiffer and brittle than ABS	Prototyping, training, decorative products
Polyamide	High impact resistance and flexibility	Requires special printing conditions to prevent deformation	Mechanical Parts, Flexible Structures
Polycarbonate	Very durable and heat-resistant	Requires high printing temperatures	High Temperature Parts
Polyethylene	Good chemical resistance	Not very suitable for precision parts due to possible lubrication of the layers	Pipelines, chemically resistant parts
Thermoplastic Rubber Material	Flexibility and elasticity	Requires a specialized extruder and printing setup	Prototyping of flexible parts, shoes, seals
PVA	Dissolves in water and is used to support printing	Not suitable for creating parts, requires additional post-printing processing	Printing stand, water-soluble

Based on an overview of the materials used in additive manufacturing using SLS, the advantages and disadvantages of each of these materials can be similarly highlighted. The main summary data of the comparison are shown in Table 4.

Table 4. Comparative Analysis of the Main Materials Used in SLS Technology

Material	Advantages	Disadvantages	Application
Acrylate Resin	High precision and detail	Materials may be prone to shrinkage	Prototyping, decorations, highly detailed details
Epoxy Resin	Very high detail and smooth surface	Materials can be more fragile and less flexible	Medical Models, Jewelry, Electronic Components
Polyurethane Resin	Flexibility and elasticity	Materials may be more prone to wear and tear and deformation	Flexible Parts, Resilient Prototypes, Test Products
Dental Resin	Biocompatibility and safety when used in orthodontics and dentistry	High Cost and Requirements for Resin Processing and Curing Equipment	Dental implants, dentures, orthodontic appliances, models for surgical planning
High-strength resin	High strength and resistance to mechanical stress	Higher Price and Requirements for Resin Recycling Equipment	Mechanical Parts, Functional Prototypes, High Load Capacity Parts

Based on an overview of the materials used in additive manufacturing using SLA, the advantages and disadvantages of each of these materials can be similarly highlighted. The main summary data of the comparison are shown in Table 5.

Table 5. Comparative analysis of the main materials used in SLA technology

Material	Advantages	Disadvantages	Application
Polyamide	High strength and flexibility	Material shrinkage is possible	Functional Prototypes, Mechanical Parts
Polyurethane	Flexibility and elasticity	Materials may be less durable and wear-resistant	Flexible Parts, Resilient Prototypes, Test Products
Polyethylene	Good chemical resistance	Less suitable for precision parts due to possible layer lubrication	Pipelines, chemically resistant parts
Polypropylene	Low density and good chemical resistance	Less durable and resistant to mechanical stress	Packaging Materials, Lightweight Parts
Polyamide with filler	Improvement of mechanical properties due to the addition of filler	Can be more rigid and less flexible	Specialized Functional Parts, Prototypes
Metal powders (e.g. stainless steel, aluminum, titanium, etc.)	High strength and heat resistance	Requires specialized printing equipment and processes	Manufacture of metal parts, prototyping of metal products
Ceramic powders (e.g. alumina, silicon carbide, etc.)	Heat resistance and chemical inertness	Requires specialized printing equipment and processes	Production of ceramic parts, prototyping of ceramic products

Based on an overview of the materials used in additive manufacturing using DMLS, the advantages and disadvantages of each of these materials can be similarly highlighted. The main summary of the comparison is shown in Table 6.

Table 6. Comparative Analysis of the Main Materials Used in DMLS Technology

Material	Advantages	Disadvantages	Application
Stainless Steel	High strength and corrosion resistance	Limited geometry complexity	Production of functional metal parts, tools
Aluminium	Light weight and good thermal and electrical conductivity	Less durable compared to some other metals	Prototyping, production of light metal parts, components
Titanium	Very high strength at low weight	High cost of material and equipment	Production of medical implants, aerospace components
Cobalt-chromium	High strength and heat resistance	Limited choice of colors and finishes	Manufacture of medical prostheses, dental structures, instruments
Inconel	High temperature and corrosion resistance	Requires specialized printing equipment and processes	Production of parts for high-temperature and corrosive environments
Aluminum alloys	Variety of alloys with different properties	May have limitations in strength and durability	Production of various metal parts and components
Nickel alloys	High corrosion resistance and heat resistance	High cost and limited choice of finishes	Production of parts for the aerospace, energy and chemical industries

Based on an overview of the materials used in additive manufacturing using DLP, the advantages and disadvantages of each of these materials can be similarly highlighted. The main summary data of the comparison are shown in Table 7. As mentioned above, the wrong selection of materials can critically affect not only the quality of printing, but also the condition of the 3D printer.

Table 7. Comparative Analysis of the Main Materials Used in DLP Technology

Material	Advantages	Disadvantages	Application
Photopolymers	Highly detailed and smooth surface	Limited mechanical properties	Jewelry, Medical Models, Highly Detailed Parts
Elastomeric resins	Flexibility and elasticity	May be less durable and wear-resistant	Flexible parts, seals, shock-absorbing components
Ceramic Resins	Heat Resistance and Chemical Resistance	Limited mechanical properties, requiring specialized machining	Production of ceramic parts, heat-resistant products, insulation components
Metal-containing resins	Simulating the properties of metals	High cost, require specialized processing	Production of parts with metallic properties, decorations, decorative elements
Dental Resins	Biocompatibility and safety in dental prosthetics	High cost, require specialized processing	Manufacture of dentures, orthodontic appliances, dental models

3. Practical Results

Based on the analysis, it is possible to select a technology taking into account the project, which will be developed using modern printing technologies. The resulting analysis provides an assessment of print quality based on each of the five existing technologies, which forms a complete picture of the features of each of the technologies, the description of which is presented in this article.

4. Discussion

The obtained analysis of the comparison of modern 3D printing technologies will make it possible to continue the search for optimal materials for 3D printing of the project, form an understanding of the pricing policy, this is the cost of consumables, as well as build mathematical models for the selection of optimal printing materials in accordance with the requirements for the project, which are the relevant requirements for the project.

Although the number of materials available for 3D printing is constantly increasing, it is still limited compared to the materials available in traditional manufacturing. This can limit the ability to create products with certain properties, such as strength, flexibility or heat resistance. It should be noted that products that are made using 3D printing may have less smooth surfaces compared to products created by traditional methods. This may require additional processing or processing to achieve the desired quality. While 3D printing technologies are often used to create small batches or individual products, scaling the process for large series can present challenges in terms of time and resources.

5. Conclusions

In the course of the study of modern technologies of additive manufacturing, the spheres of their application were analyzed, the main advantages and disadvantages of each additive manufacturing technology were determined. It should be noted that before choosing a specific technology of additive manufacturing, it is necessary to determine the goals of this kind of production, its volumes, the total financial costs that are necessary for the formation of the full volume of products, the scope of application of production products. Also, an important factor in additive manufacturing is a clear selection of printing technology for a specific type of parts, since the mechanical characteristics of the 3D printing product depend on it. Each technology uses different printing materials, which determine the quality of the product and its durability. If the material does not meet the requirements of the final product (e.g., does not have the required temperature resistance, chemical resistance, or other characteristics), this may result in defects or unsuitability of the product for use. The use of unsuitable material may result in poor print quality and degradation of the product's strength characteristics. An incorrectly selected material may not provide the necessary strength or rigidity, which can lead to deformations or breakage of the product.

Additive manufacturing technologies provide the flexibility to customize processes and make changes to product designs without the need to create new molds or tooling. This allows production processes to be adapted to different customer needs or changing market conditions. The use of such technologies makes it possible to effectively create products with complex geometric shapes, which often turns out to be difficult or impossible when using traditional production methods. This opens up new opportunities for designers and engineers to develop innovative products. Unlike traditional methods, where creating molds and tools requires significant time and money, in additive manufacturing these costs are significantly reduced because production is based on the principle of adding material rather than cutting material from a block.

References

1. Beltagui, A., Kunz, N., & Gold, S. (2020). The role of 3D printing and open design on adoption of socially sustainable supply chain innovation. *International Journal of Production Economics*, 221, 107. https://doi.org/10.1016/j.ijpe.2019.07.035
2. Lu, J., & Zhuo, L. (2023). Additive manufacturing of titanium alloys via selective laser melting: fabrication, microstructure, post-processing, performance and prospect. *International Journal of Refractory Metals and Hard Materials*, 111, 106110. https://doi.org/10.1016/j.ijrmhm.2023.106110
3. Colorado, H. A., Velasquez, E. I. G., & Monteiro, S. N. (2020). Sustainability of additive manufacturing: the circular economy of materials and environmental perspectives. *Journal of Materials Research and Technology*, *9*(4), 8221–8234. https://doi.org/10.1016/j.jmrt.2020.04.062
4. Wegner, M. (2022). New trends in aviation and medical technology enabled by additive manufacturing. *Frontiers in Manufacturing Technology*, 2, 1–14. https://doi.org/10.3389/fmtec.2022.919738
5. Dejene, N. D., & Lemu, H. G. (2023). Current status and challenges of powder bed fusion-based metal additive manufacturing: literature review. *Metals (Basel)*, *13*(2). https://doi.org/10.3390/met13020424
6. Galati, M., Calignano, F., & Minosi, F. (2022). Numerical and experimental investigations of a novel 3D bucklicrystal auxetic structure produced by metal additive manufacturing. *Thin-Walled Structures*, 180, 109850. https://doi.org/10.1016/j.tws.2022.109850
7. Chua, K., Khan, I., Malhotra, R., & Zhu, D. (2021). Additive manufacturing and 3D printing of metallic biomaterials. *Engineered Regeneration*, 2, 288–99. https://doi.org/10.1016/j.engreg.2021.11.002
8. Maroti, P. (2019). Printing orientation defines anisotropic mechanical properties in additive manufacturing of upper limb prosthetics. *Materials Research Express*, *6*(3). https://doi.org/10.1088/2053-1591/aaf5a9
9. Morais, M. M., de Camargo, I. L., Colombo, P., & Fortulan, C. A. (2023). Additive manufacturing of calcium carbonate parts through vat-photopolymerization and sintering in carbon dioxide atmosphere. *Open Ceramics*, 100348. https://doi.org/10.1016/j.oceram.2023.100348
10. Rejeski, D., Zhao, F., & Huang, Y. (2018). Research needs and recommendations on environmental implications of additive manufacturing. *Additive Manufacturing*, 21–28. https://doi.org/10.1016/j.addma.2017.10.019
11. Bakhshi, R., Mohammadi-Zerankeshi, M., Mehrabi-Dehdezi, M., Alizadeh, R., Labbaf, S., & Abachi, P. (2023). Additive manufacturing of PLA-Mg composite scaffolds for hard tissue engineering applications. *Journal of the Mechanical Behavior of Biomedical Materials*, 138, 105655. https://doi.org/10.1016/j.jmbbm.2023.105655
12. Adeniran, O., Cong, W., & Aremu, A. (2022). Material design factors in the additive manufacturing of carbon fiber reinforced plastic composites: a state-of-the-art review. *Advances in Industrial and Manufacturing Engineering*, 5, 100100. https://doi.org/10.1016/j.aime.2022.100100

ПОРІВНЯЛЬНИЙ АНАЛІЗ СУЧАСНИХ ТЕХНОЛОГІЙ АДИТИВНОГО ВИРОБНИЦТВА

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Анотація. *В умовах сьогодення 3D-друк використовується для створення унікальних моделей, прототипів та обладнання, необхідних для проведення експериментів та вивчення різноманітних явищ та процесів, для швидкого створення прототипів різних деталей та пристроїв у наукових та інженерних дослідженнях. Технології 3D-друку активно застосовуються для створення індивідуальних медичних імплантатів, протезів, моделей органів для навчання та планування операцій, що значно покращує якість медичного обслуговування. В авіаційній та автомобільній промисловості адитивне виробництво використовується для створення легких та міцних деталей, що сприяє зниженню ваги та покращенню ефективності транспортних засобів. Використання методів, технологій та засобів адитивного виробництва дозволяє перевіряти та тестувати* *дизайн та концепції перед масовим виробництвом. У даній роботі проведений детальний аналіз різних існуючих 3D-принтерів залежно від завдань, досліджено сучасні технології адитивного виробництва залежно від поставлених цілей і науково-прикладних завдань. До таких технологій відносять: Fused Deposition Modeling, Stereolithography, Selective Laser Sintering, Direct Metal Laser Sintering, Digital Light Processing. У роботі проведено порівняльний аналіз даних технологій за різними критеріями, такими як: принцип роботи, матеріали, роздільна здатність, фінішна обробка поверхні, точність, швидкість, міцність, застосування, вартість, складність деталей, постобробка. Для кожної технології визначено переваги і недоліки її використання залежно від поставлених цілей і завдань. Слід зазначити, що деякі матеріали можуть погано підходити для друку складних деталей або вимагати додаткової підтримки під час процесу друку. Це може призвести до складності в обробці виробів і збільшити час і витрати на друк. Неправильний підбір матеріалів для 3D-друку може бути шкідливим для навколишнього середовища або здоров'я людини при неправильному використанні. Наприклад, деякі пластикові матеріали можуть виділяти токсичні елементи або мати низьку біорозкладність. Також використання надлишкового дорогого матеріалу без необхідності може збільшити вартість проєкту.*

Ключові слова: адитивне виробництво, 3D-друк, технології адитивного виробництва, моделювання наплавлення, стереолітографія, вибіркове лазерне спікання, пряме лазерне спікання металу, цифрова обробка світла.

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