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ADDITIVE TECHNOLOGIES: RESEARCH, APPLICATION IN THE DESIGN AND MANUFACTURING OF AVIATION INDUSTRY STRUCTURAL ELEMENTS

The article **focuses on** the application of additive technologies in the design and manufacturing of aviation structural elements under modern requirements for strength, weight reduction, reliability, and economic efficiency. The **goal** of the study is to develop and substantiate an integrated analytical approach to optimizing additive manufacturing processes in aircraft production. The tasks addressed include: analyzing of current additive technologies in aerospace engineering; developing mathematical models of thermomechanical processes and porosity formation; optimizing of printing parameters and material composition; and conducting a comparative evaluation of traditional and additive manufacturing methods. The **methods** employed comprise the finite element method, thermomechanical and porosity modeling, multi-criteria optimization, and experimental investigation of the mechanical properties of metallic and polymer materials. The following **results** were obtained: mathematical models for predicting thermal deformation, structural heterogeneity, and strength characteristics were developed; the influence of process parameters on microstructure formation and defect minimization was determined; it was established that the optimization of printing parameters reduces material consumption by up to 30%, decreases product weight by 10–25%, reduces production time by a factor of 2–3, and lowers costs by up to 40%. A tensile strength of up to 1260 MPa was achieved for SLM-manufactured titanium components. In addition, the proposed integrated modeling approach enabled quantitative prediction of porosity levels and residual stress distribution, improving dimensional accuracy and structural reliability of critical aviation components. Comparative analysis confirmed that additive technologies demonstrate the highest efficiency in manufacturing geometrically complex and weight-critical parts, where traditional methods are limited in design flexibility and material utilization efficiency. **Conclusions.** The scientific novelty lies in the development of an integrated modeling and optimization framework for the additive manufacturing of aviation components, ensuring improved structural integrity, reduced defect levels, enhanced production efficiency, and increased competitiveness in aviation manufacturing.

Keywords: finite element method; porosity analysis; optimization methods; printing parameters; experimental methods; mechanical strength; structural integrity; part quality.

1. Introduction

Today, aviation is one of the most technologically complex and knowledge-intensive industries, requiring constant improvement of production processes, materials, and structures [1, 2]. As noted in [3], the modern development of the aviation industry directly depends on improving production technologies that allow creating lighter, stronger, and more economically profitable structures. One of the key areas of modern aviation engineering is the use of Additive Technologies (AT), which opens new opportunities for designing and manufacturing aircraft elements. By [4], AT in modern aviation engineering provides flexibility, cost-effectiveness, and efficiency in creating aviation components. In turn, the need to introduce AT into the production of aviation structures is also dictated by the growing requirements for the reliability, strength, and adaptability of aircraft and unmanned aerial vehicle elements [5]. According to

[6, 7], additive manufacturing allows you to create unique designs that traditional methods cannot implement, which are especially important for the aerospace industry. The relevance of the study of the issues raised in the article was due to the urgent need in the aircraft industry to find production and design ways to reduce the mass of aircraft structures, optimize their strength, increase fuel efficiency, and reduce production costs. From the technical side, the relevance of the study of additive manufacturing in designing and producing aircraft structures is due to the rapid development of new production methods that allow for significant increases in efficiency, reductions in costs, and optimization of the manufacturing process of complex parts. According to [8, 9], traditional material processing methods have significant limitations in creating complex geometric shapes and lead to considerable waste of materials. In contrast, additive manufacturing, based on layer-by-layer material deposition, allows you to minimize production waste, reduce



the number of assembly units, and improve the aerodynamic characteristics of parts.

1.1. Motivation

The studies presented in this article belong to the field of engineering sciences and aerospace manufacturing, particularly to the area of additive technologies (AT) applied to the design and production of structural elements of the aviation industry.

The relevance of the topic is обусловлена (justified by) the rapid development of additive manufacturing technologies and their increasing adoption in leading aerospace companies for producing critical components of aircraft structures and engines. The integration of AT makes it possible to create complex-shaped parts, reduce structural weight, shorten production cycles, and improve material utilization efficiency. At the same time, a number of technological, material, and organizational challenges remain unresolved, especially those related to mechanical properties, surface quality, repeatability of results, and post-processing requirements.

In general, the problem addressed in this paper is the need for a comprehensive analysis and optimization of additive technologies in the context of aviation manufacturing, taking into account both technological capabilities and practical limitations. From a scientific and practical point of view, this problem is directly related to the tasks of increasing the reliability, efficiency, and economic feasibility of producing aircraft structural elements. This section provides an analysis of recent research and publications devoted to the application of additive technologies in aerospace engineering, with particular attention paid to the previously unresolved aspects of the problem, such as optimization of printing parameters, improvement of material properties, and integration of additive and traditional manufacturing processes. The purpose and objectives of the study are interrelated and correspond to the topic stated in the title of the paper. The research objectives are formulated and listed below.

1.2. State of the art

According to [10], the current state of research in the field of the application of additive technologies in the design and production of structural elements of the aviation industry indicates the active development of 3D printing technologies using metal powders, composite materials, and polymers. The authors emphasize that leading aircraft manufacturing companies, such as Boeing, Airbus, General Electric, and Rolls-Royce, already use AT to manufacture elements of aircraft engines and wings. At the same time, one of the promising directions is the development of methods for optimizing printing processes and combining additive technologies with

traditional manufacturing methods, which allows achieving high accuracy and mechanical strength of products [11]. In [12], it is noted that the aviation industry is currently undergoing significant changes due to the integration of 3D printing and other additive methods, which contribute to the creation of lighter, stronger, and functionally optimized structural elements. In [13], special attention is paid to the use of additive technologies for manufacturing aircraft structural components. The authors investigate various additive manufacturing methods, including topological optimization, which makes it possible to create highly loaded structures with minimal weight. They also propose approaches to assessing the economic feasibility of implementing additive technologies and analyze their impact on overall production efficiency. The results show a significant reduction in development and manufacturing time, although the need for further research aimed at improving materials and processes is emphasized. The work [14] analyzes the current state of additive manufacturing in aviation and rocketry, focusing on its implementation in leading companies worldwide. The authors demonstrate that 3D printing is effective for producing parts operating under high temperatures and mechanical loads. Their results confirm that additive methods enable the creation of complex structures with reduced mass, which contributes to improved fuel efficiency. However, it is also noted that some technologies still require refinement to increase material strength and part durability. In [15], the main attention is paid to the use of additive technologies in the production of robotic components and parts related to the aviation industry. The authors classify parts according to the materials used and printing technologies, and also consider the prospects of 4D printing, which involves the creation of elements capable of transformation over time. The results indicate significant potential for manufacturing parts with complex geometries, while emphasizing the need for additional machining and quality control to meet aerospace standards. The work [16] focuses on the fundamental aspects of additive manufacturing, various 3D printing technologies, and their applicability in the aviation industry. The authors analyze key quality parameters, such as mechanical properties, manufacturing accuracy, and structural integrity. A hybrid approach combining additive methods with traditional machining is proposed, which allows achieving higher accuracy and increased durability, but requires significant costs for post-processing and quality control. In [17], the application of selective laser melting (SLM) and electron beam melting (EBM) in the production of aviation parts is considered. The authors emphasize that these methods ensure high material density and excellent mechanical characteristics, making them promising for aerospace applications. They propose the use of special alloys optimized for additive manufacturing to improve thermal and

mechanical stability. At the same time, certain limitations related to surface quality and the need for additional processing are noted. A separate group of studies [18, 19] is devoted to analyzing the influence of printing parameters on the microstructure and mechanical properties of parts produced by laser sintering of metal powders. The authors show that controlled regulation of the melting process allows minimizing the formation of microcracks and defects, which is especially important for aviation components. However, the need for careful selection of parameters for each material complicates large-scale implementation.

In [20], the authors focus on the use of additive technologies for producing composite aviation materials that combine low weight and high strength. They investigate the prospects of using carbon and ceramic fillers in combination with polymer or metal matrices and propose a multilayer printing method with material combination, which improves mechanical properties. Although such materials show high potential for aerospace applications, further improvement of technological processes is required for their widespread use.

Thus, the analysis of foreign research confirms that additive technologies open wide opportunities for the aviation industry, enabling the creation of complex geometries, reduction of aircraft weight, and improvement of performance characteristics. At the same time, the need for further research aimed at improving materials, printing quality, and post-processing methods is clearly emphasized.

1.3. Objectives and tasks

Purpose of the study

The purpose of this study is to analyze and optimize the use of additive technologies in the design and production of structural elements in aviation, as well as to identify the advantages and challenges of implementing 3D printing in aircraft construction.

Research objectives

To achieve the stated purpose, the following research objectives are defined:

1. To conduct a review of modern scientific approaches and principles related to the optimization of 3D printing parameters in the design and production of structural elements of the aviation industry.
2. To assess the advantages and challenges of implementing 3D printing in aircraft construction in terms of quality, cost-effectiveness, and reliability of parts.
3. To perform a comparative analysis of traditional and additive manufacturing methods in order to identify the most effective production approaches for aviation structural components.

Structure of the article

The article is structured as follows. Section 2 presents the materials, methods, and modeling approaches used in the study. Section 3 discusses the obtained results and their analysis. Section 4 concludes the article by summarizing the main findings and outlining prospects for further research.

1.4. The goal and tasks

The goal of this article is to scientifically substantiate and develop a comprehensive approach to improving the efficiency of applying additive technologies in the design and manufacturing of aviation structural elements, taking into account requirements for mechanical strength, weight reduction, technological reliability, and economic feasibility.

Research Objectives. To achieve the stated purpose, the following objectives are defined:

- to analyze the current state and development trends of additive technologies in aviation manufacturing;
- to formalize the key physicomachanical processes occurring during layer-by-layer material synthesis, including heat transfer, thermal deformation, porosity formation, and structural heterogeneity;
- to develop and adapt mathematical models for predicting part quality, mechanical performance, and defect formation;
- to substantiate multi-criteria optimization approaches for selecting 3D printing parameters and material composition;
- to conduct a comparative assessment of traditional and additive manufacturing methods in terms of technical performance and economic efficiency.

2. Materials and methods of research

The study used systematic analysis methods, critical review, and synthesis of scientific sources devoted to using additive technologies to design and produce aviation structural elements.

The selection of scientific works was from authoritative international databases, such as Scopus, Web of Science, IEEE Xplore, and ScienceDirect, focusing on publications of the last 10 years.

The main criteria for selecting sources were relevance to the topic (3D printing in the aviation industry), practical or experimental results, citation, and scientific novelty.

During the analysis, thematic classification of works was carried out in the following areas: optimization of printing parameters, mechanical characteristics of materials, economic feasibility, comparison of traditional and additive technologies, and prospects for the development

of the industry. Based on the generalization of data, an analytical synthesis was performed to identify leading trends, challenges, and potential areas for improving additive technologies in the aviation industry.

3. Results and Discussion

3.1. Results

The use of AT to manufacture metal components can lead to uneven heating of the material during the printing process. This causes thermal deformations that affect the product's geometry and can degrade mechanical properties, especially strength and accuracy. According to [3], the heat transfer equation can be used to predict thermal deformations:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{Q}{\rho \alpha}, \quad (1)$$

where:

T is temperature,

t is time,

α is thermal conductivity coefficient,

$\nabla^2 T$ is Laplacian of temperature (spatial change in temperature),

Q is the amount of heat used for production,

ρ is density of the material,

α is heat capacity.

The solution to this problem allows you to model the temperature distribution throughout the object and identify areas with elevated temperatures where deformations can occur. Then, using the deformation model [4], you can take these temperature changes into account to adjust the printing process parameters:

$$\varepsilon = \alpha \Delta T, \quad (2)$$

where:

ε is thermal expansion,

α is coefficient of thermal expansion,

ΔT is temperature change.

A solution to the problem raised by [2, 4] may include:

- the use of controlled cooling conditions ensures uniform temperature distribution;

- simulation and optimization of the cooling process to prevent a significant amount of thermal deformation.

At the methodological level, when considering the problem of material structure heterogeneity (structural defects), it should be noted that, according to [3], during the additive manufacturing process, the material may

possess a non-uniform microstructure, which leads to defects (e.g., porosity or insufficient particle bonding). These defects can reduce mechanical properties, particularly tensile strength and fatigue resistance. One of the mathematical modeling approaches for this issue, according to [7, 9], is the use of finite element methods to assess stresses and defects in the material. In this case, the solution of the equations for material displacements under conditions of structural heterogeneity can be expressed through:

$$Ku = f, \quad (3)$$

where:

K is stiffness matrix,

u is displacement (deformation) vector,

f is force vector.

According to [10], the consideration of structural inhomogeneities can be modeled through discretizing the material at the micro level, where each particle or zone will have its properties (porosity, hardness, etc.). This approach allows a more accurate prediction of the material's behavior under loads. In practice, the methodological solution to this problem is:

- using more “precise” materials for 3D printing, such as composite materials or alloys with better microstructural uniformity;

- increased control over process parameters to minimize defects (temperature, printing speed, powder type, etc.).

In the works [10, 11], the problem of increased material porosity is partially raised: one of the common problems is the formation of porosity in final products, especially when using metal powders.

Pores can result from incorrect printing parameters or low-quality materials [12]. To analyze porosity in materials, the theory of porous media can be used, modeling the processes of sintering and crystallization, which include changes in volume and pore shape. One of the mathematical models that describes porosity in materials, according to [13], may look like this:

$$V_{\text{pores}} = V_{\text{initial}} - V_{\text{final}}, \quad (4)$$

where:

V_{pores} is pore volume,

V_{initial} is initial volume,

V_{final} is final volume after the sintering process.

According to [3], porosity prediction can also be performed by modeling in the case of fluid flow through a porous material using Darcy's equation:

$$\vec{q} = -\frac{k}{\mu} \nabla P, \quad (5)$$

where:

\bar{v} is flow rate,

k is permeability of porous media,

μ is liquid viscosity and pressure gradient. In practice, the methodological aspects of solving this problem are reduced to the following areas:

- improving the quality of powder materials [6];
- optimizing the printing process parameters to minimize porosity (temperature, printing speed) [7];
- using methods that control the structure of the powder and its uniform distribution [9, 10].

In the works [11, 13], the problem of surface defects and manufacturing accuracy is partially addressed: Surface defects, such as irregularities or defects, can occur during the printing process due to process instability or incorrect parameter settings. This is especially critical for aviation components, where accuracy is crucial [22].

For modeling and optimizing the printing process, equations for estimating displacements and temperature differences [12], as well as loss and wear functions in the processing process [10, 14], are often used:

$$F_{\text{surface}} = \frac{\sum_{i=1}^n (T_{\text{actual}} - T_{\text{target}})^2}{n}, \quad (6)$$

where:

T_{actual} is actual temperature at the point,

T_{target} is target temperature,

n is number of measurement points.

According to [23], the solution to this problem is:

- using methods of constant control of temperature and printing speed;
- more precise technologies, such as laser polishing or mechanical finishing after printing, are used to achieve high surface quality.

Optimization problems associated with using AT in the design and production of structural elements of the aviation industry include several complex tasks that require an integrated approach to improving the quality, accuracy, and efficiency of processes. One of the main problems is the selection of optimal process parameters, such as printing speed, temperature, layer thickness, material flow, etc. Incorrect choice of these parameters can lead to product defects, such as porosity, thermal deformations, or insufficient strength. Optimization of process parameters can be carried out using mathematical models that include multi-criteria optimization methods. The main task is to minimize several loss functions. Losses on surface defects:

$$L_{\text{surface}} = \sum_{i=1}^n (T_{\text{actual}} - T_{\text{target}})^2, \quad (7)$$

where:

T_{actual} is the actual temperature at the point, and

T_{target} is the target temperature.

Porosity losses:

$$L_{\text{porosity}} = \sum_{i=1}^n (P_{\text{actual}} - P_{\text{target}})^2 \quad (8)$$

where:

P_{actual} is actual porosity level,

P_{target} is desired porosity level.

The optimization process can be formulated as a problem of minimizing a loss function with resource and time constraints $\min_{\{x_1, x_2, \dots, x_k\}} f(x_1, x_2, \dots, x_k)$ provided that:

$$g_i(x_1, x_2, \dots, x_k) \leq 0 \forall_i, \quad (9)$$

where:

$f(x)$ is loss function (e.g., total defects),

$g_i(x)$ is resource or parameter restrictions [22].

The selection of optimal materials for 3D printing is a principal factor in achieving high strength and accuracy of the final product. The materials must have properties that meet the requirements of the aviation industry, such as high temperature resistance, strength, and corrosion resistance.

Optimizing the material composition can be described as finding the best ratio of material components to achieve maximum properties. This can be done using multi-criteria optimization methods, evaluating material characteristics such as strength, ductility, and heat resistance.

Mathematically, the above can be expressed in terms of the cost or quality function of the material:

$$f_{\text{material}}(a_1, a_2, \dots, a_n) = \sum_{i=1}^n \omega_i \cdot \alpha_i, \quad (10)$$

where:

α_i is characteristic of the i^{th} component of the material (e.g., strength, ductility),

ω_i is a weighting factor that determines the importance of each characteristic. The selection of optimal material parameters is a maximization problem:

$$\max_{\{x_1, x_2, \dots, x_k\}} f_{\text{material}}(\alpha_1, \alpha_2, \dots, \alpha_k). \quad (11)$$

Also, aviation components have complex geometry, and additive technologies allow manufacturing parts with an optimized shape to ensure minimal weight and maximum mechanical properties. However, complex optimization modeling is required for each specific part to achieve the ideal shape. The problem of optimizing the geometry of the structure can be posed as minimizing a loss function that considers loads and mechanical properties:

$$\min_{\{x\}} \left[\int_V \sigma(x)^2 dV \right], \quad (12)$$

where:

- $\sigma(x)$ is stress at a point,
- V is volume of the structure,
- x is geometry parameter set constructions.

Mathematical modeling uses finite element methods to analyze stresses and deformations of structures.

After printing, the structural elements require additional processing to achieve the required accuracy and surface finish. Post-processing can include grinding, polishing, heat treatment, etc. Post-processing optimization aims to minimize the time and resource costs while achieving a given accuracy. Mathematically, this can be expressed as the processing time minimization problem with accuracy constraints:

$$\min_{\{t\}} \sum_{i=1}^n t_i, \quad (13)$$

where:

- t_i is time required to process the i^{th} stage.
- Accuracy limitations:

$$|P_{\text{actual}} - P_{\text{target}}| \leq \epsilon. \quad (14)$$

Next, we will consider a model for integrating virtual modeling with additive technologies, which involves using simulation and mathematical models to optimize the geometry of components before their actual manufacture. This reduces design time and ensures production processes' safety and high efficiency. The model considers all production stages, from design development and material selection to testing and post-processing.

Mathematical modeling of component geometry:

$$V(x) = \sum_{i=1}^n \omega_i \cdot f_i(x), \quad (15)$$

where:

- $V(x)$ is the geometry of the component in space,
- ω_i is the weight of each element,
- $f_i(x)$ is a function describing the geometric characteristics of the i^{th} component.

Next, we will consider a model for automated material selection using artificial intelligence methods for aviation components. This model involves using artificial intelligence to select optimal materials that meet the requirements of the aviation industry. Thanks to machine learning algorithms, it is possible to predict which material will be best for a particular component in terms of its mechanical properties, thermal resistance, costs, variability of printing processes, etc. Modeling material characteristics:

$$M(x_1, x_2, \dots, x_n) = \sum_{i=1}^n \omega_i \cdot P_i(x_i), \quad (16)$$

where:

- $M(x_1, x_2, \dots, x_n)$ is material characteristics,
- $p_i(x_i)$ is function for each material property (strength, ductility, heat resistance),
- ω_i is weighting factor for each characteristic.

Consider a multi-criteria optimization model focused on solving problems where it is necessary to ensure maximum efficiency according to several criteria, such as weight reduction, strength increase, and durability [22].

This approach can be applied to the design of aircraft components, where each criterion has a weight, and as a result, it is necessary to find a compromise between them. The problem can be formulated as minimizing (or maximizing) several functions simultaneously.

Analyzing the adaptive post-processing control model, which is the automation of the processing process of 3D printed components to achieve a given accuracy and surface quality. This approach involves using embedded sensors and algorithms that can adjust processing parameters in real time based on data about defects that appear in the process. Analyzing the model of advanced simulation of thermal and mechanical properties of additively manufactured structures [11], it is worth noting that this model allows simulating the thermal and mechanical properties of components manufactured using additive technologies.

This is important for assessing materials' behavior during operation, particularly for aircraft structures subjected to significant loads and changes [12].

As we can see, the models considered open new opportunities for increasing production efficiency, accuracy, and reliability in the aviation industry, using additive technologies to create innovative components. Mathematical analysis of problems in additive technologies allows accurate modeling of the processes occurring in materials and the development of optimization methods to achieve high quality of the final product.

Mathematical models allow for predicting possible defects and reducing their impact on the final product, which is especially important in the aviation industry. Next, we will consider models that consider the main process parameters, such as accuracy, printing speed, minimum part size, layer thickness, and material strength [22, 23].

1. Selective Laser Melting (SLM) A productivity model based on laser energy and powder melting parameters:

$$E_{\text{SLM}} = \frac{P}{\theta_s \cdot d_b}, \quad (17)$$

where:

E_{SLM} is specific energy of fusion (J/mm²),
 P is laser power (W),
 ϑ_s is scanning speed (mm/s),
 d_b is laser beam diameter (mm).
 Layer thickness model:

$$h_{SLM} = \frac{E_{SLM}}{\rho \cdot c_p \cdot \Delta T}, \quad (18)$$

where:

ρ is material density (kg/m³),
 c_p is specific heat capacity (J/kg·K),
 ΔT is temperature difference (K).

2. Selective Laser Sintering (SLS) Density model of the structure after sintering:

$$D_{SLS} = (1 - e^{-\alpha \cdot E_{SLS}}) D_0, \quad (19)$$

where:

D_{SLS} is density of the final product,
 E_{SLS} is specific laser energy (J/mm²),
 α is energy penetration coefficient,
 D_0 is initial powder density.

Production speed:

$$V_{SLS} = \vartheta_s \cdot d_b \cdot h, \quad (20)$$

where h is layer thickness (mm).

3. Stereolithography - SLA:

$$d = \frac{D_p}{\beta} \ln \left(\frac{E}{E_c} \right), \quad (21)$$

where:

d is depth of resin hardening (mm),
 D_p is light penetration coefficient (mm),
 β is exponential light absorption factor,
 E is laser power (J/mm²),
 E_c is critical power for polymerization.

4. Direct Metal Laser Sintering (DMLS) for which the formula for the rate of layer formation is:

$$R_{DMLS} = \frac{P \cdot \tau}{\rho \cdot L}, \quad (22)$$

where:

R_{DMLS} is layer formation rate (mm³/s),
 τ is laser efficiency coefficient,
 ρ is metal density (kg/m³),
 L is specific heat of fusion (J/kg).

5. Fused Deposition Modeling (FDM) for which the material delivery rate is:

$$Q = A \cdot \vartheta_f, \quad (23)$$

where:

Q is volume of material being fed (mm³/s),
 A is cross-sectional area of the thread (mm²),
 ϑ_f is feed rate (mm/s).
 Layer thickness:

$$h_{FDM} = d_{nozzle} \cdot f, \quad (24)$$

where:

d_{nozzle} is nozzle diameter (mm),
 f is layer compression ratio.

6. Electron Beam Melting (EBM). Electron beam absorption model:

$$T_{EBM} = \frac{P}{A \cdot h \cdot \rho \cdot c_p}, \quad (25)$$

where:

T_{EBM} is melting point (K),
 A is beam exposure area (mm²).

7. Multi Jet Fusion (MJF). Fill factor:

$$F = \frac{m_p}{V_p}, \quad (26)$$

where:

m_p is powder mass (g),
 V_p is product volume (cm³).

8. Wire Arc Additive Manufacturing (WAAM)

Wire melting equation:

$$M = \frac{P \cdot \tau}{H_f}, \quad (27)$$

where:

M is mass of molten material (g/s),
 H_f is heat of fusion (J/g).

The above models help assess each technology's effectiveness and predict the production process's parameters. Table 1 presents the review results of the main types of modern additive technologies used to produce elements of the aviation industry.

Table 1 shows that modern additive technologies cover many methods for manufacturing parts for the aviation industry, from inexpensive polymer prototypes to high-tech metal structures.

Technologies such as SLM, EBM, and DMLS produce strong, complex, and lightweight parts from titanium, aluminum, and nickel alloys, which are critical for reducing aircraft weight and increasing efficiency. More affordable methods like FDM or LOM are used to create mock-ups, aerodynamic models, and internal elements. It is also noticeable that from 2000 to 2024, innovative technologies such as CLIP, MJF, WAAM, and Binder Jetting have appeared, significantly expanding the capabilities of 3D printing in aviation regarding materials and production scale.

Table 1

Results of considering the main types of modern additive technologies
used to produce elements of the aviation industry

Technology type	Description	Developer	Applications in the aviation industry	Features	Features of application in aircraft structures
FDM (Fusion Deposition Modeling)	Applying a layer of molten plastic to form a part	Stratasys (USA), 1980s	Prototypes, plastic, and composite parts	Low cost, easy to use, limited durability	Layouts, body elements, ventilation ducts
SLM (Selective Laser Melting)	Laser melting of metal powder	Fraunhofer Institute (Germany), 1995	Metal parts made of titanium, aluminum, nickel	High precision and durability	Structural elements, fasteners, wing parts
SLS (Selective Laser Sintering)	Laser sintering of polymer and metal powders	Carl Deckard, Univ. of Texas, 1980s	Prototypes, functional elements made of polymers	No need for supports	Internal components, seals
EBM (Electron Beam Melting)	Electron beam melting of metal powders in vacuum	Arcam AB (Sweden), 1997	Engine structures, supporting elements	Vacuum operation, high density	Turbine parts, power units
LOM (Laminated Object Manufacturing)	Overlaying and gluing layers of paper or plastic	Helisys Inc. (CIIA), 1990	Large prototypes, models	Cheapness, simplicity	Aerodynamic models, demonstration elements
DMLS (Direct Metal Laser Sintering)	Like SLM: Laser sintering of metal powder with greater precision	EOS GmbH (Germany), 2000-present	Parts made of high-strength metals	Detailing, automation	Complex supports, structures with channel openings
CLIP (Continuous Liquid Interface Production)	Rapid polymer molding from photopolymer resin	Carbon 3D (USA), 2015	Flexible prototypes, injection molds	Extremely high speed, smooth surface	Production of molds for composite materials

Note: The author developed the Source of the figure based on the analysis [22,24].

Most modern solutions are focused on increasing speed, accuracy, and reducing cost, and allowing the production of unique designs with minimal processing costs, which indicates the active integration of additive manufacturing into key design and manufacturing processes of aircraft structures.

Table 2 presents the analysis of the properties of basic materials for additive technologies in the aviation industry.

Table 2 shows that each material has unique properties determining its optimal application in the aviation industry. Due to its high strength, corrosion resistance, and lightness, titanium is ideal for manufacturing critical structural elements, such as engine parts. Aluminum, which is characterized by lightness and high thermal conductivity, is used in components operating under high

temperatures and mechanical loads. With its high strength and ability to withstand high loads, steel is used to manufacture power elements and frame structures, where maintaining stability under high pressure is critical. Titanium alloys, with high corrosion resistance and a high melting temperature threshold, are used to manufacture parts operating under challenging conditions, such as high loads and extreme temperatures. Polymers and composites, due to their lightness and flexibility, are used to manufacture prototypes, lightweight structures, and additional components, where high mechanical strength is not required. Still, low weight and the ability to combine with other materials are essential in Table 3. The latest advances in the application of additive technologies in producing parts for the aviation industry are reviewed.

Table 2

Results of analysis of properties of basic materials for additive technologies in the aviation industry

Material	Properties	Applications in the aviation industry
Titanium	High strength, corrosion resistance, light weight	Manufacturing important structural elements such as engine parts
Aluminum	Lightness, high thermal conductivity	Components operating under high temperatures and mechanical loads
Steel	Strength, ability to withstand heavy loads	Manufacturing power elements, frame structures
Titanium alloys	High corrosion resistance, high melting point	Production of parts operating in critical conditions (temperatures, loads)
Polymers and composites	Lightness, flexibility, possibility of combination with other materials	Prototypes, lightweight designs, additional components

Note: The author developed the Source of the figure based on the analysis [25,26].

Table 3 shows that recent advances in the use of additive technologies in the aviation industry indicate significant progress in manufacturing high-tech components. In 2023, Selective Laser Melting (SLM) technology was used to manufacture turbine blades from titanium alloys, which have high strength and can withstand temperatures up to 1668°C, increasing engine reliability. Another innovative achievement was the integration of intelligent sensors into parts through additive technologies, which allows monitoring the condition of components during operation. In 2024, the development of composite materials based on carbon fibers made it possible to manufacture lightweight and durable components for aircraft structures. In parallel, introducing multi-laser systems in SLM technology significantly improved the production speed of complex turbine elements and aircraft fuselages. Another significant achievement was using electron beam melting (EBM) technology to manufacture complex geometries from nickel alloys, which allows the creation of parts that can withstand extreme temperatures and loads. These achievements open new opportunities for improving production processes and increasing the reliability of aviation systems. Table 4 presents the results of a review of the latest materials for additive technologies in the aviation industry.

Reviewing the latest materials for additive technologies in the aviation industry shows significant progress in developing materials that meet the high requirements for aviation components. In 2023, titanium alloys Ti-6Al-4V are used to manufacture turbine blades and engine components due to their high strength (1000-1100 MPa) and melting point of 1668°C. In 2024, aluminum alloys AlSi10Mg provide good strength (350-450 MPa) and are used to manufacture structural elements such as aircraft fuselages and wings. Carbon fiber-based composites (strength 600 MPa) manufacture lightweight components of suspension structures and aircraft wings. Fiberglass with a strength of 250-350 MPa is used for the manufac-

ture of interior trim elements and panels, and nickel alloys Inconel 718 with a strength of 1300 MPa and heat resistance up to 1000°C are used in the manufacture of turbine blades and high-temperature engine components. These materials significantly improve the performance of aviation systems. Table 5. analyzes the main modern achievements in using additive technologies to reduce weight and improve aerodynamic properties.

Table 5 clearly shows that the latest advances in the use of additive technologies for the aviation industry focus on two main areas: weight reduction and improved aerodynamic performance. Various 3D printing methods allow the production of components with high mechanical properties, such as high strength and thermal stability, directly affecting the efficiency of aircraft and their engines. Innovative technologies such as electron beam melting (EBM) and selective laser melting (SLM) are essential, as they allow the creation of parts with high strength and resistance to high temperatures, which are especially important for turbine blades and other high-temperature components. Latest trends emerging from the table include the significant integration of porous materials for weight reduction, the use of composite materials to reduce the weight of the fuselage and wings, and the continuous development of methods such as Direct Energy Deposition (DED) for modeling aerodynamic components. These trends contribute to creating elements that are not only lightweight but also have high strength and flexibility, which allows for improved aerodynamic properties and reduced fuel consumption, which is a key factor in reducing the cost of air transportation. Modern technologies are actively used by companies such as GE Aviation, Rolls-Royce, Boeing, Airbus, and Pratt & Whitney, which indicates their enormous potential and future application in the aviation industry. Table 6 presents the analysis results of the latest technologies and materials used in additive technologies in aircraft construction.

Table 3

Recent advances in the application of additive technologies
in the production of parts for the aviation industry

Achievement	Technology	Parameters and characteristics	Manufactured parts and applications
Manufacturing turbine blades from titanium alloys	Additive manufacturing (Selective Laser Melting)	Titanium (Ti-6Al-4V), tensile strength 1000 MPa, melting point 1668°C	Turbine blades for aircraft engines operating at high temperatures.
Integrating smart sensors into parts via AT	SLS, FDM, Direct Energy Deposition	Sensor integration into materials, high temperature resistance, high accuracy	Engines, components for real-time condition monitoring during operation.
Development of composite materials for blood pressure	Fused Deposition Modeling (FDM)	Carbon fiber composite, strength 600 MPa, modulus of elasticity 70 GPa	Lightweight components for aircraft structures.
Improving production speed with multi-laser systems	Multi-laser Metal Printing (SLM)	Titanium alloys, high printing speed, layer thickness 30 microns	Complex elements of turbines and aircraft fuselages.
Manufacturing complex part geometries using EBM	Electron Beam Melting (EBM)	Nickel alloy Inconel 718, temperature resistance up to 1000°C, tensile strength 1300 MPa	Turbine blades, high-temperature parts for jet engines.

Note: The author developed the Source of the figure based on the analysis [27,28].

Table 4

Results of the review of new materials for additive technologies in the aviation industry

Material	Technology	Mechanical properties	Aviation applications
Titanium alloys (Ti-6Al-4V)	Selective Laser Melting (SLM)	Tensile strength 1000-1100 MPa, melting point 1668°C	Manufacturing turbine blades and engine components.
Aluminum alloys (AlSi10Mg)	Fused Deposition Modeling (FDM)	Tensile strength 350-450 MPa, modulus of elasticity 70 GPa	Structural components of fuselages, wing elements, skin.
Carbon fiber composites	Continuous Filament Fabrication (CFF)	Strength 600 MPa, modulus of elasticity 70 GPa	Lightweight components for suspension structures and aircraft wings.
Склопластик (Glass-Fiber Reinforced Plastics)	FDM, SLS	Strength 250-350 MPa, modulus of elasticity 30-45 GPa	Production of interior decoration elements and panels.
Nickel alloys (Inconel 718)	Electron Beam Melting (EBM)	Tensile strength 1300 MPa, heat resistance up to 1000°C	Turbine blades, high-temperature engine components.

Note: The author developed the Source of the figure based on the analysis [29,30].

Table 5

The main current achievements in using additive technologies are reducing mass and improving aerodynamic properties.

Achievement	Technology	Characteristics	Application
Turbine blade optimization	Selective Laser Melting (SLM)	Strength 1000 MPa, melting point 1668°C	Turbine blades to reduce fuel consumption
Integrating porous materials for weight reduction	SLS, FDM	Density 2.7 g/cm ³ , strength 500 MPa	Components for aircraft wings and fuselages
Modeling of aerodynamic components	Direct Energy Deposition (DED)	Strength 900 MPa, flexibility 20%	Aerodynamic components, drag reduction
Development of turbine blades with aerodynamic elements	Electron Beam Melting (EBM)	Strength 1200 MPa, heat resistance up to 950°C	Turbine blades for engines
Using composite materials to reduce weight	Continuous Filament Fabrication (CFF)	Strength 650 MPa, modulus 80 GPa	Fuselage and wing components
Manufacturing of aerodynamic grilles for engines	Fused Deposition Modeling (FDM)	Strength 500 MPa, flexibility 15%	Engine grilles, drag reduction
High-strength piston parts for aircraft	Multi-Laser Metal Printing (SLM)	Strength 1100 MPa, heat resistance up to 900°C	Piston components for engines

Note: The author developed the Source of the figure based on the analysis [31, 32].

Table 6 shows that the latest technologies and materials used in additive technologies in aircraft manufacturing demonstrate significant progress in improving mechanical properties, reducing weight, and optimizing manufacturing processes. For example, titanium Ti-6Al-4V in Selective Laser Melting (SLM) technology allows for strength up to 1260 MPa. It reduces the weight of parts by 20%, reducing production time by 3 times.

Nickel alloy Inconel 718 in Direct Metal Laser Sintering (DMLS) technology shows strength up to 1180 MPa and provides a homogeneous microstructure, reducing costs by 35%. These results confirm the effectiveness of using additive technologies to manufacture highly loaded components of aviation systems. The results obtained are visually shown in Fig. 1.

Table 6

Results of the analysis of the latest technologies and materials used in additive technologies in aircraft construction

Material	Technology	Mathematical model	Strength (MPa)	Production time (hours)
Ti-6Al-4V (titanium)	SLM	Finite Element Method (FEM), Thermomechanical Model	1260	12
Inconel 718 (nickel alloy)	DMLS	Porosity analysis, laser parameter optimization	1180	15
17-4PH (stainless steel)	Binder Jetting	Darcy's equation for modeling binder sintering	up to 1400	24
Al-Si (aluminum alloy)	SLM	Heat conduction models, FEM	at the casting level	10
ULTEM 9085 (plastic)	FDM	Optimization model of layer/temperature parameters	up to 100 MPa	2
Photopolymers	CLIP	Kinetic model of polymerization, light diffusion equation	up to 70 MPa	1

Note: The author developed the Source of the figure based on the analysis [33,34].

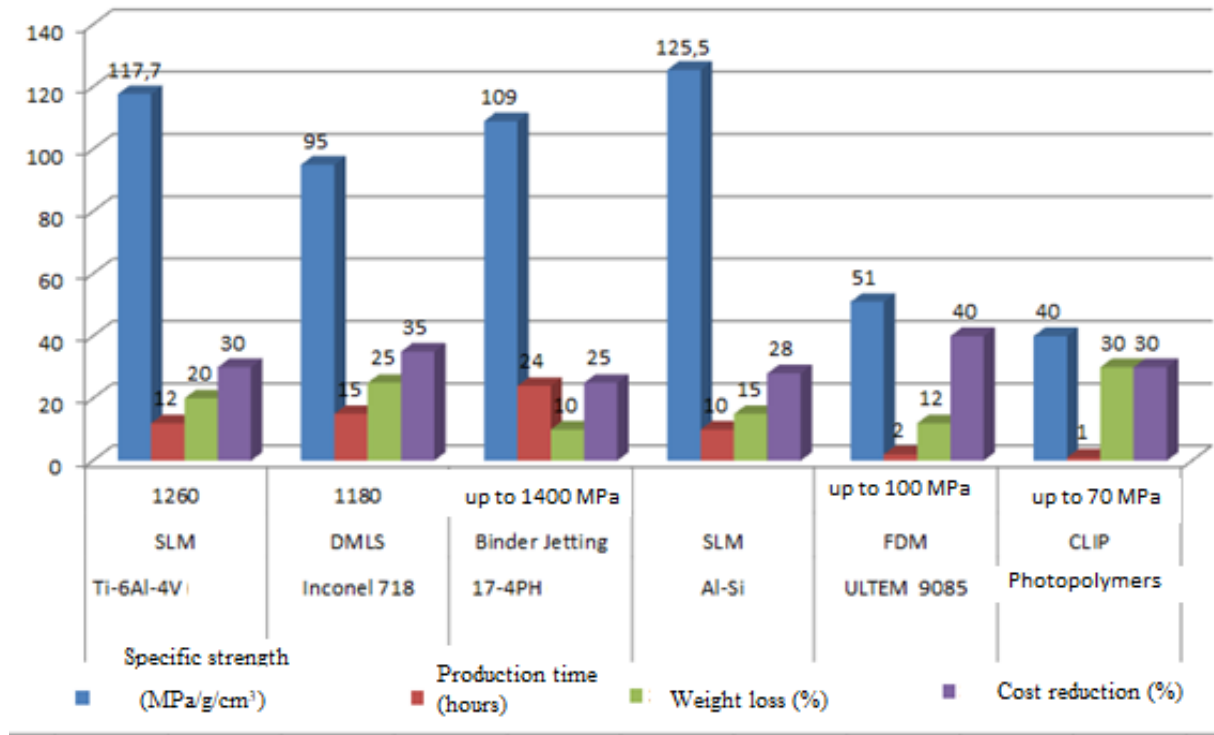


Figure 1. Results of the comparison of additive technologies by key parameters to produce aviation parts

From Fig. 1, it is seen that the latest trends in the use of additive technologies in the aircraft construction industry are aimed at significantly reducing the time for manufacturing parts and reducing costs while maintaining or improving the strength of materials. Fused Deposition Modeling (FDM) technology for ULTEM 9085 plastic allows you to reduce manufacturing time to 2 hours, increasing stiffness by 12% and reducing costs by 40%. Another significant trend is using photopolymers in CLIP technology, which provides high accuracy and reduces waste by 30%. All these achievements indicate that additive technologies have enormous potential for application in aircraft construction, providing production speed, high mechanical properties, and cost-effectiveness.

Thus, using technologies such as SLM, DMLS, Binder Jetting, and FDM allows you to achieve high strengths, reduce production costs, and significantly reduce the time for manufacturing parts. This indicates the importance and potential of additive technologies for modernizing aviation production, where efficiency and production speed are critical [21]. The latest trends include using materials such as Ti-6Al-4V, Inconel 718, and ULTEM 9085, contributing to significant cost reduction and increased efficiency in manufacturing aviation components.

This highlights the importance of innovative approaches to create lighter, stronger, and more economical aircraft structures that meet the requirements of the modern aviation industry.

3.2. Discussion

The mechanical characteristics obtained in this study are consistent with data reported in recent publications on additive manufacturing for aerospace applications. In particular, the achieved tensile strength of up to 1260 MPa for Ti-6Al-4V components produced by SLM corresponds to the strength range reported in studies on fatigue and structural performance of additively manufactured titanium alloys [18]. Similar strength levels for Inconel 718 fabricated by DMLS (above 1100 MPa) are confirmed in investigations devoted to nickel superalloys produced by wire-arc and laser-based additive technologies [15]. These comparisons demonstrate that the experimental results obtained in this work are aligned with established material performance benchmarks for aviation applications.

The influence of printing parameters on porosity formation and microstructural heterogeneity, identified in this study, also agrees with conclusions presented in works analyzing process parameter optimization and defect formation in metal additive manufacturing [34], as well as in comprehensive reviews of additive technologies for aerospace applications [26]. While many studies focus on isolated technological factors, the present research extends these findings by integrating thermomechanical modeling, porosity analysis, and multi-criteria optimization into a unified predictive framework. The economic results obtained – including material savings of up to 30%, production time reduction by 2–3 times,

and cost reduction up to 40% – are comparable with trends reported in recent analyses of additive manufacturing implementation in aerospace production systems [25]. However, in contrast to some literature emphasizing large-scale substitution of conventional methods, the findings of this study support a more balanced perspective: additive technologies demonstrate the highest efficiency when applied to geometrically complex, weight-critical, and highly loaded components. Furthermore, the modeling approaches developed in this work are consistent with thermomechanical simulation and finite element strategies described in studies addressing process stability and structural reliability of additively manufactured parts [6], [23]. At the same time, the novelty of the present research lies in combining these modeling approaches with multi-criteria optimization procedures specifically adapted to aviation structural elements. Overall, compared with existing publications that primarily analyze materials or specific technologies separately [9], [26], this study proposes an integrated analytical and optimization-based methodology. This approach enhances predictive accuracy, supports industrial decision-making, and strengthens the practical feasibility of implementing additive technologies in aircraft structural manufacturing under real production constraints.

4. Conclusions

As a result of the study, it can be concluded that additive technologies have significant potential for optimizing the design and production of aircraft structures. They allow for reducing the time for manufacturing parts, reducing the weight of components, and improving aerodynamic characteristics. At the same time, introducing 3D printing in aircraft construction faces several challenges, such as ensuring the necessary mechanical properties and standardization of processes. However, with the development of materials and technologies, additive methods may become key in the future to increase the efficiency and innovation of the aviation industry. According to the results of the analysis, the use of additive technologies, such as SLM, DMLS, and FDM, in aircraft construction allows us to improve the characteristics of materials significantly. For example, titanium Ti-6Al-4V using SLM technology provides strength up to 1260 MPa, a reduction in the weight of parts by 20%, and a reduction in production time by 3 times. For Inconel 718 in DMLS, strength up to 1180 MPa and a decrease in costs by 35% are achieved. FDM and Binder Jetting technologies also demonstrate high accuracy and 25-40% cost reductions, making them cost-effective for producing aviation components. These results highlight the effectiveness of additive technologies in reducing costs and improving the performance of aviation parts.

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Conflict of Interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, author ship or otherwise, that could affect the research and its results presented in this paper.

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Data Availability

Data will be made available upon reasonable request.

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence methods while creating the presented work.

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АДИТИВНІ ТЕХНОЛОГІЇ: ДОСЛІДЖЕННЯ ТА ЗАСТОСУВАННЯ У ПРОЄКТУВАННІ Й ВИГОТОВЛЕННІ КОНСТРУКТИВНИХ ЕЛЕМЕНТІВ АВІАЦІЙНОЇ ПРОМИСЛОВОСТІ

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Предметом вивчення в статті є застосування адитивних технологій при проектуванні та виготовленні елементів конструкцій авіації за сучасних вимог щодо міцності, зниження маси, надійності та економічної ефективності. **Метою** є розробка та обґрунтування комплексного аналітичного підходу до оптимізації адитивних виробничих процесів у авіабудуванні. **Завдання:** аналіз сучасних адитивних технологій в аерокосмічній техніці; розробка математичних моделей термомеханічних процесів і пористості; оптимізація параметрів друку та складу матеріалу; та порівняльна оцінка традиційних та адитивних методів виробництва. Використані методи: метод скінченних елементів, термомеханічне та пористе моделювання, багатокритеріальна оптимізація та експериментальне дослідження механічних властивостей металевих та полімерних матеріалів. Отримані такі **результати**. Розроблено математичні моделі прогнозування термічних деформацій, структурної неоднорідності та характеристик міцності; визначено вплив параметрів процесу на формування мікростру-

ктури та мінімізацію дефектів; встановлено, що оптимізація параметрів друку дозволяє зменшити матеріаломісткість до 30%, знизити масу виробу на 10–25%, скоротити терміни виготовлення у 2–3 рази та зменшити витрати до 40%; досягнуто міцності на розрив до 1260 МПа для титанових компонентів, виготовлених методом SLM. Крім того, запропонований інтегрований підхід до моделювання забезпечив кількісне прогнозування рівня пористості та розподілу залишкових напружень, що підвищує точність геометричних параметрів і структурну надійність відповідальних авіаційних елементів. Порівняльний аналіз підтвердив, що адитивні технології демонструють найвищу ефективність під час виготовлення геометрично складних і масокритичних деталей, де традиційні методи мають обмеження щодо гнучкості проектування та ефективності використання матеріалу. **Висновки.** Наукова новизна полягає в розробці інтегрованої основи моделювання та оптимізації для адитивного виробництва авіаційних компонентів, що забезпечує покращення структурної цілісності, зниження рівня дефектності, підвищення ефективності виробництва та підвищення конкурентоспроможності авіаційного виробництва.

Ключові слова: адитивні технології; метод скінченних елементів; аналіз пористості; методи оптимізації; параметри друку; експериментальні методи; механічна міцність; цілісність конструкцій; якість деталей; авіаційна промисловість.

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