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Methodology for optimizing parameters and processes of metal component production for aerospace structures via additive manufacturing technologies

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This article provides an overview of current approaches to optimizing parameters and processes in additive manufacturing for aerospace metal components. The use of 3D printing technologies such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM) is considered, which enable the creation of parts with complex geometries, reduced mass, and improved operational characteristics. The importance of accurately selecting technological parameters is emphasized, as they directly affect the mechanical properties, durability, and reliability of the produced parts. Special attention is given to issues arising during additive manufacturing, such as material porosity, residual stresses, structural inhomogeneity, and insufficient dimensional accuracy. Methods for their elimination are analyzed, including numerical modeling of thermal processes, topology optimization of structures, and the application of machine learning algorithms for automated print parameter selection. The importance of integrating a comprehensive approach that combines experimental research with digital technologies is emphasized, as it significantly enhances product quality. The article focuses on the future development of additive technologies in the aerospace industry. Specifically, the possibilities of integrating artificial intelligence (AI) into print process management are explored, enabling not only quality control automation but also the prediction of potential defects at early stages of production. Additionally, the development of new metal alloys specifically tailored for 3D printing methods and the standardization of additive parts certification processes are discussed, as these are key factors for the widespread adoption of these technologies in aerospace manufacturing. Thus, the article summarizes the latest research in the field, identifies key problems, and outlines potential solutions. The comprehensive analysis and implementation of modern additive manufacturing optimization methods will improve efficiency, reliability, and cost-effectiveness in aerospace 3D printing applications.
Key words: Additive technologies; 3D metal printing; aerospace structures; parameter optimization; topology optimization; artificial intelligence; quality control.

Introduction

Aerospace engineering is one of the most demanding industries, where continuous efforts are made to improve production technologies. Contemporary challenges, such as the need to reduce the mass of structures, enhance their strength characteristics, and improve eco-nomic efficiency, drive the development of new manufacturing methods. In this context, additive technologies, particularly metal 3D printing, are becoming increasingly in demand. These technologies enable the creation of parts with complex geometries, minimize waste, and significantly speed up the production process. However, for the successful application of these technologies in aviation, thorough optimization of printing parameters and post-processing methods is required, making the optimization of these processes especially relevant.

Unlike traditional methods such as casting, machining, and assembly, additive manufacturing allows for the formation of parts with complex geometries, high precision, and minimal waste. However, despite its significant advantages, the technology remains limited by several technical and economic factors that require

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further development.

Reduced lead time and related costs, as well as the capacity to design and produce intricate geometries that facilitate lightweighting, component consolidation, and performance enhancements - all while adhering to budgetary and schedule constraints - are the benefits of using additive manufacturing for aerospace components [1]. It is feasible to improve the material distribution and reduce bulk while preserving the component's mechanical and other performance criteria by leveraging the design freedom of metal additive manufacturing (AM). It is also possible to merge components, lowering the risk and cost of many components while simultaneously minimizing potential joint failure mechanisms. Furthermore, improved performance (above that of conventional manufacturing) can be achieved by using mechanical, thermal, and other optimization approaches to design complex parts that were previously impossible to manufacture, such as conformal cooling channels on combustion chambers or turbine blades. While decreased lead times are now the primary motivation for the usage of AM in aerospace applications, certain manufacturing scenarios give AM an edge over traditional manufacturing [2].

Currently, various additive manufacturing methods are used in aerospace engineering, including Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Directed Energy Deposition (DED). Despite their advantages, the application of these technologies is associated with a number of challenges, such as the emergence of internal defects, residual stresses, insufficient shape accuracy, and material structure heterogeneity. Addressing these issues requires the development of effective approaches to controlling the printing processes, from selecting optimal parameters to improving post-processing methods.

A game-changing technique for creating intricate shapes with specialized mechanical qualities is metal additive manufacturing. However, exact control over processing factors including laser power, scan speed, layer thickness, and hatch spacing is necessary to achieve the best possible part quality and performance - they are critical process parameters used to customize the final part's microstructure, mechanical properties (e.g., strength, density), and surface quality). Customizing design for additive manufacturing (DfAM) and carefully managing process variables are essential to optimizing metal additive manufacturing for aircraft structures. DfAM allows for the production of complicated geometries that are difficult to obtain through typical manufacturing methods. This is accomplished by making sure material qualities are suitable with the selected method and application and by predicting results using computational tools and machine learning, which minimizes trial-and-error. The ultimate objective is to create high-performance, lightweight, and complicated components with shorter lead times, lower prices, and enhanced dependability [3].

State of the art. Objectives and tasks of research. For crucial metal components used in the aerospace sector, additive manufacturing (AM) holds great promise. However, issues with geometry and quality pose a danger to cost-effectiveness and expansion. AM continues to show variations in quality over time, between runs, and between machines. In terms of geometry, AM can only achieve a surface polish that is extremely rough for aerospace requirements and a dimensional precision of roughly 100μm with a positioning accuracy of roughly 20μm. Expensive post-process inspection methods like X-ray computed tomography scanning are required to quantify geometry [4]. Because of these difficulties, aerospace companies require a new standard for quality assurance.

One promising direction for advancing additive manufacturing is the use of

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digital modeling tools, topology optimization methods, and artificial intelligence algorithms. Numerical simulation allows for the prediction of material behavior during printing and reduces the risk of defects, while artificial intelligence aids in automating the selection of parameters and improving the quality of finished products. These technologies not only simplify the adaptation of 3D printing to mass production but also make it more reliable and economically viable [5, 6].

Daily technological advances are being made, but the ability to solve the current issues and challenges of AM, particularly those related to consistency, repeatability, and high quality, is critical to successfully industrializing additive manufacturing in the aviation sector. With this in mind, the objective of this article is to provide a comprehensive analysis of opportunities and prospects provided by modern methods for optimizing the parameters and processes of additive manufacturing for metallic components in aerospace structures, outlining practical applications of AM in rapid prototyping, functional part production, and component repair. It aims to examine ways to improve the accuracy and strength of parts, analyze key technological factors influencing their operational characteristics, and evaluate the prospects of implementing new approaches, including digital printing control technologies and the development of specialized alloys; furthermore, the article addresses the issues of product standardization and certification, which play a crucial role in integrating additive technologies into aerospace engineering; this article not only systematizes existing scientific developments in this field but also proposes potential solutions to pressing problems associated with the introduction of additive technologies into aerospace production [7, 8].

The article represents a review; the qualitative methodology was applied - narrative review method. The search for sources to be included in the sample for analysis was carried out in MDPI, ScienceDirect, ResearchGate, and IEEE libraries, both in domain of additive manufacturing optimization parameters as whole and in aerospace industry.

The optimization of additive manufacturing processes in aerospace engineering is a key direction for improving the quality, reliability, and cost efficiency of 3D-printed components. Studies highlight the variety and precision of SLA and DLP, the strength and durability of SLS, and the promise for critical component manufacture with metal-based technologies such as LPBF, SLM, EBM, and DMLS. The incorporation of AM into automotive and aircraft design emphasizes the revolutionary nature of these technologies, which drive advances in lightweight, complicated, and high-performance components. Modern aerospace structures impose strict requirements for mechanical strength, dimensional accuracy, and long-term durability, which necessitate a comprehensive analysis of the factors influencing the additive process – including printing parameters, material properties, build orientation, post-processing methods, and quality assurance procedures. Attempts to develop an analytical framework for forecasting optimal processing parameters in metal AM, with an emphasis on the interaction of mechanical characteristics, microstructure evolution, and thermal dynamics, are what distinguish current research directions. To find the best parameter combinations that optimize mechanical strength, suggested methods combine machine learning algorithms, solidification kinetics, and thermal modeling [9]. An overview of additive manufacturing technologies as they stand today is provided here, along with a list of important factors that affect product quality and the eventual goal of creating a useful optimization framework.

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1. Directions for optimization

One key direction in optimization is the selection and adjustment of printing parameters is presented in Fig. 1 [10]. The speed of laser or electron beam scanning, energy source power, layer thickness, filling strategy, and part orientation within the working area - these factors all significantly impact the mechanical properties and accuracy of the product. The use of numerical simulation methods allows for the prediction of material behavior during layer formation, reducing the likelihood of residual stresses, cracks, and porosity [7].

An integral part of the optimization process is the development and adaptation of new metal alloys that possess high thermal stability, mechanical strength, and corrosion resistance. Traditional aerospace alloys, such as titanium Ti-6Al-4V and nickel-based superalloys, require adaptation to additive technologies, which involves altering their chemical composition and structure to prevent cracking and improve layer bonding [5].

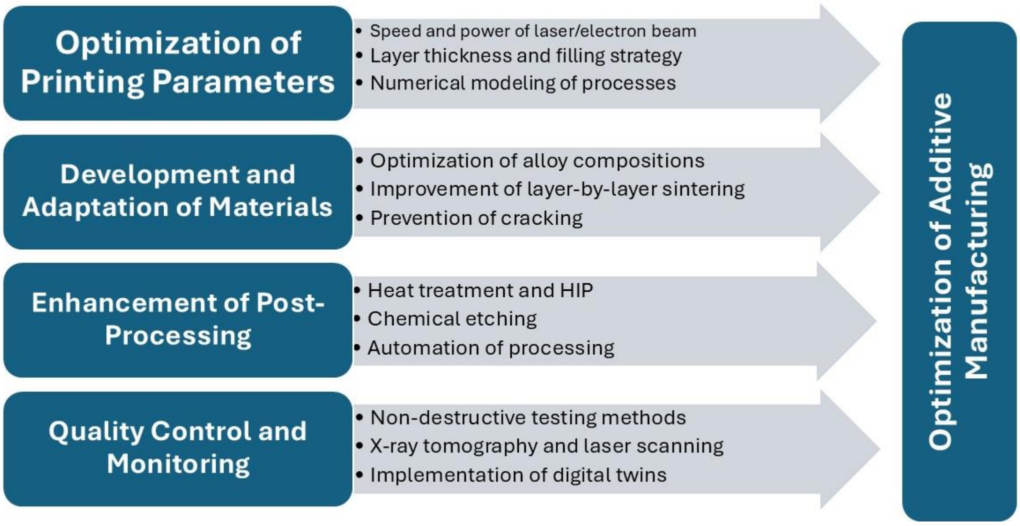

Fig. 1. Process optimization [10]

Sigma Labs Inc., based in Santa Fe, New Mexico, created the In-Process Quality Assurance (IPQA) approach for process control and quality assurance to address geometry concerns. In contrast to post-process quality assurance, IPQA is intended to assess AM process attributes in real or near-real time and detect process deviations before they become problems [11]. IPQA technology is integrated into the hardware and software of Sigma Labs' PrintRite3D AM product suite to enable serial production for metal AM technology earlier than would be otherwise feasible. Three basic issues are addressed by PrintRite3D software: ensuring product quality and metal integrity; ensuring the product's as-built geometry; and boosting productivity or AM speed. PrintRite3D provides actionable quality and manufacturing process control data in real time. It can offer producers and their end users part-by-part quality certification, supported by a file of supporting data, after no defects are found. The Sensorpak hardware suite from PrintRite3D consists of photodiodes, a high-speed data processing unit, and a non-contact pyrometer that may be retrofitted or sold with an AM production machine. An AM process's in-process state variables are measured by the hardware. PrintRite3D Inspect is used for layer-by-layer, part-by-part in-process inspection of metallurgical qualities. Sensor data establishes in-process metrics for

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each metal or alloy. Based on a thorough statistical analysis of production process data, it gives manufacturing engineers part quality reports. It can be utilized for process optimization and enhancement and permits the probing of questionable part data. PrintRite3D Contour is used to monitor part geometry in-process. The as-built and original CAD models are compared using the layer-by-layer geometry measuring tool. It uses optics, a data link, and a mechanical system to scan molten powder in two dimensions. For jobs involving trend, correlation, and investigation, use PrintRite3D Analytics. Over time, the software and data warehouse connects vital in-process data from several fabrication facilities, equipment, and builds. Throughout the whole product life cycle, users have access to both in-process and post-process data. Large volumes of layer-by-layer data are processed by the software and embedded algorithms, which also notify operators of each build's component's quality compliance status.

Another important direction is improving post-processing of parts, which is necessary to eliminate micro-defects, relieve residual stresses, and achieve the required geometric accuracy. Common post-processing methods include heat treatment, hot isostatic pressing (HIP), mechanical processing, and chemical etching [8]. Automating these processes with artificial intelligence and predictive analysis systems can significantly reduce the time required for final product finishing. Automated post-processing solutions address the issues of 3D printing operations, enabling more exact sorting, efficient handling of various parts, and faster iteration without manual bottlenecks. For example, AM-Vision, developed by AM-Flow, represents a significant improvement in post-processing efficiency because it can accurately identify 3D-printed parts based on geometric features such as shape, size, and color using advanced computer vision and AI-driven image recognition algorithms. For example, the AM-Vision system can process up to 5760 pieces in 8 hours, considerably reducing the time and labor needed for item identification and classification [12]. Overall, AI and ML are speeding up post-processing automation. AI-driven program optimizes support structure placement to reduce removal efforts. ML algorithms detect surface roughness and adapt finishing procedures in real time, while vision-based quality inspection systems verify that parts fit required tolerances, eliminating defects prior to shipment. Predictive maintenance of automated post-processing equipment reduces downtime and increases longevity. These advances improve productivity, uniformity, and cost savings in AM workflows.

Real-time print parameter optimization, precise material behavior prediction, and early defect identification utilizing computer vision and sensor data are all made possible by the incorporation of AI algorithms into 3D printing systems. By creating complex geometries, automating slicing procedures, and enabling adaptive, self-correcting control during printing, ML techniques further streamline the design-to-production pipeline. These functions directly align with the principles of Industry 4.0/5.0, where intelligent manufacturing systems are driven by cyber-physical integration, autonomous decision-making, and human-machine collaboration. This powerful combination of AI and 3D printing not only enhances operational efficiency and product consistency but also drives the development of self-learning intelligent manufacturing systems [13]. Moreover, deep learning (DL), a subset of machine learning (ML) and artificial intelligence (AI), and its applications in convolutional neural networks (CNN) and alternative deep neural network (NN) architectures demonstrated remarkable efficacy for pertinent applications like image recognition or the detection of fabrication irregularities [14].

Quality control and standardization also play a key role in optimizing additive

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manufacturing processes. Non-destructive testing methods, such as X-ray computed tomography, laser scanning, and ultrasonic flaw detection, allow for the identification of hidden defects at early stages, which is particularly important for aerospace components. The implementation of digital twins and real-time monitoring systems helps track and adjust printing parameters during the process, ensuring stability and reproducibility of results. Kantaros et al. [15] attempted to summarize and review the current trends and limitations in DTs for additive manufacturing, in order to provide more insights for further research on DT systems. According to the authors, digital twins are a recently developed and highly promising solution to a number of issues with 3D printing technologies, including process simulation, process monitoring, and control. They can assist in gaining a thorough understanding of how different processing parameters contribute to and affect the ultimate quality of the manufactured product. Additionally, they can offer feedback data so that real-time adjustments can be made to take active control of the production process. The development or testing of the initial generations of 3D printing DTs is currently ongoing. Future research, however, should concentrate on creating understandable and accessible DTs for each and every 3D printing method, which will serve as a springboard for users to embrace and contribute to their continued development. Fig. 2 depicts the process workflow of a digital twin in additive technologies.

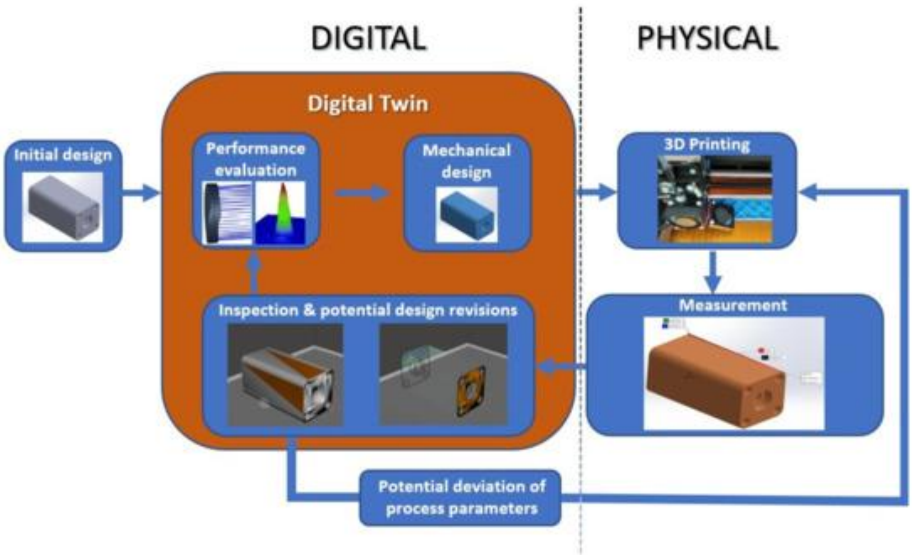

Fig. 2. Process of a digital twin in additive technologies [15]

Thus, a comprehensive approach to optimizing additive manufacturing in aerospace engineering includes improving printing parameters, developing new materials, refining post-processing methods, and implementing intelligent quality control systems. These measures not only enhance the operational characteristics of parts but also accelerate their integration into mass production, making additive technologies an integral part of the modern aerospace industry.

2. Metal 3D printing technologies

Modern additive technologies are widely used in the aerospace industry to produce metallic components with high precision, reduced weight, and improved mechanical properties. Depending on the principle of product formation, the type of

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energy source, and the material feeding method, several key metal 3D printing technologies are distinguished, among which the most commonly used are Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Directed Energy Deposition (DED). Each of these technologies has its unique features, determining its area of application in aerospace engineering is presented in Fig. 3 [6].

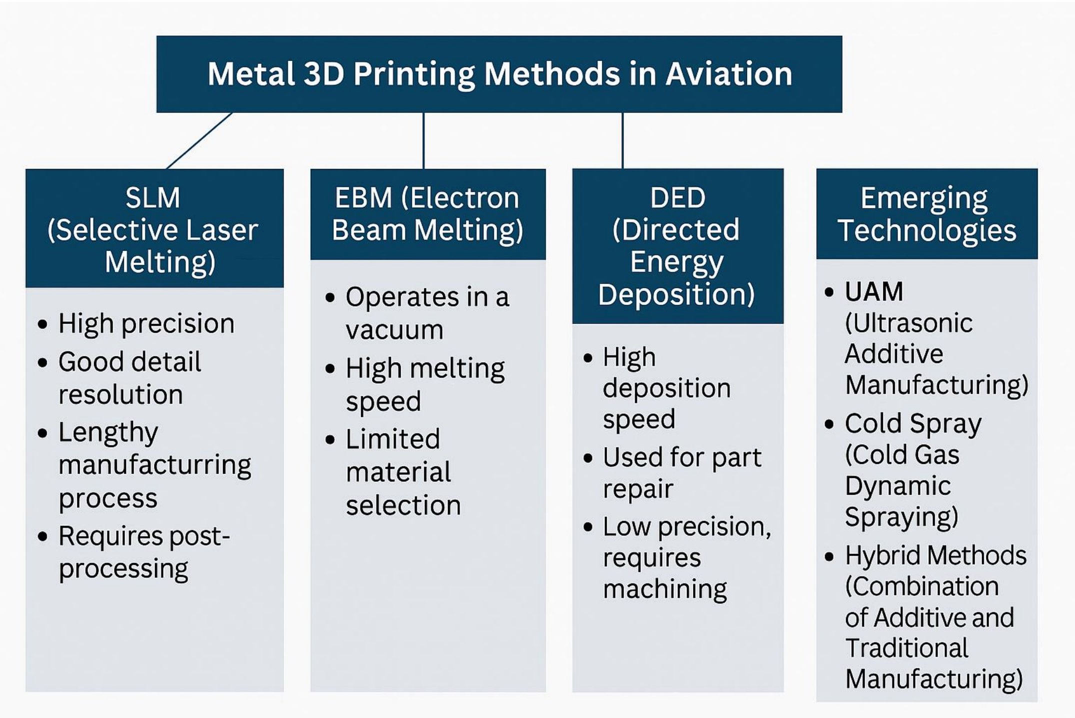

Fig. 3. 3D Printing Methods [6]

Directed Energy Deposition (DED) is a process of layer-by-layer deposition of metal powder or wire using a laser or electron beam. Unlike SLM and EBM, DED is used not only to create new parts but also for the repair or modification of existing structures. The DED technology is based on melting material being fed to a focal point on the build layer, which typically occurs in an inert atmosphere [12]. DED technologies are classed according to their feedstock (powder or wire) and energy source (laser beams, electron beams, arcs, or kinetic energy). DED technology creates 3D models layer by layer; however, this technology can be applied in a multiaxial machine to provide 3D positioning [16, 17]. This capability enables the development of complicated objects without the use of support structures. Fig. 4 depicts a schematic of the DED approach for both energy sources (laser and electron beams) [18]. The most popular DED technologies used in the aerospace and automotive industries are highlighted below.

The main advantages of the DED technology include [2,19]:

- High deposition speed, enabling the creation of large components;
- The ability to combine different materials in one process;
- Its use in the restoration and reinforcement of worn-out components.

However, this method has limitations related to lower accuracy in forming structures, the need for subsequent mechanical processing, and strict requirements for material feed control.

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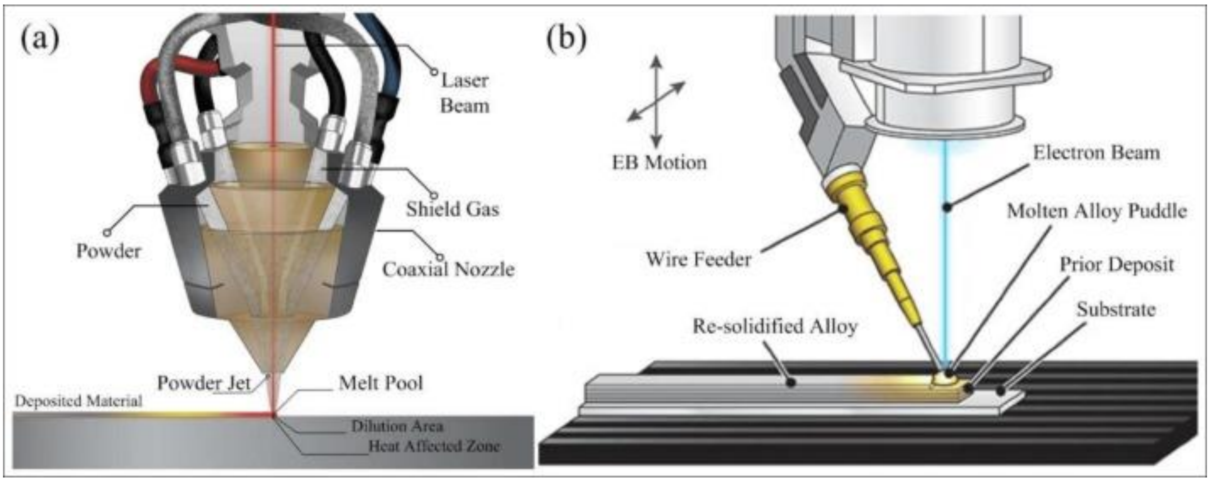

Fig. 4. Schematic diagram of the Direct Energy Deposition method for (a) Laser beam and (b) electron beam [18]

Meanwhile, the following technologies should be mentioned:

Laser Metal Deposition (LMD) - an AM method in which a laser beam is used to create a molten pool of metal powder on a metallic substrate (from which powder is fed) or an existing layer [20]. The powder melt might generate a deposit that fuses to the substrate. The metal components are formed as the substrate is traced along a predetermined path. LMD is widely used because it enables for the production of new parts, the repair of old parts, and the addition of engineering features to components.

Laser Engineering Net-Shaping (LENS) - Similar to the LMD, a laser creates a molten pool to capture the feed powder from the powder stream [21]. Once the laser has moved away, the molten pool solidifies, generating the first layer on the metallic substrate. The method is repeated to create a three-dimensional object layer by layer. LENS is a versatile and industry-friendly method due to its unique qualities, which include multi-material and functionally graded part production.

Electron Beam Freeform Fabrication (EBF^3) is an AM process that is applied when creating near-net-shape parts. Similar to laser-based DED processes, EBF^3 takes place in a vacuum chamber with an electron beam constantly focused on the material feed to melt it and add another layer [22]. EBF^3 employs less raw materials than other production techniques and provides scalable components that are only restricted by the vacuum chamber's dimensions and feedstock availability.

Wire Arc AM (WAAM) – a method that deposits materials layer by layer using an electric arc as the energy source [23]. WAAM has a better material usage ratio, a lower equipment cost, a greater deposition rate, and a more ecologically friendly production process than laser-based AM processes.

Another group of technologies - Fusion in a powder bed (PBF). The idea behind PBF techniques is to form layers by locally melting metal powder on a substrate. A roller will be used to disseminate a fresh layer of powder after the first one has created. There is no requirement for a support structure because the unmelted powder can be used again as a support for the subsequent layer. The majority of PBF methods use vacuum chambers or inert gases to stop the powder from oxidizing. PBF procedures can produce passageways and parts with greater fidelity construction characteristics than DED methods [24]. The powder bed fusion technique's schematic is displayed in Fig. 5. The following highlights the most popular PBF technologies in the automotive and aerospace sectors.

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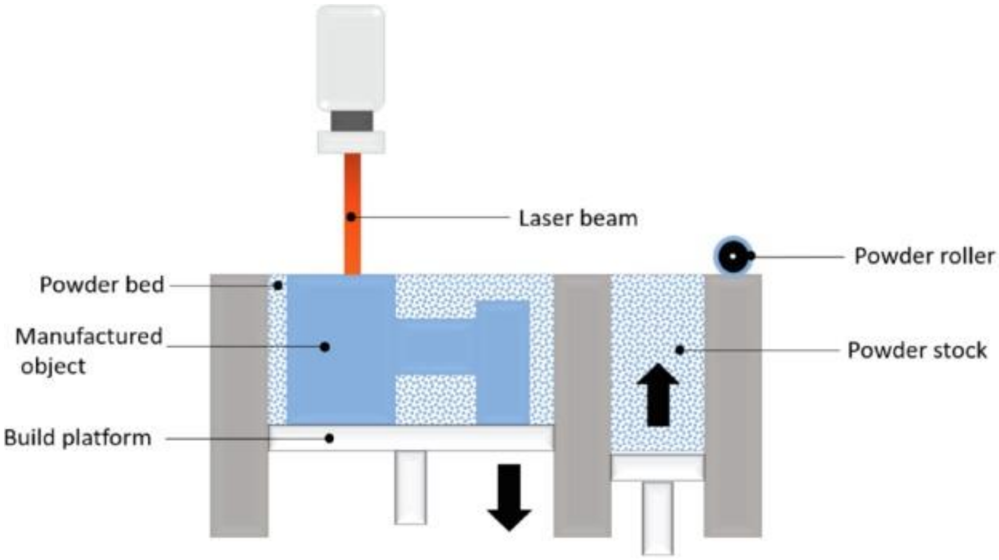

Fig. 5. Diagrammatic representation of the powder bed fusion process [24]

This category includes the following options:

Selective Laser Melting (SLM) is a layer-by-layer melting of metal powder using high-energy laser radiation. This method enables the production of parts with high precision and complex geometry, making it one of the most promising for manufacturing aerospace components.

The main advantages of the SLM method include [25]:

- High geometric accuracy and detailed structure;
- The ability to manufacture complex structures without additional assembly operations;
- Strength characteristics comparable to traditional manufacturing methods.

However, SLM has a number of technological limitations, including high equipment and material costs, long production cycles, and the need for thermal treatment to relieve residual stresses.

Selective Laser Sintering (SLS) - method that is somewhat similar to SLM, with the exception that the plastic powder is heated and then fused in the SLM process, whereas in the SLS process, it is fused using a high-power density laser.

Direct Metal Laser Sintering (DMLS) - a process producing high-performance parts with evidently high mechanical properties. The metallic powder is sinterable using a high-power density laser, just like SLS [26]. Complex shapes that are difficult to accomplish with other metal fabrication techniques can be produced via DMLS.

Electron Beam Melting (EBM) is similar to SLM, but a focused electron beam is used as the energy source. The process takes place in a vacuum chamber, which eliminates the risk of metal oxidation and allows for parts with low levels of residual stresses to be produced.

The advantages of the EBM method include [2]:

- The ability to process refractory metals and alloys;
- Reduced risk of microcracks and residual stresses;
- High melting speed due to the high-power density of the electron beam.

However, EBM has a number of limitations, such as lower precision compared to laser methods, the need for additional surface treatment, and a limited selection of available materials, mainly titanium and nickel alloys. Only metallic and alloy parts are used with EBM, and in order to prevent oxidation, the procedure is carried out in a high

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vacuum chamber. While EBM offers a high throughput, precision and surface quality are sacrificed in the process [18].

Binder jetting should also be mentioned. A binder and a powder-based substance are needed for the binder jetting AM process. Between the powder layers, the liquid-based binder serves as an adhesive [27]. Layer by layer, an object is created by a 3D nozzle moving along a path and depositing alternate layers of binding material and powder material. Although the printing process is quite quick, the lengthy post-processing time prolongs the procedure overall, and the final material is unsuitable for structural parts because the approach depends on binding.

Material extrusion is another technology worth mentioning. The feedstock, which consists of metal powder and polymeric binder filament, is heated in the material extrusion process until it becomes pliable enough to be extruded via a nozzle [28]. The 3D item is then created layer by layer by depositing the printing material onto a heated printing bed, which improves the material's adherence to the bed. Fused Deposition Modeling (FDM) is the most widely utilized material extrusion process. FDM is well-known because it doesn't need as much energy as AM techniques that rely on lasers or electron beams.

Promising Technologies. In addition to the methods discussed, other additive technologies are being researched in the aerospace industry, including Ultrasonic Additive Manufacturing (UAM) and Cold Gas Dynamic Spraying (Cold Spray). These methods show significant potential in the production of multi-component materials and the creation of protective coatings.

Thus, the choice of 3D printing technology for metal components depends on the requirements for mechanical properties, geometric accuracy, production costs, and product operating conditions. Optimizing additive manufacturing processes in aerospace engineering requires a comprehensive approach that includes material development, improvement of process control algorithms, and the implementation of intelligent quality control systems.

3. Advantages and limitations of additive technologies

One of the key advantages of additive technologies is the reduction in the mass of structures. The ability to create parts with optimized topology and internal lattice structures allows for weight reduction without compromising mechanical properties, which is critical for aerospace applications. The use of AM contributes to increased fuel efficiency and reduced operating costs [2].

Another important aspect is the high degree of design freedom. Unlike traditional manufacturing methods, additive technologies enable the production of parts with complex shapes, including integrated structures with internal cooling channels or air flow management systems. This opens up new possibilities for designing aerodynamically optimized elements that are not achievable with standard processing methods.

A significant advantage is the reduction in material costs and waste. In traditional machining, a substantial amount of material is removed during milling, leading to high material losses, especially when working with expensive alloys. In additive manufacturing, only the precise amount of material needed to create the part is used, increasing the economic efficiency of the technology [4, 29].

An additional benefit is the reduction in production lead times. By eliminating the need for mold manufacturing, stamping, and assembly operations, the part production process is accelerated, which is particularly important when developing new aviation

 ISSN 2071-1077(print)
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platforms and prototyping.

Despite the significant advantages, additive technologies have a number of limitations that hinder their mass adoption in aerospace manufacturing.

Among the main factors, the limited selection of materials remains. While metal 3D printing technologies already include aluminum, titanium, and nickel alloys, their mechanical properties do not always match those of traditionally processed materials. Moreover, some high-temperature alloys widely used in aircraft engines are still difficult to adapt to AM technologies [19, 30].

Another important aspect is the need for post-processing. After printing, parts often require thermal treatment, mechanical polishing, or additional sintering to improve material structure and reduce internal stresses. This increases the overall cost and complexity of the manufacturing process.

A technological challenge remains quality control and the predictability of mechanical properties. Unlike traditional manufacturing methods, additive manufacturing can lead to variability in density, residual stresses, and porosity of parts. This necessitates the development of new non-destructive testing techniques and mathematical modeling for predicting the material structure formation process.

A significant limitation is also the high cost of equipment and technologies. Modern laser or electron beam melting systems require substantial capital investments, as well as specialized personnel training. This hinders the widespread adoption of AM in the mass production of aerospace components [29, 31].

4. Factors Affecting the Quality of Additive Manufacturing Products

As it was emphasized above, the quality of parts produced by additive manufacturing is determined by a number of technological parameters that influence mechanical properties, geometric accuracy, density, and defect levels in the final product.

Laser (or Electron Beam) Parameters. The efficiency of metal powder melting and the quality of material structure formation depend on the parameters of the laser (in SLM and DED technologies) or electron beam (in EBM technology). This parameter plays a critical role in the powder particle melting process. If the power is too low, the material may not fully melt, leading to porosity and reduced strength. Excessive power, on the other hand, can cause overheating, structural deformation, and changes in the material's microstructure, negatively affecting its performance [29].

Beam Scanning Speed. This determines the speed at which the beam moves across the powder layer. A high scanning speed can result in incomplete melting, leading to defects and poor layer bonding. A low speed may cause overheating, increasing the risk of residual stresses and thermal deformation [32].

Laser Spot Diameter. This affects the resolution of the printing process. A smaller spot diameter allows for higher detail, but also increases print time. The optimal choice of laser spot diameter balances precision with production speed. Meanwhile, the quality of the metal powder directly influences the strength properties of the final parts. Although a smaller spot size slows down construction and may result in a rougher surface finish, it also increases energy density, enabling finer features and stronger parts due to a finer grain structure. Although a bigger spot size can produce smoother surfaces and speed up construction, it also compromises feature resolution and may result in lesser strength. The impact of beam diameter on the Laser Powder Bed Fusion (L-PBF) process is examined by Sow et al. [33]. A thorough comparison between a typical Gaussian laser spot with a diameter of 80 μm and a top-hat laser

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beam with a diameter of 500 µm is provided in their study. It has been demonstrated through experimentation that the powder bed L-PBF process may be significantly improved in terms of process stability, spatter reduction, and manufactured part density by using large beam, low VED. The primary physical rationale for the reported findings was the decrease in vaporization effects. In contrast to the typically key-hole welding mode obtained in the case of the classical small beam – high VED regime, the analysis of single tracks reveals that the large beam – low VED process is more energy efficient (higher penetration dept at the same VED) and produces near elliptical and shallow melt pools, suggesting a conduction welding regime that is more stable.

Particle Size and Shape. Uniform particle sizes ensure even distribution of powder across the build area and promote a dense structure. Spherical particles provide better packing and more stable melting, while irregularly shaped particles can negatively affect layer bonding quality [25].

Purity and Chemical Composition. Contaminants, oxides, or impurities can negatively impact the mechanical properties of the part. Control over the powder composition is critical in aerospace applications, as even slight deviations can affect strength and fatigue resistance [4].

Flowability and Packing Density. These parameters affect the even distribution of powder on the build platform. Uneven powder distribution can result in inconsistent part structure, reducing its performance characteristics [35].

Temperature control inside the build chamber is critical for preventing residual stresses and thermal deformations. Moreover, platform preheating parameters are important. Preheating the platform is used to reduce temperature gradients between layers, which minimizes the risk of cracks and internal stresses in the part. This is particularly important for materials prone to warping, such as titanium and nickel alloys [19].

Also, in additive manufacturing, rapid temperature changes can induce internal stresses that weaken the part. Optimized cooling regimes control material crystallization and improve its microstructure, enhancing part strength.

In Electron Beam Melting (EBM) technology, the build chamber is maintained at a high temperature to minimize residual stresses. This is crucial when producing large aerospace parts subject to significant mechanical loads.

Material deposition strategies and layer formation parameters affect the precision of the part and its mechanical properties presented below.

Layer Thickness. Layer thickness is a key factor influencing both precision and production speed. Thin layers (20-50 microns) provide high accuracy and smoother surface finishes, but increase print time. Thick layers (80-150 microns) speed up production but may degrade surface quality and introduce internal defects [30].

Filling Strategy. This defines the order and direction of material deposition. Common strategies include linear scanning, spiral filling, and zigzag trajectories. The chosen strategy impacts thermal stresses and mechanical strength of the material [31].

Part Growth Direction. This factor affects the anisotropy of mechanical properties. For instance, vertical layer-by-layer construction may result in varying strength depending on the direction of the applied load. In aerospace applications, this must be considered to ensure reliability and load-bearing capacity [23].

After the printing process, additive parts often require additional treatments to achieve desired characteristics:

Heat Treatment. Heat treatment is used to relieve residual stresses and enhance the mechanical properties of the material. This is especially important for

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titanium alloys, as it improves ductility and reduces the risk of part failure under load [45].

Mechanical Processing. It includes milling, grinding, and polishing to achieve required dimensional accuracy and improve surface quality, especially for critical load-bearing components in aerospace applications [30].

Non-Destructive Testing Methods. X-ray tomography, ultrasonic testing, and optical microscopy are used to detect internal defects. These methods help identify porosity, cracks, and other hidden flaws that can affect the structural integrity and reliability of the part [14].

Overall, high-quality additive manufacturing products are achieved through the optimal selection of print parameters, control over material properties, stable temperature conditions, careful layer deposition strategies, and post-processing techniques. Each factor requires careful monitoring and a tailored approach to ensure the best performance of aerospace components. Conceptual scheme of parameters for product quality optimization in AM is presented in Fig. 6 [29].

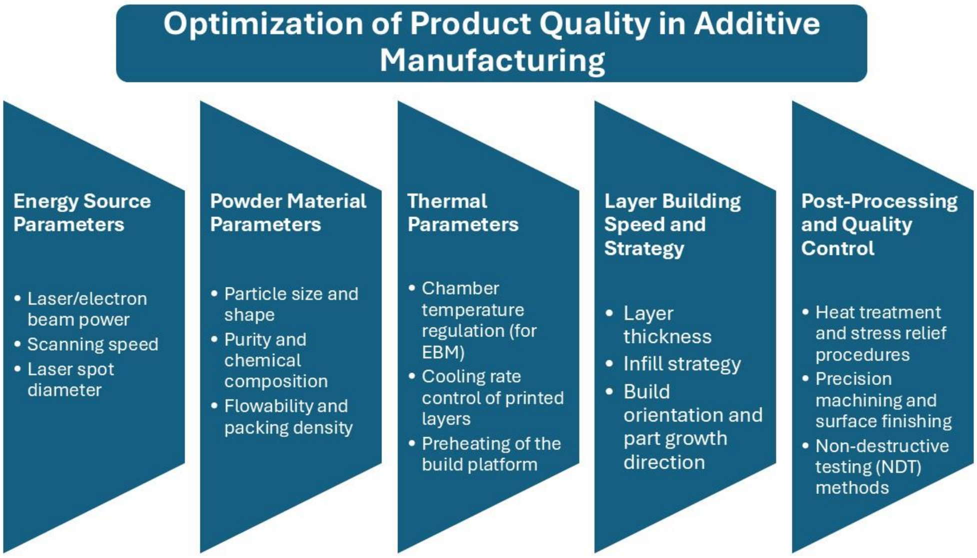

Fig. 6. Conceptual scheme of parameters for product quality optimization in AM [29]

5. Application of Numerical Modeling (CAE Analysis, Topology Optimization)

The implementation of numerical modeling in additive manufacturing processes plays a crucial role in ensuring quality and optimizing the design of metal components for aerospace structures. Computer-aided engineering (CAE) analysis enables the preliminary assessment of a component's mechanical properties, prediction of potential defects, and optimization of its geometry to reduce mass while maintaining structural integrity.

One of the most effective tools in this domain is topology optimization, which is based on numerical methods for calculating the stress-strain state of a structure. This approach redistributes material within a predefined volume to minimize the component's mass while preserving its strength characteristics [34].

Numerical Example of Topology Optimization [35].

Let us consider the optimization of a bracket manufactured via selective laser melting (SLM). Initial parameters:

• Initial mass: 1.2 kg;

 ISSN 2071-1077(print)
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- Applied load: 500 N (concentrated force);
- Material: Titanium alloy Ti-6Al-4V (elastic modulus: 110 GPa, ultimate tensile strength: 900 MPa).

By applying topology optimization, it is possible to reduce the component's mass by eliminating inefficient material regions. After optimization:

- Optimized mass: 0.85 kg;
- Maximum stress: 750 MPa (within the allowable limits for this material);
- Safety factor: 1.2.

Thus, numerical modeling enabled a 29% reduction in component mass while maintaining acceptable strength levels. This contributes to overall aircraft weight reduction and, consequently, improved fuel efficiency.

CAE analysis also allows for the prediction of thermal deformations and residual stresses arising during the additive manufacturing process. Such calculations help adjust printing parameters, including scanning speed, laser power, and layer thickness, thereby reducing the likelihood of defects such as porosity or residual stresses [36].

The integration of numerical modeling into the additive manufacturing process offers significant advantages by improving product quality and reducing material costs through the rational use of resources.

The use of artificial intelligence (AI) and machine learning (ML) in additive manufacturing unlocks new possibilities for improving quality and process efficiency. These technologies enable the analysis of large datasets, prediction of potential defects, and real-time automatic adjustment of printing parameters.

Key Applications of AI and ML in AM include the following [4]:

1. Optimization of Printing Parameters:

- Machine learning algorithms analyze correlations between printing parameters (laser power, scanning speed, layer thickness) and the quality of the final product;
- Implementation of adaptive control systems that automatically adjust process parameters based on real-time print conditions.

2. Defect Prediction and Prevention:

- Neural network models predict defect formation (e.g., porosity, cracking) based on sensor and camera data;
- Development of real-time monitoring systems that use image analysis and thermographic camera data to detect anomalies and adjust printing processes accordingly.

3. Development of Intelligent Self-Monitoring Systems:

- Integration of deep learning methods for automatic equipment calibration;
- Implementation of digital twins to model and predict material behavior during printing.

Example of Machine Learning Application in Process Optimization

Subeshan et al. [31] consider the use of a neural network model for optimizing laser melting parameters. Given initial conditions:

- Laser temperature: 1200 – 1500°C;
- Scanning speed: 500 – 1500 mm/s;
- Layer thickness: 30 – 50 µm.

The neural network is trained on experimental sample data to identify optimal parameters that ensure minimal porosity (<1%) and maximum material density (>99%). As a result, the system automatically adjusts printing parameters based on process conditions, reducing defect rates by 25% [31].

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The integration of AI and ML in additive manufacturing not only enhances product quality but also significantly reduces parameter tuning time, minimizes production costs, and decreases defect rates. These technologies are becoming an integral part of aerospace digitalization, contributing to increased efficiency and reliability in additive manufacturing.

6. Criteria for Selecting Optimal Structural Elements

When selecting aerospace components suitable for 3D printing, several key criteria are considered [32] [34] [36]:

Geometric Complexity. Components with topology-optimized structures, internal cooling channels, density gradients, or other complex shapes benefit the most from additive manufacturing.

Mass and Dimensional Characteristics. Reducing the mass of aerospace structures is a primary goal. Components that can be lightweighted using lattice structures or gradient materials are prioritized.

Functional Load. Elements subjected to significant mechanical, thermal, or aerodynamic loads require high manufacturing precision and superior material quality. Titanium and nickel alloys, commonly used in aviation, are well-adapted for 3D printing.

Manufacturing Costs. Additive manufacturing can sometimes reduce production time and costs by minimizing material waste, reducing machining steps, and lowering tooling expenses.

Repairability and Modification. Additive technologies allow for rapid design modifications, making them particularly suitable for custom components, spare parts, or adapting designs to specific operational requirements.

Optimization of Weight, Strength, and Durability. The optimization of aerospace components manufactured via additive processes is a crucial research area, as it significantly enhances aerodynamic performance and fuel efficiency. Reducing structural mass while maintaining strength and durability is achieved through innovative materials, complex geometries, and numerical modeling methods.

One of the key techniques is the use of lattice structures, which provide high stiffness at minimal weight. For example, the design of an aerospace bracket incorporating a lattice structure resulted in a 33% mass reduction without compromising load-bearing capacity.

Example of calculation is given in [37]:

- Initial component mass: 1.5 kg;
- Optimized mass: 1.0 kg (-33%);
- Safety factor: 1.4;
- Increased lifespan due to reduced residual stresses: +20%.

Another important aspect is the optimization of printing parameters, such as laser scanning speed, layer thickness, and material deposition strategy. Adjusting the filling strategy, for instance, reduced residual stress levels by 15%, extending the component's service life [38].

Additional improvements are achieved through the use of composite materials and multilayer structures, which enhance resistance to fatigue damage and dynamic loads. As a result, components manufactured with all optimization factors considered exhibit superior reliability and withstand extreme operating conditions in the aerospace industry.

Approaches to optimization schematically are depicted in Fig. 7 [39].

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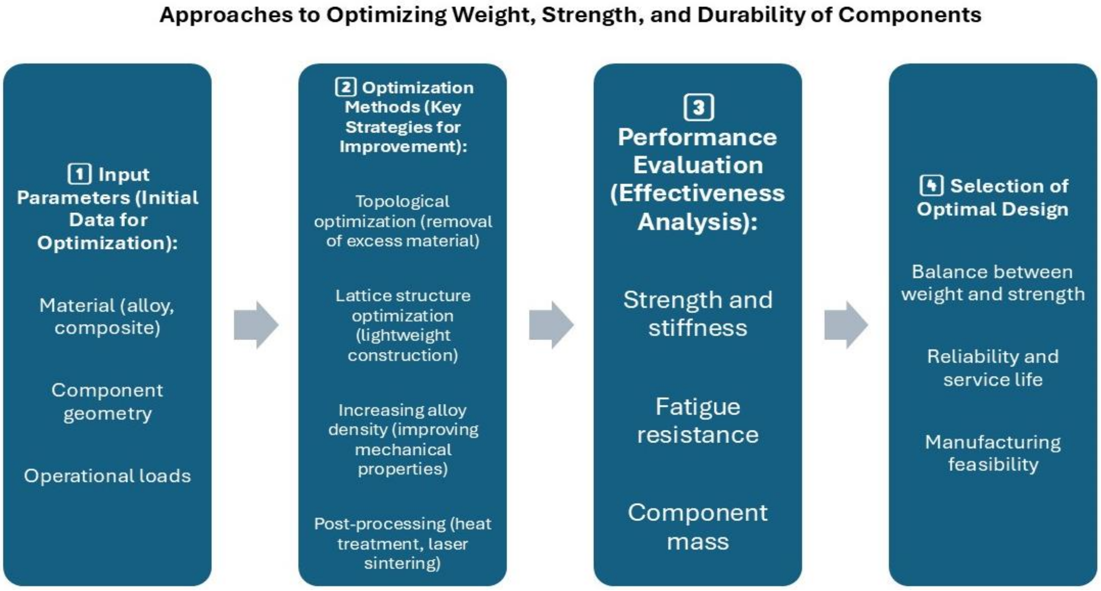

Fig. 7. Approaches to Optimizing [39]

7. Implementation of additive manufacturing in the aerospace industry

In recent years, additive manufacturing technologies have been actively integrated into the aerospace industry, as evidenced by a series of successful projects from leading global companies. 3D printing not only facilitates weight reduction and cost efficiency in component production but also accelerates the development and manufacturing processes of aerospace structures.

Notable Examples of Successful Implementation [4][37][40]:

1. GE Aviation – Fuel Nozzles for LEAP Engines:

• The application of additive manufacturing enabled the production of a single monolithic structure instead of 20 separate components, significantly enhancing reliability and simplifying assembly.

• The fuel nozzle's weight was reduced by 25%, while its mechanical performance improved.

2. Airbus – Titanium Brackets in A350 XWB Aircraft:

• The implementation of 3D printing led to a 45% reduction in bracket mass.

• The use of titanium ensured high corrosion resistance and structural integrity.

3. SLS has been successfully implemented by Boeing for the fabrication of air ducting components for both commercial and military aircraft. In particular, Boeing made these ducts using flame-retardant nylon, utilizing SLS's capacity to produce intricate and lightweight structures that are normally difficult to accomplish using traditional production techniques. By using SLS technology, Boeing was able to reduce the weight of these parts by about 30%, which greatly improved airplane performance and fuel efficiency. Furthermore, implementing SLS simplified manufacturing processes overall by improving component reliability, accelerating prototype and production cycles, and reducing assembly complexity.

4. NASA – Components for Rocket Engines:

• 3D printing enabled the fabrication of components with complex geometries that were previously unachievable using conventional manufacturing methods.

• Development and testing timelines were significantly reduced.

These examples confirm the effectiveness of additive manufacturing in aerospace engineering, allowing companies to achieve new levels of performance,

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cost-effectiveness, and structural reliability. With the continued advancement of artificial intelligence and numerical modeling techniques, further expansion of 3D printing applications in the aerospace sector is anticipated.

As additive manufacturing technologies evolve, new challenges and research directions emerge, requiring in-depth investigation. The key areas of future research include [41-43]:

• Development of Novel Materials and Alloys. Current metal powders exhibit certain limitations, such as structural inhomogeneity and susceptibility to cracking. A promising research direction involves the development of advanced composite materials with enhanced mechanical properties.

• Optimization of Topological Algorithms. Improvements in design algorithms enable the creation of lightweight components while maintaining high structural integrity. The future development of adaptive systems, incorporating real-world operational conditions into the design process, is expected.

• Enhancement of Post-Processing Techniques. Existing post-processing methods, including heat treatment and mechanical finishing, require further refinement to improve the precision and durability of printed components.

• Automation of Manufacturing Processes. The integration of digital twin technology, robotics, and predictive analytics will significantly reduce production cycles and enhance quality control.

• Implementation of Multi-Material 3D Printing. A promising direction involves the development of multi-material components, enabling the combination of diverse properties - ranging from high strength to thermal conductivity - within a single structure.

Additionally, there is an urgent need for manufacturing practices and academic research to more closely coordinate and converge. In order to enable a genuinely printability-driven design for additive manufacturing from the very beginning of component development, Omede et al.'s study [44] focuses on the integration of printability and build orientation assessments as coupled processes inside the optimization workflow. The approach is specifically used to rebuild a metallic aeronautical bracket created by Leonardo Helicopters that is now mounted on a helicopter and produced using traditional techniques. In an industrial setting, the suggested methodology shows promise for speeding up DfAM workflows, cutting down on the time between design and production, and guaranteeing the geometric and functional conformance of crucial aircraft components made with metal additive manufacturing.

Overall, the further development of additive manufacturing in the aerospace industry necessitates a comprehensive approach that includes advancements in hardware, software, materials, and quality control methodologies. The integration of innovative technologies will elevate aerospace engineering to new levels of efficiency and competitiveness.

In order to improve durability and decrease failure modes in aircraft components, additive manufacturing techniques has to be taken into consideration first. For aerospace applications, ensuring process reliability and repeatability in AM continues to be a major problem. In contrast to conventional machining, AM techniques exhibit heterogeneity in cooling rates, melt pool behavior, and layer adhesion, which can result in flaws such partial fusion, fractures, and porosity that jeopardize the integrity of the product [45]. Dimensional accuracy is further impacted by thermal warping caused by temperature gradients and residual strains, particularly in large

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aerospace components [46]. Extensive post-production testing is required due to the absence of real-time defect monitoring. Because of thermal distortion, large AM structures - like airplane frames - frequently need extra machining to achieve precise tolerances. Economic viability is also impacted by post-processing burdens, sluggish production rates, and high material costs. These obstacles are being addressed by advancements in AI-based quality control, powder recycling, and hybrid production. Future research should concentrate on materials unique to the aerospace industry, such as ceramic matrix composites (CMCs) and high-entropy alloys (HEAs), as well as enhanced process stability and real-time defect monitoring. Reliability and fatigue life will be further improved by post-processing innovations including laser peening and hot isostatic pressing (HIP). AM will be essential to creating aircraft components that are stronger, lighter, and more dependable as these advancements progress.

Maximizing the advantages of AM in aerospace requires the development of simulation and design software. Better predictions of material behavior, thermal stresses, and possible flaws are made possible by improved simulation tools, which provide more precise and effective design optimization. Additionally, topology optimization and generative design methods are being employed more and more to develop high-performance, lightweight structures that are specifically tailored to AM procedures.

Conclusions

The potential of additive manufacturing to produce intricate, lightweight, and extremely durable parts that are not feasible or financially feasible to build using conventional methods has revolutionized aircraft design. Since each technique has pros and cons, the decision to choose an additive manufacturing process is necessary for the performance enhancement.

Modern additive manufacturing technologies offer new opportunities for designing and producing aerospace components by reducing production costs, decreasing component weight, and improving operational performance. However, despite these advantages, unresolved challenges remain, including the refinement of technologies, the development of new materials, and the enhancement of printed component reliability. The future of additive manufacturing in aviation depends on continued research in numerical modeling, automation, and the implementation of intelligent quality control systems.

The conducted analysis highlights the significant potential of additive manufacturing for the aerospace industry. Key findings include:

- The application of topology optimization enables the creation of lighter and stronger structures tailored to specific operational loads.
- The integration of computational simulation, artificial intelligence, and machine learning techniques significantly enhances the precision of printing parameters, reduces the probability of defect formation, and minimizes errors throughout the manufacturing process.
- The integration of additive manufacturing in aerospace production has already proven effective, as demonstrated by successful projects from Airbus, GE Aviation, and NASA.
- A promising area for future development is the creation of new materials with improved mechanical properties and increased durability for printed components.

Current challenges include improving process reproducibility, enhancing the characteristics of powder materials, and integrating additive technologies into mass production. Addressing these issues will significantly expand the adoption of 3D printing in aerospace manufacturing.

For aircraft components, combining structural optimization and printability analysis ought to be a focus of future research. Furthermore, although we did not cover this aspect due to limitation of article scope, it should be emphasized that there is a clear need to close the gap between the cutting-edge research conducted in universities and industry and the practical production readiness of AM parts, in order to unite efforts of scholars and manufacturing companies R&D practicians and mutual exchange of knowledge.This will allow for a more comprehensive design workflow that takes into account both structural performance and additive process constraints.

As technology advances, there is a possibility of an increase in fully 3D printed major airplane components. This could comprise wing structures, fuselage portions, and even engine parts. The capacity to make these vital pieces using 3D printing would not only speed the production process, but would also provide unparalleled design flexibility.

One significant trend for the aerospace sector is the combination of AM with digital twin and digital thread technologies. Throughout the entire product lifecycle, from design and production to maintenance and decommissioning, a digital thread offers an extensive data record. Digital twins are virtual representations of real-world parts that are useful for predictive maintenance, monitoring, and simulation. In the end, these technologies increase the performance and longevity of aeronautical components by facilitating more effective design procedures, improved traceability, and enhanced maintenance methods.

In AM for aerospace, sustainability is becoming a more significant priority. The sector is looking into ways to recycle materials, cut down on energy use, and limit waste. Innovations like closed-loop metal powder recycling systems and the creation of recyclable or biodegradable materials are important research topics. Adopting more sustainable methods will improve AM's economic competitiveness in addition to lessening its environmental effect.

In conclusion, additive manufacturing is revolutionizing the aerospace sector by facilitating creative designs, enhancing productivity, and providing fresh approaches to challenging manufacturing problems. The technology's importance in aerospace is anticipated to increase as it develops further and gets beyond current obstacles, creating more sophisticated, effective, and environmentally friendly aerospace systems, which in particular should be the object of further studies.

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Методологія оптимізації параметрів та процесів виробництва металевих компонентів для аерокосмічних конструкцій за допомогою технологій адитивного виробництва

У цій статті наведено огляд сучасних підходів до оптимізації параметрів та процесів в адитивному виробництві металевих компонентів аерокосмічної галузі. Розглянуто використання технологій 3D-друку, таких як селективне лазерне плавлення (SLM) та електронно-променеве плавлення (EBM), які дозволяють створювати деталі зі складною геометрією, зменшеною масою та покращеними експлуатаційними характеристиками. Підкреслено важливість точного вибору технологічних параметрів, оскільки вони безпосередньо впливають на механічні властивості, довговічність та надійність виготовлених деталей. Особлива увага приділяється проблемам, що виникають під час адитивного виробництва, таким як пористість матеріалу, залишкові напруження, структурна неоднорідність та недостатня точність розмірів. Проаналізовано методи їх усунення, включаючи чисельне моделювання теплових процесів, оптимізацію топології конструкцій та застосування алгоритмів машинного навчання для автоматизованого вибору параметрів друку. Підкреслено важливість інтеграції комплексного підходу, що поєднує експериментальні дослідження з цифровими технологіями, оскільки це значно підвищує якість продукції. У статті основна увага приділяється майбутньому розвитку адитивних технологій в аерокосмічній галузі. Зокрема, досліджуються можливості інтеграції штучного інтелекту (ШІ) в управління процесами друку, що дозволяє не тільки автоматизувати контроль якості, але й прогнозувати потенційні дефекти на ранніх стадіях виробництва. Крім того, обговорюється розробка нових металевих сплавів, спеціально розроблених для методів 3D-друку, та стандартизація процесів сертифікації адитивних деталей, оскільки це ключові фактори для широкого впровадження цих технологій в аерокосмічному виробництві. Таким чином, у статті підсумовано останні дослідження в цій галузі, визначено ключові проблеми та окреслено потенційні рішення. Комплексний аналіз та впровадження сучасних методів оптимізації адитивного виробництва підвищить ефективність, надійність та економічну ефективність застосувань 3D-друку в аерокосмічній галузі.

***Ключові слова**:* адитивні технології, 3D-друк металом, аерокосмічні конструкції, оптимізація параметрів, оптимізація топології, штучний інтелект,

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