UKRAINIAN JOURNAL OF MECHANICAL ENGINEERING AND MATERIALS SCIENCE
Vol. 11, No. 4, 2025

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TECHNICAL AND ECONOMIC ANALYSIS OF THE ALTERNATIVE APPLICATION OF ADDITIVE, SUBTRACTIVE, AND HYBRID TECHNOLOGIES FOR THE MANUFACTURE OF COMPLEX-PROFILE MECHANICAL ENGINEERING PRODUCTS: SYSTEMATIC REVIEW

Received: December 1, 2025 / Revised: December 8, 2025 / Accepted: December 21, 2025

https://doi.org/10.23939/ujmems2025.04.083

Abstract. The article provides a comprehensive technical and economic assessment of additive, subtractive, and hybrid manufacturing technologies for producing complex-profile mechanical engineering products. The present study focuses on determining the optimal technological approach in terms of accuracy, structural integrity, material efficiency, and production cost. The analysis is based on a systematic comparison of key processes, including Powder Bed Fusion, Directed Energy Deposition, and CNC machining, which considers their capabilities for forming intricate geometries, internal channels, lattice structures, and functionally graded materials. The review synthesises industrial case studies from the aerospace, medical, and automotive sectors, demonstrating the efficacy of hybrid manufacturing, which integrates near-net-shape additive fabrication with high-precision subtractive finishing. This integration has been shown to result in a reduction of material waste by up to 70–80%, a decrease in production cycles by 30–50%, and a significant enhancement of mechanical performance through post-processing steps, such as hot isostatic pressing, heat treatment, and CNC finishing. The findings demonstrate that hybrid technologies facilitate the attainment of high-dimensional accuracy and surface quality, while preserving the design freedom characteristic of additive methods. The novelty of the research lies in the proposal of a unified decision-making framework for selecting a manufacturing strategy based on production volume, geometric complexity, material type, and economic feasibility. This approach provides a structured methodology that supports the implementation of hybrid systems in high-value, high-precision industries where traditional methods are either insufficient or economically impractical.

Keywords: additive technology, subtractive technology, hybrid manufacturing, material extrusion, powder bed fusion, material jetting, binder jetting, directed energy deposition.

Introduction

The production of complex mechanical engineering products, particularly molds and dies with curved surfaces, medical implants, or parts with intricate internal channels and cantilever structures, requires striking an optimal balance between design complexity, ensuring critical operational functions, manufacturing precision, material efficiency, and economic feasibility. To ensure the long-term operational reliability of such products, it is crucial to achieve high-quality functional surfaces under complex conditions of high thermal deformation loads. Additionally, it is necessary to consider cyclic and alternating force effects during operation and prevent the active influence of aggressive external environments.

Subtractive Manufacturing (SM) is based on conventional manufacturing methodologies that involve removing excess material from a workpiece, aiming to achieve the desired geometry, dimensions, and microgeometry of the machined surfaces of products. The aforementioned methods include milling, grinding, drilling, and turning, which are primarily executed on numerically controlled (NC) machines. These processes ensure a high level of accuracy and reproducibility of results, which is why they remain the basis of modern mechanical engineering in the manufacture of parts from metals and alloys. However, despite the significant advantages of classical mechanical processing methods, generative technologies that implement the principles of additive shaping are becoming increasingly widespread in modern production. The process involves constructing the product through the gradual addition of layers of material, as opposed to the conventional method of material removal. Additive Manufacturing (AM), particularly represented by Selective Laser Melting (SLM) and Directed Energy Deposition (DED) technologies, utilizes powder or wire additives to achieve high material efficiency, design flexibility, and the capability to manufacture complex internal product structures.

The integration of additive and subtractive processes within a unified technological framework constitutes a manifestation of hybrid manufacturing (HM). This combination allows for a synergistic effect, combining the advantages of high precision and quality of machined surfaces, characteristic of subtractive machining, with the possibilities of geometrically complex shaping and the formation of heterogeneous structures, characteristic of additive methods. The utilisation of hybrid systems is particularly pertinent in the fabrication of complex-profile components, especially within the aerospace, tooling, and medical industries, where there is an increased demand for surface quality, geometric accuracy, and the cost-effectiveness of the production process. It is evident that the concept of hybrid manufacturing is a modern one, characterized by the integration of technological processes. The combination of additive and subtractive operations is a key feature of this integrated technological environment. The benefits of this integration include optimisation of material costs, reduction of manufacturing time, and improvement of overall production efficiency.

Problem Statement

The present article is devoted to a thorough comparative analysis of the feasibility and effectiveness of utilising these technologies. This analysis is based on technical criteria, with an emphasis on ensuring the accuracy, strength, and operational quality of products, as well as the ability to implement complex geometric shapes and form specific physical and mechanical properties. It is also based on economic indicators, taking into account costs, cycle time, and production scalability. These criteria are based on current scientific research and the proposed methodology for selecting the optimal structure of the product manufacturing process.

General comparative characteristics of additive technologies for manufacturing complex-profile mechanical engineering products

Over the preceding two decades, Additive Manufacturing (AM), a process that entails the successive layer-by-layer construction of products based on three-dimensional digital models, has undergone substantial advancements. The most common principles of additive technologies are Fused Filament Fabrication (FFF) and Stereolithography (SLA). FFF technology is based on the use of thermoplastic filaments made primarily from polymers such as Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) to create three-dimensional products with specified geometric (dimensional and precision), mechanical (hardness, density, etc.), and operational (strength, specific wear, stability, etc.) parameters. The SLA method is based on the process of photopolymerization, where ultraviolet radiation solidifies the additive material from a liquid resin layer by layer, thereby forming the final product structure with predetermined geometric and physical-mechanical properties. It is evident that both of these methodologies are conventionally employed in the fabrication of products composed of polymer and composite materials [1, 2].

An alternative approach to additive manufacturing is the use of laser technologies, in particular Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) processes. These methods broaden the range of materials available, encompassing steels, titanium alloys, composites, and other materials suitable for surfacing. In accordance with ISO/ASTM 52900:2015, the classification of additive manufacturing comprises seven fundamental processes: Material Extrusion (ME, for example, FDM), Material Jetting (MJ), Binder Jetting (BJ), powder bed fusion (PBF), sheet lamination (SL or LOM), Directed Energy Deposition (DED), and Binder Jetting (BJ). The following processes are to be considered: Powder Bed Fusion (PBF), Sheet Lamination (SL or LOM), Directed Energy Deposition (DED), and Vat Photopolymerization (VP, e.g., SLA) (Fig. 1) [3-8].

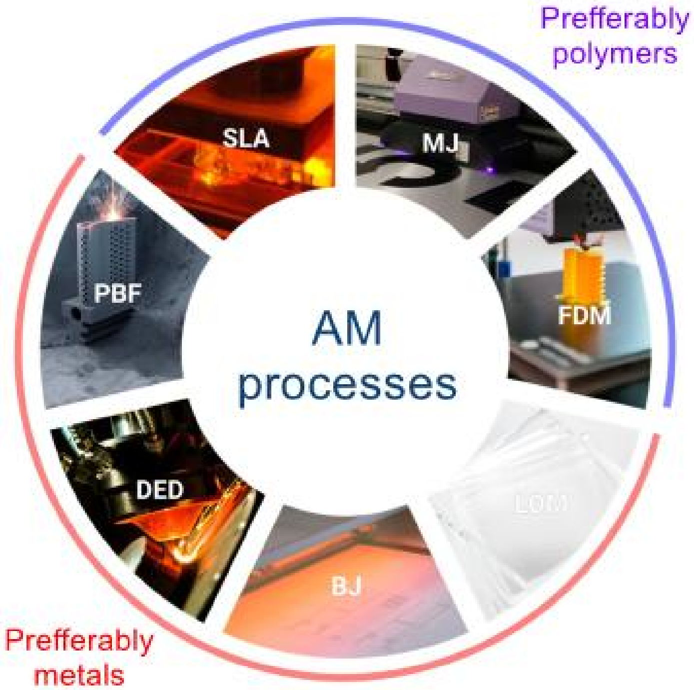

Fig. 1. Classification of additive manufacturing processes in accordance with ISO/ASTM 52900:2015. Material Extrusion (FDM and FFF), Photopolymerization (SLA and DLP), Powder Bed Fusion (PBF, SLS, DMLS, and SLM), Material Jetting (MJ), Binder Jetting (BJ), Directed Energy Deposition (DED), and Laminated Object Manufacturing (LOM) [8-12].

Among the methods of multi-layer material application used in modern additive manufacturing systems, PBF and DED technologies are the most prevalent. The PBF process encompasses Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM). SLS and SLM technologies belong to the Laser Powder Bed Fusion (LPBF) subgroup. During the implementation process of SLS technology, a three-dimensional solid or skeletal model of a product, created in Computer-Aided Design systems (such as SolidWorks and AutoCAD), is cut into successive cross-sections. The working platform is first covered with a thin layer of metal powder, after which a laser beam selectively scans and sintered (in the case of SLS) or completely melts (in the case of SLM) the powder particles of the material, according to the shape of the current layer (Table 1). Following the formation of the initial layer, a subsequent layer of powder is applied, and the process is repeated to ensure interlayer adhesion. It is evident that the thinness of the layers and the high thermal conductivity of the material result in the natural fusion of the adjacent layers, thereby ensuring the homogeneity of the three-dimensional structure. This iterative cycle is repeated until the product is fully manufactured [13-16].

Comparative features of additive manufacturing processes

Type of additive process	Principle of applying layers	Cost of realization	Materials
ME (e.g. FDM)	Extrusion of material through a heated nozzle (rapid prototyping)	+	PL A, ABS, PETG, nylon
VPP (e.g. SLA)	Photopolymerization using a UV laser (dental models)	++	Photopolymer resins
PBF	Laser melting of powder material	+++	Metals, ceramics, nylon
MJ	Drop jet photopolymerization under the action of UV radiation	+++	Photopolymers
BJ	A liquid binder that selectively forms a powder bed (metal casting models)	++	Metal powders, ceramics
DED	The laser beam melts the raw material during coating (repair of parts/bonding)	+++	Steel, titanium, Inconel
LOM	Assembling and binding sheet material	+	Paper, metal foil, sheets

Explanation of costs: + — entry-level and mid-range desktop systems and low material costs; ++ — professional and small industrial systems and moderate material costs; +++ — industrial machines and expensive materials/post-processing [9–12])

A salient feature of additive manufacturing is the capacity to generate heterogeneous (gradient) structures within a single product or separate production component. This capability enables localised alterations in mechanical, physical, or functional properties without the necessity of mechanical connections between the component materials. A paradigmatic illustration of the implementation of these properties is delineated in article [17]. The subject of the study was Directed Energy Deposition (DED) technology, which was utilised to fabricate a bimetallic femoral implant exhibiting a gradient transition from Ti-6Al-4V titanium alloy to CoCrMo cobalt-chromium alloy. Such a seamless transition fosters an integrated structure with optimised properties in different areas of the implant. The design of such a gradient orthopaedic implant involves combining high strength and wear resistance in the area of contact with the hip joint. This objective was realised through the implementation of a high-strength material based on a CoCrMo cobalt-chromium alloy coating on the implant. The biocompatibility of the product is ensured by the use of Ti-6Al-4V titanium alloy. Firstly, it has been demonstrated that this material does not cause toxic or allergic reactions in human tissues. Secondly, it has been shown that the material has a modulus of elasticity that is close enough to that of bone tissue (osseointegration). Furthermore, the seamless gradient transition between these materials serves to minimise the concentration of stresses at the joint boundary. The equipment required for executing this technological operation is illustrated in Fig. 2.

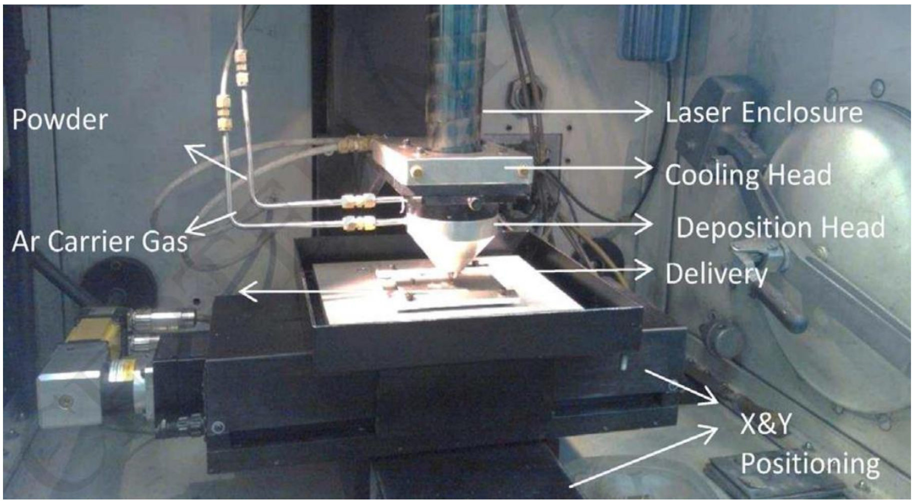

Fig. 2. Equipment for additive manufacturing of a multilayer structure of an orthopedic implant based on titanium alloy Ti-6Al-4V and cobalt-chromium alloy CoCrMo [17].

The technological implementation of the proposed model is based on the additive manufacturing method using Directed Energy Deposition (DED). The technology is predicated on the sequential application of powder materials. The primary technological apparatus comprises a DED system, accompanied by a hopper segmented into discrete divisions for the sequential or concurrent introduction of Ti-6Al-4V and CoCrMo powders. In addition, the system incorporates a laser head equipped with a coaxial nozzle, enabling localised heating and melting of these powders (Deposition Head – Fig. 2). The manufacturing process commences with the initial deposition of 100% Ti-6Al-4V in the lower part of the implant (stem). It is important to note that the modulus of elasticity of this titanium alloy is approximately 80-110 GPa, which is comparable to that of bone tissue (~10-30 GPa). This has been demonstrated to reduce the impact of stress concentration, thus improving biointegration and high functionality of the implant. At this stage, the laser beam gradually melts the powder at a feed rate of approximately 800 mm/min. The radiation power is measured to be within the range of 800–1200 W, and the thickness of the applied layer is found to be in the range of 0.5–0.7 mm. The additive processing is carried out in a protective argon atmosphere with the objective of preventing oxidation of the layered material. At the opportune moment during the processing cycle, the proportion of powder feed intensity to the sintering zone is meticulously programmed in the transition zone. The initial stage of the mixing process involves a reduction in the proportion of Ti-6Al-4V, accompanied by an increase in the proportion of CoCrMo. The process is conducted in stages, with the initial mixture consisting of 75% Ti and 25% Co. Subsequently, the ratio transitions to 50% to 50%, and finally, a gradient transition is achieved by mixing 25% Ti with 75% Co. This stage is characterised by a gradual increase in the elastic modulus from 110 to 210 GPa and an increase in the tensile strength from 950 to 1200 MPa. This transition process has been demonstrated to reduce local stress concentrations and mitigate the risk of microcracks. In the final stage of powder sintering, 100% CoCrMo is deposited on the upper part of the implant, ensuring maximum wear resistance in the area of contact with the hip joint. The process is meticulously regulated to guarantee the stability of the layer and the distinctive microstructure necessary for sustained operation. It is imperative to note that the protective argon atmosphere is sustained throughout the process, thereby minimising oxidation, as well as the potential for scaling and defects in the implant structure.

It is evident that the benefits inherent in forming heterogeneous structures within the domain of additive manufacturing encompass numerous pivotal domains. From a mechanical perspective, the transition of the elastic modulus between different materials is characterized by a smooth progression, which has the effect of reducing the concentration of peak stresses at the interface by approximately 60% compared to traditional sharp joints. This assertion is supported by finite element analysis (FEA). From a biological standpoint, the presence of a titanium layer is conducive to effective osseointegration, while the incorporation of a cobalt-chromium alloy ensures the artificial joint's exceptional wear resistance. From a manufacturing perspective, the absence of welds eliminates the cause of thermal effects on the formation of residual tensile stresses, which significantly increases the fatigue strength of the product.

Scientific research, notably the aforementioned study [17], has demonstrated that interlayer adhesion in the gradient transition zone between Ti-6Al-4V and CoCrMo attains 98% of the strength of the base material. Microscopic analysis demonstrated the occurrence of epitaxial growth of crystallites across the phase boundary, thereby ensuring the implant structure is characterised by high strength and stability. It is evident that the employment of Directed Energy Deposition (DED) technology, in conjunction with programmable powder mixing, facilitates the fabrication of functionally graded materials (FGMs) within a single production cycle. This accomplishment is wholly unattainable through conventional subtractive or casting methodologies. This approach generates a plethora of opportunities for creating customised products with local properties, tailored to the specific functional requirements of the customer or designer of a particular product.

Problem-oriented features of applying subtractive methods for shaping complex-profile products

Classic subtractive methods of shaping complex-profile products are based on the principle of sequentially removing excess material (allowances set by the technologist) from a monolithic blank to achieve the specified geometric shape, dimensions, quality of machined surfaces, and functional characteristics of the product. In contrast to this method, additive technologies implement the opposite task: the synthesis of a production object by layering material in a step-by-step process. These fundamental differences determine the distinct technological capabilities and areas of rational application for these conceptual technologies.

The subtractive method has been demonstrated to possess several objective advantages over additive manufacturing, particularly in the production of high-precision, complex-profile products. Firstly, it should be noted that subtractive manufacturing products exhibit a superior degree of dimensional and geometric accuracy, in addition to a surface layer of machined surfaces that is of a higher quality. This quality is such that the need for post-operational finishing is minimised, if not entirely eliminated. Secondly, such technologies are distinguished by enhanced mechanical strength and structural isotropy of manufactured products, a consequence of employing a solid blank devoid of interfaces between layered surfaces, which is characteristic of additive synthesis. Thirdly, it is worth noting that the use of mechanical processing in serial and mass production is effective due to the high productivity and stability of these technological processes. Furthermore, the materials employed in subtractive manufacturing are diverse, encompassing a wide range of heterogeneous materials in a solid initial state, including metals, polymers, ceramics, and composite materials. It is evident that the majority of these materials are not conducive to additive processing methods. It is also imperative to optimise the adaptation to the manufacture of parts with strict requirements for tolerances, surface roughness, and operational mechanical properties. Achieving this with generative manufacturing methods for complex-profile products is a significant challenge.

Nevertheless, it is evident that subtractive methodologies are accompanied by several disadvantages when compared to additive technologies in the fabrication of topologically intricate structures, prototypes, or products with internal cavities and lattice structures. However, these advantages of additive methods are partially offset by the necessity for additional post-processing steps (mechanical, thermal, or chemical) to achieve the strength, dimensional accuracy, and surface quality specified by the designer.

The level of accuracy of subtractive methods significantly exceeds the capabilities of most additive technologies. To illustrate this point, consider the example of contemporary CNC machining systems, particularly milling and turning centres. These systems are capable of achieving linear tolerances within the range of 0.001–0.01 millimetres, contingent upon the rigidity of the system, the tooling employed, the machining strategy, and the vibration control mechanisms. This process enables the fabrication of surfaces with a roughness of Ra 0.002–0.008 μm, eliminating the need for additional superfinishing.

It is evident that, due to the discrete nature of layered forming, additive methods are typically characterised by significantly greater deviations than those that can be achieved by subtractive processing. The most accurate of these methods is stereolithography (SLA), which provides tolerances of 0.01–0.05 mm. However, even this figure is significantly inferior to subtractive technologies, especially when processing metal products with complex geometries. It is evident that alternative additive processes (e.g., FDM, SLS, DMLS) generally exhibit tolerances ranging from 0.05 to 0.2 mm and beyond, thereby necessitating additional machining operations for post-processing.

Consequently, in the fabrication of complex-profile products with stringent requirements for dimensional accuracy, tolerances, surface quality, and mechanical strength, conventional subtractive methodologies remain the more technologically and economically rational alternative. The purpose of these measures is to ensure the integrity of the machined parts' material, minimize the anisotropy of properties, and guarantee compliance with high product quality standards. Conversely, additive technologies are optimally employed during the prototyping stages or in the fabrication of products characterised by intricate internal architectures, where the emphasis is on topological freedom rather than extreme precision. Additionally, these technologies find application when deviations in the tolerances of machined surfaces can be compensated for by subsequent hybrid machining processes, which entail the integration of additive synthesis with subtractive finishing. In other words, the rational choice of a forming method should be based on a systematic analysis of the technical task, taking into account priorities in terms of accuracy, strength, serial production, and economic efficiency.

Analysis of the application of hybrid methods for forming complex-profile mechanical engineering products

The integration of additive manufacturing technologies, specifically Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS), with subsequent machining on numerically controlled machines, has been shown to be a highly efficient method for producing complex-profile products. This is particularly relevant for the high-tech sectors of the machine-building industry, where the ability to create products with intricate geometry and high precision is paramount. Typically, objects of such production have complex curved configurations, asymmetrical internal cavities, thin-walled elements, or complex lattice structures. A paradigmatic illustration of the efficacious implementation of hybrid technologies in single-unit or small-batch production is evident in the fabrication of turbine blades, medical implants, and complex-profile components employed in aerospace technology. A significant rationale for the viability of additive manufacturing in these scenarios is the inherent technical limitations and economic inefficiencies of conventional subtractive methods. The complexity inherent in machining geometric profiles often renders them technically challenging and economically inefficient. Conversely, additive manufacturing techniques are unable to achieve the high precision and dimensional tolerances specified by the designer, as well as the stringent requirements for the surface quality of functional surfaces.

Numerous examples of hybrid technologies being used in practice are available. For instance, within the aerospace industry, GE Aviation has successfully implemented selective laser melting (SLM) for the additive manufacturing of fuel injector blocks for the LEAP family of engines, followed by the finishing of individual functional surfaces on CNC machines. This hybrid approach has resulted in a more compact design, reducing the number of different parts in the assembly from 18 to one. This has resulted in a 25% decrease in the overall weight of the fuel injector block and a 15% reduction in fuel consumption [18].

Another illustration of the efficacy of hybrid methodologies in the realm of manufacturing complex-profile machine-building products in the automotive industry is exemplified by the technology implemented by Bugatti for the production of brake calipers for the Chiron model. The components in question are composed of a Ti6Al4V titanium alloy. The intricate processing of these products entails the amalgamation of direct metal laser sintering (DMLS) with milling operations performed on CNC machines. Consequently, the weight of the product has been reduced by 40% compared to traditional casting methods. Concurrently, the brake calipers have undergone a 20% increase in strength, as stated in a press release from Bugatti [19]. The technology in question utilises a 3D printer equipped with four lasers, each with a power output of 400 watts. The fabrication process involves the gradual application of Ti6Al4V titanium alloy powder in successive layers. The total number of layers is 2,213. The fabrication process involves the sequential sintering of each layer using a laser beam, enabling the production of complex product geometries with wall thicknesses ranging from 1 to 4 mm. This stage of the additive process is scheduled to take approximately 45 hours. The resulting parts are characterized by high tensile strength, reaching 1250 N/mm^2, which is critical for the brake caliper's functionality. Subsequent to the completion of the additive stage, the subtractive processing stage is initiated. The technology encompasses an initial heat treatment of the component to eliminate residual thermal stresses and enhance the mechanical properties (i.e. homogenisation) of the material. It also involves the removal of support elements utilised during the additive operation as auxiliary components. The subsequent stage in the process involves the final grinding of some surfaces to improve their microgeometry (roughness) and increase their dimensional accuracy. The machining of critical functional surfaces, including contact planes for pistons and threaded connections, is performed on a five-axis CNC milling machine. This subtractive operation provides the product with its definitive geometric shape, a process that demands a high degree of precision and takes approximately 11 hours. It is evident that the hybrid technology for fabricating brake calipers under discussion combines the advantages of additive manufacturing, thereby creating a complex and durable design with high precision of functional surfaces. This is achieved by machining on CNC machines.

The analysis of the provided examples indicates that a hybrid approach to production is most appropriate in cases where this method of processing complex-profile products combines the advantages of both technologies. Additive manufacturing is a process that facilitates the creation of a so-called "near-net-shape" design, characterized by its proximity to the final shape of the product. This approach offers a high degree of freedom in terms of design ideas and the integration of complex product elements. Conversely, CNC processing methods facilitate high-dimensional accuracy, ensure high-quality surface finishing, and provide the necessary mechanical characteristics that will affect the functionality of the products. The integration of these technologies has been shown to enhance the efficiency of production processes, reduce material costs, reduce overall manufacturing time, and minimise production waste, a particularly salient benefit in contexts involving small-batch production (typically from 1 to 100 units) or the creation of prototypes.

A more detailed discussion of the advantages of the hybrid approach compared to separate additive or subtractive methods of processing complex-profile products is required, including a separate analysis of the technical and economic criteria for assessing the feasibility of their implementation

1. The capacity for producing intricate geometric forms in additive manufacturing enables the conception of designs that are wholly unattainable or economically unfeasible through the use of exclusively subtractive methodologies. This is attributable to the increased complexity of mechanical processing or the use of highly sophisticated profile cutting instruments. A notable illustration of this phenomenon is the development of internal cooling channels in machine-building products, such as engines and turbine blades, which can result in a weight reduction of 20–30% and a substantial enhancement in operational efficiency. Despite the relatively high initial surface roughness provided by additive technologies (the average Ra value is about 8–10 µm), further finishing on CNC machines allows for a significant improvement in surface parameters, achieving a roughness of less than 0.5 µm and ensuring dimensional accuracy at the level of ±0.01 mm [20]. The following technical example demonstrates the application of this technology in the small-batch production of a specially designed turbine blade [21]. It demonstrates that the selective laser melting (SLM) method is capable of forming internal cooling channels with diameters of 0.5–1 mm in 18 hours. The subsequent stage of CNC finishing involves removing a layer 0.8 mm thick, with the objective of achieving a roughness of Ra 0.2 µm. This is achieved through a combination of grinding and polishing techniques. Consequently, the thermal efficiency of the blade is enhanced by 35% compared to conventional casting methods, while ensuring installation accuracy within a tolerance of ±0.015 mm.

2. The rational utilisation of materials in the additive manufacturing process is attributable to the direct use of powder material to form a specific product configuration, thereby significantly reducing the amount of production waste (to 5–10%). Concurrently, in the context of conventional subtractive machining of substantial workpieces, material losses have been documented to range from 50 to 90%. Furthermore, the CNC finishing process, typically involving the removal of a margin ranging from 0.5 to 2 millimetres, enables the preservation of the majority of the initial material, thereby markedly enhancing the efficiency of resource utilisation within the production process [22].

3. The economic rationale for hybrid innovation is based on a comprehensive assessment of the cost of raw materials (powder or filler material for AM or HM technologies), technological, energy, and overhead costs, as well as the duration of the manufacturing process. It is evident that the manufacturing cost of a hypothetical component made from the Ti6Al4V alloy is contingent on the cost of the powder material, which is estimated to range between \$ 110 and \$ 130 per kilogram. In contrast, the traditional production method, which is exclusively reliant on mechanical processing using a computer numerical control (CNC) machine, results in a casting blank cost of \$ 80 to \$ 100 per kilogram. In the event of fabricating a hollow complex-profile part with curved surfaces weighing, for example, 1 kg, the utilisation of a hybrid method incorporating near-net shape additive manufacturing would necessitate only 1.1 kg of Ti6Al4V alloy powder. Conversely, the weight of the blank for the same component when machined on a CNC machine would be approximately 5 kilograms. Consequently, material losses amount to 80%,

resulting in substantial economic expenditures: the total cost of raw materials is estimated at approximately $600. Conversely, the utilisation of selective laser melting (SLM) technology in conjunction with CNC finishing results in a substantial reduction in the material intensity of the process. Consequently, material consumption is reduced to 1.1 kg, the level of technological waste is reduced to 9%, and the material cost is approximately $ 132. It is evident that the integration of hybrid technology in the fabrication of Ti6Al4V titanium alloy components engenders substantial savings in material resources, amounting to USD 468, which constitutes 78% of the cost of raw materials when employing the conventional method. This approach has been demonstrated to reduce production costs while concurrently enhancing the environmental efficiency of the process by recycling waste materials, a key component in the sustainable production of high-tech components.

4. No less important is the comparison of the productivity of hybrid production technologies. In the literature devoted to modern technologies for manufacturing complex-profile products, numerous studies systematically compare production times using traditional machining methods with computer numerical control (CNC) and hybrid approaches that combine additive manufacturing (AM) with subsequent finishing on CNC machines. Such comparisons typically focus on process efficiency as a function of product manufacturing productivity. To illustrate this point, consider the conventional process of manufacturing turbine blades using CNC machinery. This method entails the multi-pass machining of a solid block of stock. The process is distinguished by its protracted nature, necessitating multiple multi-pass milling, turning, and grinding operations, as well as numerous retooling operations for equipment. According to GE Aviation, the complete manufacturing cycle for a single blade from a solid titanium alloy blank in small-batch production (with a batch size of 10-100 pieces) can take approximately one week. Concurrently, the majority of the material (up to 80–90%) is removed in the form of chips, thereby significantly increasing production costs and manufacturing expenses [23]. Conversely, hybrid manufacturing technologies have the capacity to markedly reduce the utilisation rate of the workpiece material to be machined, thereby diminishing the number of technological steps. A study published in [24] demonstrates that the use of hybrid systems comprising complex-profile parts for the fabrication of aerospace components (SLM+CNC), particularly turbine blades, results in a reduction of the total production time by approximately 30% compared to the conventional subtractive machining method on CNC machines. It is evident that a hybrid approach, integrating direct energy deposition (DED) with traditional blade machining, can yield a substantial enhancement in the productivity of manufacturing such parts, with a potential increase of up to 50%. This enhancement is particularly pronounced in the machining of surfaces that exhibit critical loading and complex profiles. This effect is achieved by integrating additive build-up and subtractive machining processes within a single work area, thereby eliminating the need to transport the part between different machines and reducing machine setup time [25].

5. Furthermore, hybrid technologies have been demonstrated to exhibit significant advancements in the physical, mechanical, and structural characteristics of complex profiles when compared to parts manufactured using additive methods alone. Additive manufacturing, particularly selective laser melting (SLM) or direct energy deposition (DED) technologies, is frequently accompanied by the formation of micropores. This is due to local gas inclusions, incomplete powder melting, or thermal stresses. The typical porosity of additively manufactured components made of heat-resistant nickel alloys, such as Inconel 718, ranges from 0.5 to 1% [26]. This level of porosity is a critical factor that has a detrimental effect on the cyclic fatigue and durability of turbine engine blades. To address this issue, a hybrid approach involving multiple processing stages is employed. Initially, hot isostatic pressing (HIP) is carried out under elevated pressure (100–200 MPa) and elevated temperature (1100–1200°C), a process which allows internal pores to be virtually eliminated. Secondly, the process of CNC machining has been shown to contribute to the elimination of surface defects, including instances of incomplete melting and elevated surface roughness. Thirdly, controlled heat treatment has been demonstrated to promote microstructure homogenisation and the removal of residual stresses in the material. Consequently, porosity is reduced to 0.1%, which meets or

exceeds aviation standards (AMS 5663, ASTM F3055). This results in an enhancement of fatigue strength ranging from 25% to 40% compared to AM technology for the manufacturing of products without finishing [28].

6. The result of hybrid post-processing is a significant improvement in the microstructural and mechanical properties of high-alloy alloys (e.g., Inconel 718) manufactured by selective laser melting (SLM). In their as-built state, additively manufactured products are characterised by an anisotropic microstructure formed by columnar grains, segregation of alloying elements, and the presence of residual stresses. Such structural features result in a yield strength (σ0.2) of approximately 180 MPa, which is consistent with the material's characteristics following the SLM process [29]. The employment of hybrid post-processing, which integrates multiple technological phases, has been shown to result in a substantial enhancement of the alloy's mechanical properties. The treatment complex includes solution heat treatment at temperatures ranging from 980 to 1080 °C, with the objective of dissolving the δ-phase and intermetallic Laves phases. It also comprises a double aging operation (720 °C for 8 hours and 620 °C for the subsequent 8 hours), which ensures the controlled precipitation of the strengthening γ' and γ'' phases of the Ni□(Ti, Al) and Ni□Nb type. Finally, CNC machining of critical areas is employed to eliminate stress concentrators. Consequently, the yield strength increased to 215 MPa, representing a 19% enhancement compared to the initial state. The achieved indicators correspond to the level of properties of forged analogues and provide the necessary safety margin during operation at elevated temperatures (up to 650–750 °C) [23]. Furthermore, hybrid processing has been shown to enhance the plastic properties of the material. In their initial state, additively manufactured samples demonstrate low relative deformation (A = 5–7%) due to the presence of microcracks at the boundaries of the molten tracks, high dislocation density, and anisotropy of properties in the direction of growth. However, after complex processing, this indicator is observed to double and reach approximately 12%, which corresponds to a 100% increase [30]. This enhancement in plasticity can be attributed to three primary factors: firstly, the recrystallization of the structure during the process of hot isostatic pressing (HIP) and subsequent heat treatment, which results in the formation of an equiaxed fine-grained microstructure; secondly, the elimination of surface defects arising from blade machining on a CNC machine, which contributes to the phenomenon of "healing" of cracks; and thirdly, the optimisation of the microstructural balance between phases, ensuring a rational ratio of strength and plasticity. The collective impact of these effects substantiates the efficacy of the hybrid approach in finishing additively manufactured components made of Inconel 718. The employment of such manufacturing technologies facilitates the alignment of product properties with those of traditionally processed materials, thereby ensuring reliable operation under conditions of high-temperature loads. These enhancements have been substantiated by rigorous qualification tests conducted by leading high-tech companies, including GE Aviation, Siemens Energy, and NASA, thereby establishing a robust foundation for certifying components manufactured using hybrid technologies in aviation and rocket and space engines (e.g., LEAP, GE9X, etc.) [31].

However, it should be noted that there are significant limitations to the effectiveness of implementing hybrid technologies for producing complex-profile parts that integrate additive (layer-by-layer) material build-up with subtractive machining within a single system (e.g., DMG MORI Lasertec 65 3D). The rational application of these technologies is clearly defined. The implementation of hybrid technologies is economically justified only if a set of criteria related to serial production, geometric complexity, processed material, product added value, and production organization capital costs is systematically considered. Below is a systematic analysis of these criteria in comparative form.

1. The most significant limitation on the use of HM technologies is serial production. Hybrid systems demonstrate economic efficiency only in small and medium-scale production (with a production program of 1 to 100 units per year) [32]. It is in this segment of serial production that traditional machining methods on CNC machines require significant costs for the design and manufacture of special equipment (such as conductors, measuring templates, and fixtures), as well as the reorganization of logistics chains, reprogramming of basic technological equipment, debugging, and other related expenses. The total cost of

this work significantly increases the production cost and complicates the implementation of organizational and operational planning measures related to multi-product production. On the other hand, in the context of large-scale and mass production (over 1,000 units), specialized technological operations for manufacturing products (die casting, stamping, multi-spindle machining) are more appropriate. At the same time, capital investments in equipment and basic technological infrastructure are quickly amortized due to a large production program, resulting in a reduction in specific costs per unit of output [33].

2. The technological advantage of the hybrid method is only realised in the manufacture of parts with a high degree of geometric complexity, in particular, low-rigidity products or those containing internal long cavities, lattice structures, curved shapes (especially internal ones that are difficult to access with mechanical tools), or topologically complex structures [34]. The manufacture of these elements is either impossible or economically unfeasible using traditional subtractive methods. Conversely, for elementary geometric products derived from prisms, shafts, flanges, and plates, the implementation of hybrid machining is not warranted, as conventional turning and milling operations have been demonstrated to yield superior productivity and reduced costs [9].

3. Hybrid technologies are only effective when working with high-cost and difficult-to-machine alloys, such as Ti6Al4V titanium alloy, heat-resistant nickel alloys such as Inconel, and powdered aluminum compositions (AlSi10Mg) [34]. Since complex-profile products are characterized by a high waste coefficient during traditional mechanical processing (the "buy-to-fly ratio" can reach 10:1 or higher), difficult machinability, and a tendency to form surface defects during cutting, machining allowances are very small (0.1-0.25 mm). Therefore, the critically high cost of products manufactured by subtractive methods is obvious. A hybrid approach minimizes material loss and reduces processing time [33]. On the other hand, the use of hybrid systems for high-tech structural materials, such as carbon steel (e.g., steel 45) or aluminum alloy 6061, is economically unjustified due to the low cost of blanks, ease of machining, and the absence of significant technological limitations [32].

4. The economic viability of hybrid production is contingent upon the extent of added value in the total cost structure of the processed product [9]. It is evident that technological innovations are most profitable when manufacturing products with a value exceeding $5,000, a phenomenon that is exclusively observed in high-tech industries. These industries include aerospace (impellers, turbine blades, nozzle housings), medical (individual implants, surgical instruments), and energy (gas turbine components) [34]. For products with a price tag of less than US$500, the utilisation of hybrid technology does not result in a return on investment, as it falls within the category of mass production, characterised by low profit margins. The approximate cost of the main technological equipment required for implementing the hybrid technological process in the manufacture of complex-profile products ranges from $650,000 to $1,200,000 [35]. Achieving a payback period of 2–3 years is only possible with high-intensity equipment operation, which requires: an annual production program of at least 50 units; an average unit cost of over $3,000; and a 40–60% reduction in material consumption and processing time compared to traditional machining operations for such products [32].

Outside the above limitations (in terms of mass production, simple geometric shapes of products, use of traditional materials, or low profit margins), the capital costs of implementing hybrid technology are not offset by the economic benefits achieved, and the level of productivity is lower than that provided by specialized CNC metal-cutting equipment. Thus, the final decision on implementing hybrid technology should be based on a comprehensive technical and economic analysis of innovations, along with a justification that considers all the above criteria.

Conclusions

1. The article proposes a unified approach to selecting the optimal technology for manufacturing complex-profile parts based on a comprehensive analysis of technical, economic, and technological criteria. The criteria for choosing between additive, subtractive, and hybrid technologies have been systematised, taking into account production volume, geometric complexity, material type, and economic

feasibility. This approach facilitates the selection of a technologically sound strategy for specific production tasks, a matter of particular significance in high-tech industries where conventional methods are inadequate in terms of accuracy, efficiency, and cost-effectiveness.

2. The integration of additive shaping technologies, such as SLM and DED, with high-precision subtractive machining on multi-operation CNC machines, is a key feature of hybrid manufacturing. This integration offers significant advantages over the separate application of these methods. The implementation of hybrid systems has been shown to result in substantial reductions in material costs, with estimates suggesting a decrease of up to 70-80% compared to conventional technologies. This is particularly significant in the context of high-cost alloys, such as titanium and nickel alloys. Moreover, hybrid approaches have been demonstrated to reduce production cycles by 30–50%, thereby increasing productivity and accelerating product launch.

3. The introduction of hybrid technologies ensures high precision and quality of surface treatment, which meets modern requirements for the dimensions, roughness, and mechanical properties of products. They also open up opportunities for the manufacture of complex internal structures, cavities, grids, and gradient materials that cannot be achieved using traditional methods. Practical examples of the application of hybrid systems in the aviation, automotive, and medical industries demonstrate the ability of these technologies to produce lightweight, durable, and functionally advanced parts, which stimulates innovation in design and manufacturing. At the same time, the effectiveness of hybrid production is limited by certain economic and technological factors. Their use is most feasible in small and medium series (1–100 units per year), where investments in special equipment for traditional methods become unacceptable. For mass production (more than 1,000 units per year), specialized technologies such as casting, stamping, or multi-spindle machining remain more cost-effective. In addition, hybrid systems are only justified for the production of parts with complex geometries, internal cavities, grids, and high-cost materials; for simple components, traditional methods remain more productive and economical. The high cost of equipment (approximately $650,000–$ 1.2 million) also limits its widespread use in low-margin market segments. Thus, hybrid manufacturing is a promising direction for creating innovative products in niche and high-tech sectors of industry, but its implementation requires a sound economic and technological analysis.

4. The future development of hybrid technologies is closely linked to the increased integration of additive and subtractive processes on a single platform, the automation of process cycle management, the expansion of the range of materials, and increased processing accuracy. To ensure the effective implementation of hybrid systems, it is advisable to develop specialized CAD/CAM systems for automating production preparation and to introduce methods for modeling and optimizing technological processes. This will minimise material losses and increase productivity. The implementation of hybrid technologies in mechanical engineering can yield novel opportunities for innovation; however, their successful integration necessitates a comprehensive approach. This approach must encompass all technical and economic dimensions, as well as strategic investment planning. The findings of this study support the notion that hybrid systems are a pivotal instrument in resolving complex problems within high-tech industries. These systems combine the advantages of additive manufacturing — namely, the freedom of form and material efficiency — with the benefits of subtractive methodologies, most notably the attainment of high precision, the improvement of surface quality, and the enhancement of structural robustness. To facilitate the advancement of hybrid technologies, it is imperative to continue research endeavors in the domains of materials science, technological process optimization, and the integration of such systems into digital production environments. This will contribute to increasing the competitiveness of Ukrainian enterprises in the international market and the development of innovative areas in mechanical engineering.

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