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Textbook

Digital Manufacturing in 3D Printing: Aerospace Applications



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Digital Manufacturing in 3D Printing: Aerospace Applications

Edited by Selim Gürgen
Mehmet Alper Sofuoğlu
Fábio A. O. Fernandes
Virginija Leonavičiūtė



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Editors

Selim Gürgen, Mehmet Alper Sofuoğlu, Fábio A. O. Fernandes and Virginija Leonavičiūtė

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Preface

This textbook has been developed within the framework of a European Union-funded project under the Erasmus+ Programme KA220-HED: Cooperation Partnerships in Higher Education. The project, entitled DIGI3D: Digital Manufacturing in 3D Printing for Eco-Friendly and Sustainable Aerospace Applications (Project No. 2024-1-TR01-KA220-HED-000245462), is carried out by a consortium of four partners: Eskişehir Osmangazi University (Türkiye), the University of Aveiro (Portugal), Vilnius Gediminas Technical University (Lithuania), and TUSAŞ Engine Industries Inc. (Türkiye).

As digitalization continues to transform a wide range of industries, the aerospace sector has also greatly benefited from these technological advancements. As a cutting-edge manufacturing technology, 3D printing is designed and operated within a digital environment, providing advanced solutions for aerospace applications. To keep pace with these rapid developments in higher education, the DIGI3D project aims to enhance understanding of digital manufacturing technologies and their applications in the aerospace industry.

This textbook provides comprehensive knowledge of 3D printing technologies enhanced by digital manufacturing approaches for aerospace applications. Chapter 1 introduces the fundamentals of digital manufacturing and 3D printing technologies. Chapter 2 focuses on aerospace materials used in additive manufacturing. Chapter 3 discusses the application of 3D printing processes in the production and maintenance of aerospace components. Finally, Chapter 4 presents case studies that demonstrate the practical implementation of digital manufacturing and 3D printing technologies in aerospace applications.

Editors

Selim Gürgen

Mehmet Alper Sofuoğlu

Fábio A. O. Fernandes

Virginija Leonavičiūtė

CHAPTER 1

Digital Manufacturing and 3D Printing

Gabriel F. Serra^{1,2}, Sara P. Magalhães da Silva^{3,4,5}, Afonso J.C. Silva^{1,2}, Amirhossein Gandomirouzbahani^{1,2}, Carlos G.S. Cardoso^{1,2}, Guilherme J. Antunes e Sousa^{1,2}, Victor Neto^{1,2}, Ricardo J. Alves de Sousa^{1,2}, José Martinho Oliveira^{3,4,5}, Fábio A.O. Fernandes^{1,2,*}

¹TEMA - Centre for Mechanical Technology and Automation, Department of Mechanical Engineering, University of Aveiro, 3810-193 Aveiro, Portugal

²LASI - Intelligent Systems Associate Laboratory, Guimarães, Portugal

³EMaRT Group—Emerging: Materials, Research, Technology, University of Aveiro, Aveiro, Portugal

⁴School of Design, Management and Production Technologies Northern Aveiro (ESAN), University of Aveiro, Aveiro, Portugal

⁵Aveiro Institute of Materials (CICECO), University of Aveiro, Aveiro, Portugal

*Corresponding author: fabiofernandes@ua.pt

1.1. Introduction

Additive manufacturing has emerged as a major enabler for the aerospace sector, opening up new options for lightweight design, part consolidation, and more efficient material and resource utilization. Such abilities are especially important in a sector with stringent performance requirements, high safety standards, and growing pressure to reduce environmental impact. As aerospace components become geometrically more complex and functionally integrated, additive manufacturing's viability increasingly depends not only on printing technologies but also on digital manufacturing frameworks that enable their reliable and sustainable development. In this context, digital workflows play a critical role in ensuring quality, repeatability, and compliance with certification requirements throughout the manufacturing lifecycle.

In this context, this chapter focuses on the digital ecosystem that enables the effective implementation of additive manufacturing technologies in aerospace industrial environments rather than the technologies themselves. This ecosystem includes integrated computer-aided design (CAD), computer-aided engineering (CAE), and Computer-Aided Manufacturing (CAM) tools, physics-based modelling and simulation, design approaches tailored to additive manufacturing, and their integration with larger digital production systems (DPS). From this

standpoint, additive manufacturing is viewed as a digitally driven workflow in which design, analysis, manufacturing, and validation stages are all interconnected. This approach is critical for addressing the complexity, qualification requirements, and sustainability goals that characterize aerospace manufacturing.

This chapter provides a structured overview of the digital foundations that enable additive manufacturing in aerospace applications, from design conception to production integration. It first discusses the many types of digital tools used in additive manufacturing, emphasising their importance in geometry generation, analysis, and process planning. It then addresses the modelling, simulation, and digital preparation steps required for reliable and predictable manufacturing outcomes. The chapter then examines digital design approaches for additive manufacturing, focusing on strategies that leverage process-specific freedoms and constraints. Finally, the integration of additive manufacturing into broader DPS is examined, highlighting its role in modern paradigms such as digital twins (DT) and smart manufacturing.

This chapter adopts a structured digital manufacturing perspective, treating design, simulation, and production as an interconnected workflow. To avoid fragmentation, it is organised progressively, from digital design tools to validation and production integration, addressing the reliability, certification, and sustainability requirements of aerospace applications.

1.2. Digital Tools for Additive Manufacturing

Digital tools for additive manufacturing (AM) have become indispensable in harnessing the transformative potential of AM technologies, which have revolutionised parts design and production [1,2]. AM enables the creation of highly complex geometries that are often impossible to produce with traditional manufacturing methods [3]. This design freedom enables innovative solutions such as integrating kinematics, multi-material parts, reducing component numbers through part consolidation, and increasing mass customisation [2]. The value of AM products is increasingly seen in their design rather than just the physical item [2].

To fully leverage AM's capabilities and address its inherent limitations, the concept of Design for Additive Manufacturing (DfAM) has emerged. DfAM involves considering specific design prescriptions and standards to mitigate process limitations and enhance the functional performance of fabricated parts [1]. While AM offers significant advantages, it also presents challenges, including geometric characteristics such as tolerances in wall thicknesses, holes, rounding, cantilevers, and angles, as well as the anisotropy of mechanical properties in printed parts [1,4,5]. Other crucial factors relate to process execution, such as part orientation, support structure definition, deposition rates, surface finishes, and production times [6]. In metal AM, supports are particularly crucial, serving as heat-transfer structures to prevent excessive distortion and residual stresses [5]. Furthermore, the high cost of materials and 3D printers, along with the need for post-processing, are significant limitations [6].

In this context, digital tools, encompassing Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) software, play a critical role in optimizing designs for manufacture and supporting designers throughout the product development process. These tools, which continuously appear and evolve, allow designers to manage the complexity of AM and address its specific constraints [1,7]. Traditional CAD software, such as SolidWorks, Inventor, Catia, and NX, is often complemented by advanced surface design tools, such as Rhino, Alias, and 3D Studio, which facilitate the creation of organic and complex shapes using NURBS or editable polygonal meshes, without the traditional manufacturing limitations [1]. While many of these are updated versions of existing tools rather than AM-specific developments, there is a recognized need to improve interactive practices between users and tools within the design workflow [6]. DfAM workflows involve several stages and are challenging, requiring CAD, CAE, and CAM knowledge at different abstraction levels, underscoring the crucial role of holistic guided-design frameworks [5].

The effective integration of these tools into a coherent, interactive design workflow is crucial to fully exploit AM's potential. An integrated approach enables early consideration of AM-specific engineering requirements and technological constraints, reducing time-consuming iterative redesigns and costly physical prototypes [2,5]. While a fully automated workflow with self-parametric design interpretation, integrating AM simulation, cost evaluation, and support structures, has not yet been achieved, platforms like 3DEXperience and Ansys are integrating geometry preparation, topology optimisation, Finite Element Method (FEM) validation, additive preparation, and AM process simulation into single interfaces to facilitate data interchange [5]. This chapter aims to provide an overview of the digital tools available for AM, introducing their functionalities, applications, and their roles in creating designs that capitalize on the unique advantages of this advanced manufacturing technology.

While these tools define the design and preparation stages, their integration into predictive workflows is addressed in Section 3. Section 2 introduces the main topics of this chapter, which are further detailed in subsequent sections.

1.2.1. Design Tools

For the development of parts to be manufactured by AM, CAD tools are the starting point for generating three-dimensional models. AM's design freedom, enabled by layer-by-layer fabrication, allows a wide range of geometries, creating objects with organic shapes and high geometric complexity without significantly increasing manufacturing costs. However, this freedom is constrained by process-specific manufacturability requirements.

- **Traditional CAD Software:** Programs such as Catia, SolidWorks (Dassault Systèmes), Inventor (Autodesk), and NX (Siemens) are commonly used for solid and surface parametric modelling. While originally not AM-specific, recent versions incorporate features that support the creation of complex geometries.
- **Advanced Surface Design Tools:** To fully leverage AM's capabilities for organic and free-form shapes, tools such as Rhino (Robert McNeel & Associates), Alias, and 3ds

Max (Autodesk) are also widely employed. These tools typically rely on NURBS or editable polygonal meshes, providing greater design flexibility.

The design stage involves creating a conceptual representation of the object, followed by its digital concretisation. For AM, this means considering specific engineering requirements and technological constraints early in the workflow.

1.2.2. Topology Optimisation

Topology Optimisation (TO) is a computational design methodology that allows engineers to find an optimal material layout within a pre-defined design space, subject to specific boundary conditions, loads, and performance requirements (**Figure 1.1**) [5,8]. Unlike shape or size optimisation, TO does not require a predefined initial structural topology [3]. Its primary objectives often include minimising mass or maximising rigidity [9,10], and solutions derived from TO serve as conceptual reference shapes for part designs [1].

TO has experienced rapid growth since the early 1990s, evolving from a primarily academic concept to widespread industrial adoption, and is frequently used for redesigning existing products [10]. The advent of AM technologies has enabled the physical production of the complex, organic shapes generated by TO algorithms [5].

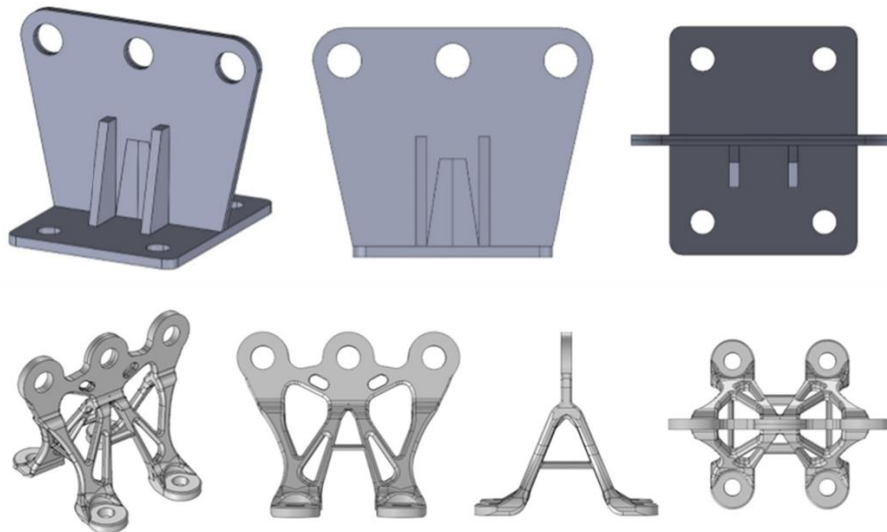


Figure 1.1. An aerospace bracket part going through topology optimisation: on the top, the original part; on the bottom, the optimised version [11].

1.2.2.1. Core Topology Optimisation Methodologies

TO methods can be broadly classified into deterministic (gradient-based) and stochastic (heuristic) methods, depending on whether they require gradient information from the objective functions.

1.2.2.1.1. Homogenization Methods

This approach uses the mathematical theory of homogenisation to analyse a complex domain, which has been discretised into microstructures or finite elements [2,12]:

- It treats this domain as a continuum composed of a 'virtual' or 'effective' material [2,12].
- The structural topology evolution is achieved by iteratively modifying the size variables of each unit cell [3,13].
- The mathematical complexity of the homogenisation approach has historically limited its widespread application [3].

1.2.2.1.2. Density-Based Methods

In these methods, a density variable is assigned to each finite element within the discretised design space. This variable typically ranges from 0 (representing void or no material) to 1 (representing solid material) [2,12].

The Solid Isotropic Microstructure with Penalisation (SIMP) method is the most popular numerical technique for addressing intermediate densities (between 0 and 1) that naturally arise during the optimisation process. SIMP penalises intermediate density values using a power law scheme, effectively driving the pseudo-densities towards either 0 or 1 to achieve clear solid-void distinctions [3,12]:

- The stiffness derived from the SIMP model can be interpreted as that of a microstructure composed of void and a corresponding fraction of solid material [3].
- SIMP is widely used in industrial software, such as SolidWorks Simulation, due to its efficiency, ability to handle various design constraints, multiple load conditions, and multiphysics problems. It is also known for requiring relatively few iterations and its straightforward implementation [2,5,12].

1.2.2.1.3. Discrete methods

Evolutionary Structural Optimisation (ESO) methods, also known as "hard-kill" methods, iteratively remove elements from the design space [2,5]. In ESO, a selection criterion is calculated for each element, and elements with the lowest criterion values are progressively eliminated at each iteration. This process continues until a predefined volume constraint is met [3]:

- The Bi-directional Evolutionary Structural Optimisation (BESO) method is an extension of ESO that allows both the removal and addition of elements at each iteration, often resulting in better-defined boundaries [2,3].
- These methods are conceptually simpler than density-based methods and show great potential for DfAM applications, particularly for generating complex structures such as porous and lattice structures, with fewer mathematical constraints [5,8].

- Historically, a criticism of ESO has been the absence of a "restitution mechanism" for removed elements, which could lead to suboptimal designs. BESO was developed to address this deficiency [3].
- Modified BESO methods, such as Iso-XFEM, have been developed to generate high-resolution TO solutions with smoother boundaries, accounting for discontinuous material distributions within single finite elements [8,12].

1.2.2.1.4. Level-set Methods

Level-set Methods (LSMs) implicitly define the interface between material phases (solid and void) using iso-contours of a level-set function. This approach inherently produces sharp, smooth, and well-defined boundaries between solid and void regions, which is beneficial for creating "digitally print-ready" designs [2,5,12]:

- These methods offer advantages in parameterisation based on geometric features and potentially link manufacturing and digitalisation. The topology generated by LSMs is independent of the underlying mesh, which helps avoid the "stepped boundaries" artifacts often seen in density-based methods [12].
- LSMs are gaining traction due to their ability to naturally generate smooth boundaries [12]. Research has explored their use in incorporating AM constraints, such as toolpath or deposition constraints to control sharp angles, deposition gaps, minimum inner hole size, and minimum strut size during topology formation [8]. In addition, they can be used to mitigate gap formation caused by sharp geometrical transitions and to generate paths that follow principal stress trajectories, potentially increasing overall performance [8,12].
- Despite their distinct advantages in representing complex geometries and producing smooth boundaries, LSMs are still considered not fully mature for widespread industrial adoption [3].

1.2.2.2. Generative Design

Generative Design (GD) is a design exploration process that leverages artificial intelligence and evolutionary algorithms to automatically generate multiple optimised design alternatives based on defined functional and performance requirements [5,8,12]. Unlike traditional TO, GD does not require a predefined design domain; instead, it operates within design space constraints, often related to assembly interfaces or non-design regions. An evolutionary algorithm then generates material distributions or geometries that satisfy these constraints, offering greater design freedom [5]. Some key aspects and advantages of generative design are:

- Exploration, not just optimisation: GD provides a portfolio of alternative solutions, optimised for multiple objectives under varying constraints, allowing designers to select the most suitable option for specific use cases [5,8,13]. This contrasts with TO's tendency to converge towards a local optimum influenced by initial boundary conditions [10].

- Focus on function: GD enables designers to prioritise functional requirements over predefined geometries, delegating the generation of design alternatives to computational optimisation tools [10].
- Efficiency: GD can generate multiple design solutions simultaneously across different materials and manufacturing processes, improving design efficiency by providing a comprehensive comparative overview [5,10]. This can shorten and streamline the development process compared to TO, which often requires iterative redesign and validation of separate concepts [10].
- CAD Integration: GD tools provide enhanced integration with CAD systems, enabling modelling, optimisation, and refinement within a unified environment, thereby reducing data loss during translation and redesign [5,10].
- Part Consolidation: A key advantage of GD is its capability to consolidate complex assemblies into fewer components, reducing part count and potentially improving performance and manufacturability [5].

The integration of AM constraints into GD remains challenging, although methods have been proposed to incorporate manufacturability, including bio-inspired approaches (e.g., mimicking termite behaviour for volumetric construction) [8]. GD can be computationally intensive and time-consuming, and may not be suitable for simple design problems where traditional TO approaches are more effective [5]. Commercial GD Software: Examples of commercial software incorporating GD capabilities include MSC Apex Generative Design (MSC Software Corporation, USA), nTop (nTopology, USA), and Autodesk Fusion360 (Autodesk, San Rafael, USA).

1.2.2.3. Lattice Structures

Lattice structures (**Figure 1.2**), also known as cellular solids or mesostructures, are an essential aspect of AM, primarily used for lightweighting components while maintaining or enhancing mechanical properties [1,4,5]. They can also serve as internal supports, heat dissipators, and help mitigate thermal warping in metallic AM [2]. These structures are lightweight alternatives to continuous material ones.

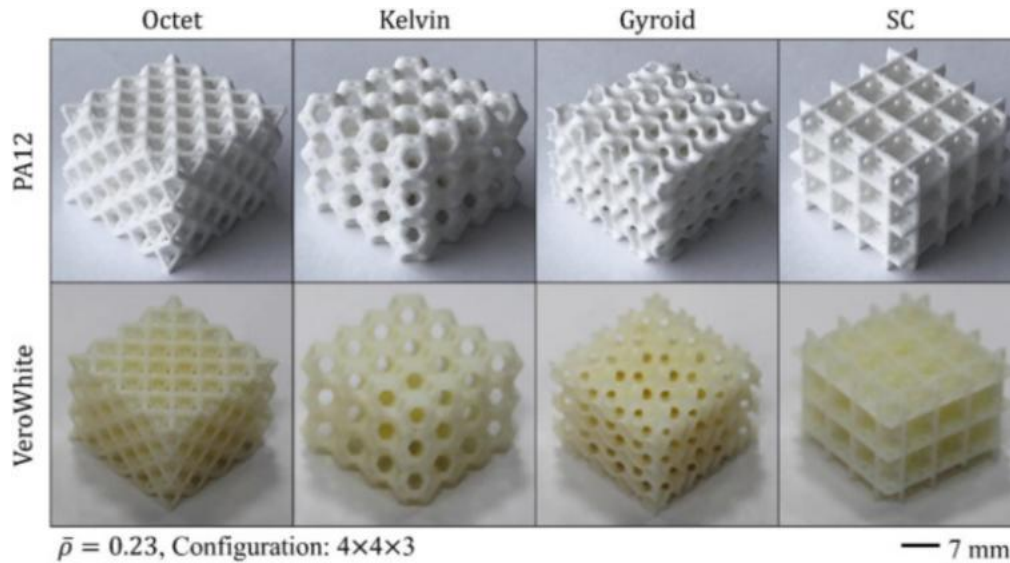


Figure 1.2. Examples of different lattice structure unit cells – Octet, Kelvin, Gyroid, SC [14].

In order to generate lattice structures, the following methods are possible to implement:

- **Homogenisation Methods:** These convert lattice structures into representative volume elements (RVEs), treating them as solid materials with special properties derived from their microstructure. This allows the application of traditional TO or other structural optimisation methods to these 'homogenised' volumes [5,8].
- **Density-Based Mapping:** This approach maps the density values obtained from TO results onto predefined explicit lattice structures. This can result in uniform or graded lattice structures, with varying densities or strut diameters across the part [5,8].

Regarding types of lattice structures, these can be categorised into:

- **Disordered, periodic, and pseudo-periodic:** Disordered structures are randomly distributed, periodic structures use a standard unit cell distributed uniformly, and pseudo-periodic structures adapt a standard cell to the overall geometry of the design [4].
- **Homogeneous and heterogeneous:** Homogeneous structures have uniform cell sizes, while heterogeneous structures allow cell size to vary [4].
- **Conformal lattices:** These adapt their unit cell topology to perfectly interface with the part's boundaries, often yielding greater structural performance [2,12].
- **Functionally Graded Materials (FGM):** This advanced application involves creating porosity or density gradients by modulating the spatial microstructure or morphology of lattice structures, which can be readily achieved with implicit definitions such as Triply Periodic Minimal Surface (TPMS) lattices [8,12].
- **Truss-based and surface-based unit cells:** These are the building blocks of lattices, with numerous cell topologies available in libraries. Surface-based unit cells often outperform truss-based ones in stiffness for lightweight designs [12].

Lattice infill optimisation is increasingly integrated into earlier design phases to fully exploit AM capabilities [5,7]. This typically involves the inclusion of lattice structures into the TO process through the following steps [5,15]:

1. Performing a TO process to obtain a density field.
2. Applying a density threshold to preserve high-density regions as solid boundaries.
3. Using the remaining domain as input for lattice generation.
4. Applying size optimisation using appropriate meshing and FE analysis (FEA). This process results in graded infill lattices in low-density regions, which typically require reduced support generation.

The digitalisation, representation, and simulation of lattice structures can be computationally intensive due to the large number of 3D elements required [2,8]. Ensuring manufacturability requires consideration of factors such as minimum section thickness, hole diameter, and powder removal (for powder bed fusion) [4,12]. While beneficial for certain functionalities such as energy absorption and heat conduction, lattices can significantly reduce stiffness compared to solid structures and may therefore be suboptimal when stiffness is the primary design objective [8].

1.2.2.4. Software Tools and Applications

Many commercial software tools support the design and optimisation of TO and lattice structures. These include SolidWorks Simulation (for SIMP method TO), Altair Inspire (with OptiStruct solver), Ansys Mechanical (for FEA), COMSOL Multiphysics (for multi-objective optimisation), and Abaqus (for TO and FEA). For lattice design, nTop (nTopology) provides a wide array of lattice structures and enables regional density and lattice parameter modification. Other tools like Netfabb, 3-Matic, and Simpleware are widely recognized as mesostructured and lattice design tools. Some advanced tools, such as those in Siemens NX, facilitate the direct modelling of lattice structures in the CAD environment.

1.2.3. Modelling and Simulation as Digital Tools for Additive Manufacturing

After the initial design and optimization phases, the generated geometric models, particularly those resulting from topology optimization, often require significant post-processing to be suitable for AM. The output from topology optimisation (TO) is frequently a density map, which is then contoured to a specific density level (threshold) to produce a mesh surface [2,5]. Similarly, for designs involving lattice structures derived from size optimisation, an initial wireframe model must be represented as a boundary mesh [2]. A significant challenge in the DfAM workflow is that these raw mesh models are often not directly usable for production due to various deficiencies [2,10]. These can include a lack of proper connection zones, coarse regions resulting from the discretisation process, or poorly defined organic geometries.

There are several approaches to convert these raw mesh models into manufacturable geometries. Many designers resort to manually remodelling the part within a CAD

environment, using the generated mesh as a guideline [2,10]. For instance, a mesh resulting from topology optimisation in SolidWorks Simulation can be manually remodelled into a Non-Uniform Rational B-Spline (NURBS) surface using software such as Inspire Studio CAD 3D [2]. This process, however, can be time-consuming, particularly for complex shapes generated during optimisation, and human errors during this phase can make the final FEA verification more prone to failure [2]. Software tools for automatic remodelling are also available, commonly employing quad-remesh and subdivision surface approaches [2]. Advanced platforms like nTop, Fusion 360, and Creo offer automatic optimisation-to-CAD reconstruction, converting designs into editable and watertight boundary representations (B-reps) using Boolean operations. This technique minimises post-processing while preserving the details of the optimisation result [5,16].

Process simulation is also a vital digital tool in DfAM that aims to predict potential issues during the AM build process, thereby avoiding costly and time-consuming experimental trials [1]. Its primary function is to predict residual stress and geometric distortion in printed parts [1,2] (**Figure 1.3**), thereby significantly reducing the likelihood of defects, such as crack initiation and propagation, during both printing and product use.

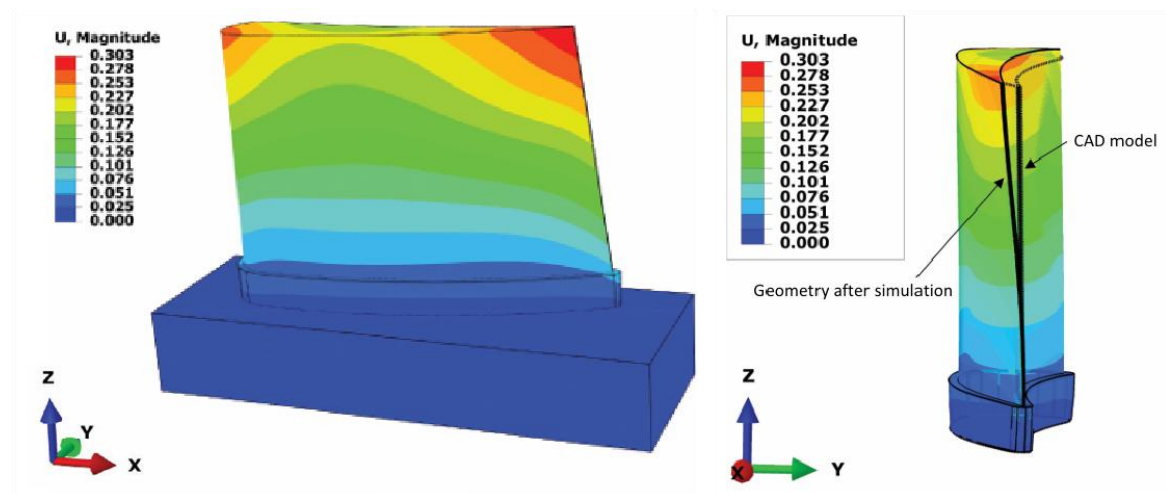


Figure 1.3. Example of a powder bed fusion simulation part. Zones highlighted in red indicate high levels of displacement [17].

Commercial simulation tools such as Simufact™, Ansys, Netfabb, and Digimat (for polymers) are used to calculate geometric deformations and post-printing residual stresses. These tools enable the optimisation of process parameters to minimise accumulated tensions and deformations in parts during and after printing. Designers can also use simulation to support decisions on printing position, material selection, and support structure optimisation [1]. A notable method for AM printing simulation is the inherent strain approach, used by platforms like MSC and Ansys [18]. This method replaces complex thermo-mechanical simulations with a quasi-static FEM simulation in which distortions are induced by user-defined inherent strains

[5,19]. It typically involves a coarse voxel discretisation domain for the part and its support structures, simulating each voxel layer as a manufactured layer [5].

In addition, in-service simulation focuses on validating the mechanical performance and predicting the behaviour of AM-produced parts under real-world loads and constraints during their operational lifetime [1,7]. This crucial step typically involves an additional FEA to mechanically validate the final design after any optimisation and remodelling phases [2]. For TO parts, in-service simulation is mandatory, especially when manual remodelling might have introduced weak zones. However, it may be less critical for lattice structures if their beam diameters have already been extensively optimised through prior FEA [2]. CAE tools, such as FEA and Computational Fluid Dynamics (CFD), are used to analyse structural performance and fluid dynamics, respectively (**Figure 1.4**) [4].

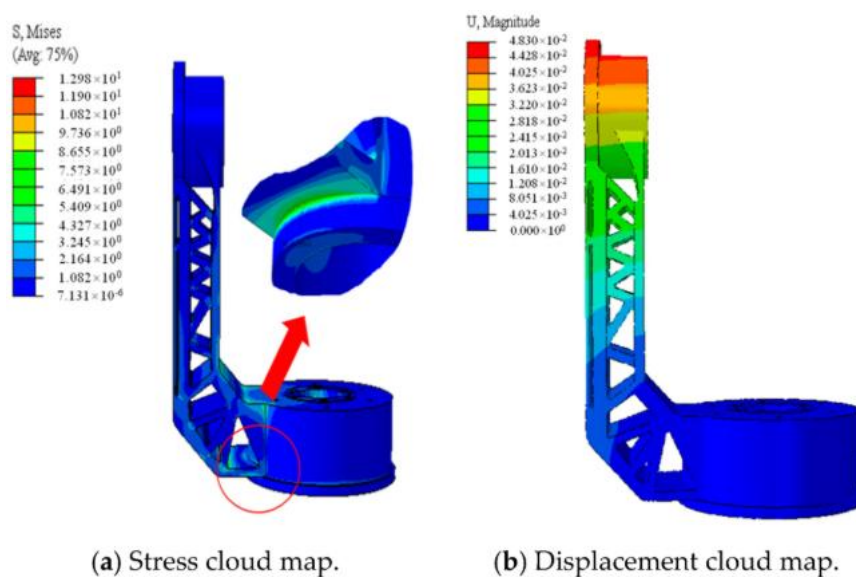


Figure 1.4. Stress and displacement map of a topology optimized part [20].

These simulation tools can handle anisotropy, which is common in AM parts, though accurate calculations require considerable expertise [4]. For example, a simplified FEM can predict the mechanical behaviour of parts made by fused filament fabrication (FFF) from polymeric pre-structured materials, accounting for filament orientation along principal stress directions and material anisotropy [7]. An integrated multidisciplinary design optimisation framework can also incorporate multiple design objectives from both process and structure domains, such as strain energy and maximum von Mises stress, for a comprehensive in-service performance evaluation [21].

The final stages before physical production involve pre-printing and slicing, which prepare the digital model for the AM machine. Pre-production tools such as MeshMixer, MeshFix, and MeshLab are used to review and repair 3D printing files (often in Stereolithography (STL) format), ensuring they have closed surfaces and correctly oriented normals, which are essential for successful printing [1]. Process planning encompasses all the necessary

operations once the AM technology and machine have been selected (**Figure 1.5**). Key considerations in this phase include:

- The part orientation within the build chamber is critical, as it impacts surface texture, mechanical properties, material and energy consumption, and overall production time. Optimal orientation is determined by factors such as achieving the lowest height for faster printing, minimising the supported area or support volume, and ensuring the desired dimensional and geometrical accuracy for functional surfaces [2].
- Support design and generation, if necessary for manufacturing (e.g., for overhanging features).
- Print path strategy that defines how the material will be deposited layer by layer.

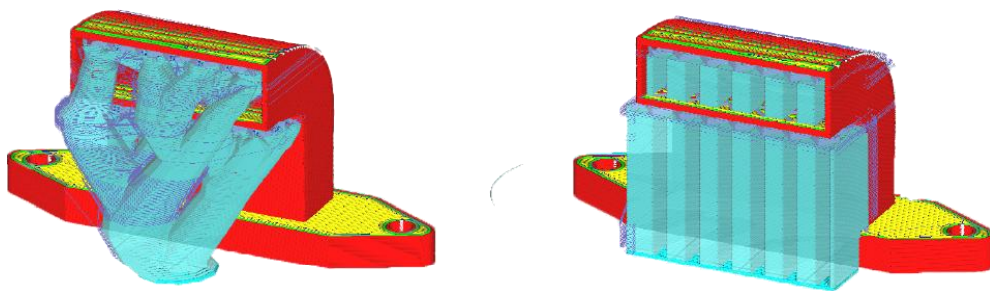


Figure 1.5. On the left, the 'tree support' type; on the right, a normal support.

Commercial software like Netfabb Premium, Magics, and Delmia (for powder bed fusion AM) is widely used for preliminary process planning, part orientation, and support generation. Slicers are specific software for transforming geometric models into machine-specific code. Popular slicers include Cura, Slicer3D, and Simplify3D. These tools offer extensive control over the part's position, size, and orientation, as well as numerous process variables, such as layer height, temperature, and printing speed. A crucial feature of advanced slicers is the ability to virtually recreate the 3D printing process, which aids in the early detection of potential printing errors [4].

Section 2 introduced the main topics of this chapter, which are further detailed in the next sections.

1.3. Modelling, Simulation, and Print Preparation

To benefit from AM while ensuring safety and reliability, such processes must be well characterized and modelled to predict the final microstructure and mechanical properties. Modelling and simulation are vital tools that enable engineers to gain insight into these aspects. Models based on the physics of the processes are needed to understand better the complex links between process parameters and final part quality [22-25].

This section extends the digital workflow introduced earlier to create and validate an AM component for aerospace applications. It will cover the simulation and modelling techniques used to design and optimize a part, including FEM and TO to achieve lighter weight and improved structural performance (Section 3.1). It will then address the Process Simulation

(Section 3.2) to predict and mitigate thermal defects, such as residual stress. There will be an outline of the critical Validation process (Section 3.3), in which the simulation model's correctness will be proven through re-analyses and inspections [25,26].

1.3.1. Finite Element Modelling for Additive Manufacturing

FE modelling is a numerical method that supports TO in AM procedures [22,25-27]. While AM provides freedom to build different complex shapes [26], TO is considered a technology" that could determine what an optimal shape should be [23]. In AM, FE-based computational simulation is commonly implemented using a sequential thermo-mechanical modelling strategy [28,29]. By following the layer-by-layer nature of the build process, such transient simulations would be performed. Initially, a thermal analysis is performed to compute the temperature evolution. This temperature change is due to a localized heat source that moves during material deposition [28,29]. Therefore, heat conduction within the part and heat losses through other mechanisms, i.e., convection and radiation at the boundaries, are explored and accounted for; in this way, detailed temperature histories throughout the build part are available.

The computed thermal field is subsequently transferred to a mechanical analysis, where thermally induced strains are used to evaluate the development of residual stresses and distortions [28,30]. Material addition is represented numerically using an element activation approach. This is usually named element birth and death. In this regard, elements that are initially inactive are progressively activated according to the deposition sequence [28,29]. The heat input is commonly modelled using a volumetric heat source formulation, which enables a realistic distribution of energy within the deposited material [29].

The computational cost of a fully coupled thermo-mechanical simulation can become considerable, leading to the adoption of simplified numerical approaches more frequently. A strategy that has been useful for this aspect is the inherent strain method. In this approach, the effects of thermal expansion and plastic deformation are introduced via predefined strain fields applied during layer activation. As a result, the explicit resolution of melt pool dynamics can be avoided [9]. Such an FE framework helps predict residual stresses and part distortion and maintains a balance between accuracy and computational efficiency, which is reasonable [30]. Such features could make the mentioned method particularly well-suited for simulating additively manufactured aerospace components. This is because parts with rather large sizes and strict performance requirements are common [28,29]. An example of an FE-based thermo-mechanical simulation is shown in **Figure 1.6**. This figure illustrates the influence of process parameters on the evolving temperature field during AM.

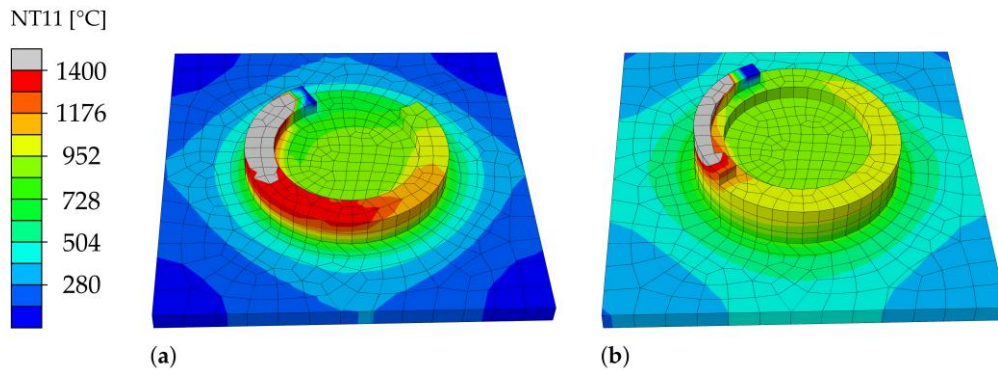


Figure 1.6. Depiction of the predicted temperature fields, obtained from a thermo-mechanical FE simulation (a) when a higher weld power and wider bead and (b) when a lower weld power and narrower bead were used [29].

TO is a mathematical design method used to determine the optimal material distribution within a defined design space [25,31]. It works by reducing material in areas that do not require structural support or have low requirements. This process may be the key to achieving greater mass reduction and, hence, lighter weight in aerospace components, such as brackets and frames [25,27,32]. An example of the fundamentals of TO is shown in **Figure 1.7**.

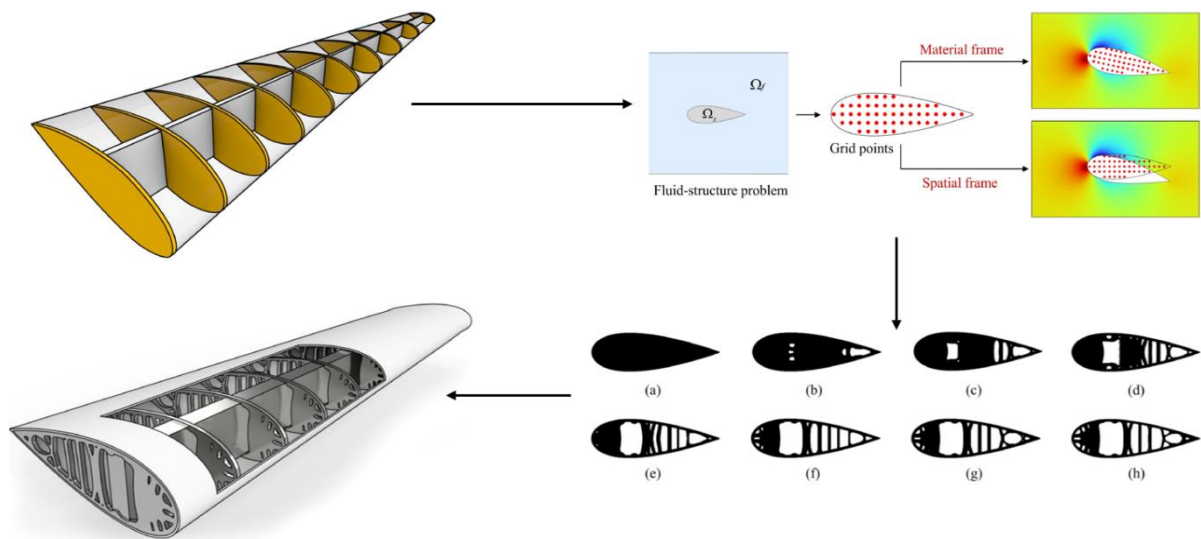


Figure 1.7. Overview of aerodynamics-driven topology optimisation of compliant airfoils [33].

The process of creating an optimised FE model follows a specific chain of events, as demonstrated in several aerospace case studies:

1. Defining a Design Space (Master Part): The process begins with a "master part" that defines the total available design envelope [34]. Within this solid model, the engineer

defines all boundary conditions, such as loads, interfaces, and the desired envelope [26]. This includes specifying designable regions where material can be removed and non-designable regions (such as bolt holes or mating surfaces) that must be preserved [34].

2. FE Model Setup and Pre-processing: The master part is imported into FE analysis software (e.g., ANSYS, Abaqus) and prepared for simulation [24,27,31]. This pre-processing step involves:
 - Meshing: The entire design space is meshed into finite elements [31,34].
 - Applying Loads: All known operational loads are applied. For aerospace, it becomes important to go further and include aerodynamics, fatigue, and thermal loads [22,27].
 - Defining the Objective: An objective function is set. A common objective for aerospace structures is to "Minimise compliance" (i.e., maximise stiffness) [22,25,34].
3. Iterative Optimisation: The FEA software then runs several iterations [31], systematically removing elements from the designable space to find the most efficient load path. During this process, AM-specific constraints, such as a minimum member size, can be applied to ensure the resulting features are printable [34].
4. Optimised Model Result: The output would be a new, lightweight, improved mesh geometry [32]. This digital process achieves favourable results, with case studies showing approximately a 20-60% range of mass reductions [24,30,34].

One FE analysis-driven optimisation method, "Advanced Modelling: Lattice Structures", is not limited to solid external surfaces. The same principles are used to design interior structures such as lattices and trusses [23,25,26]. These porous cellular architectures [25] are used to fill internal voids, offering high specific strength, good energy absorption, and robust thermal characteristics [25], which would contribute to mass reduction and enhance the component's performance [22]. **Figure 1.8** shows one example of a lattice architecture that has been modeled internally for a specific component. This has become possible through advanced computational design methods.

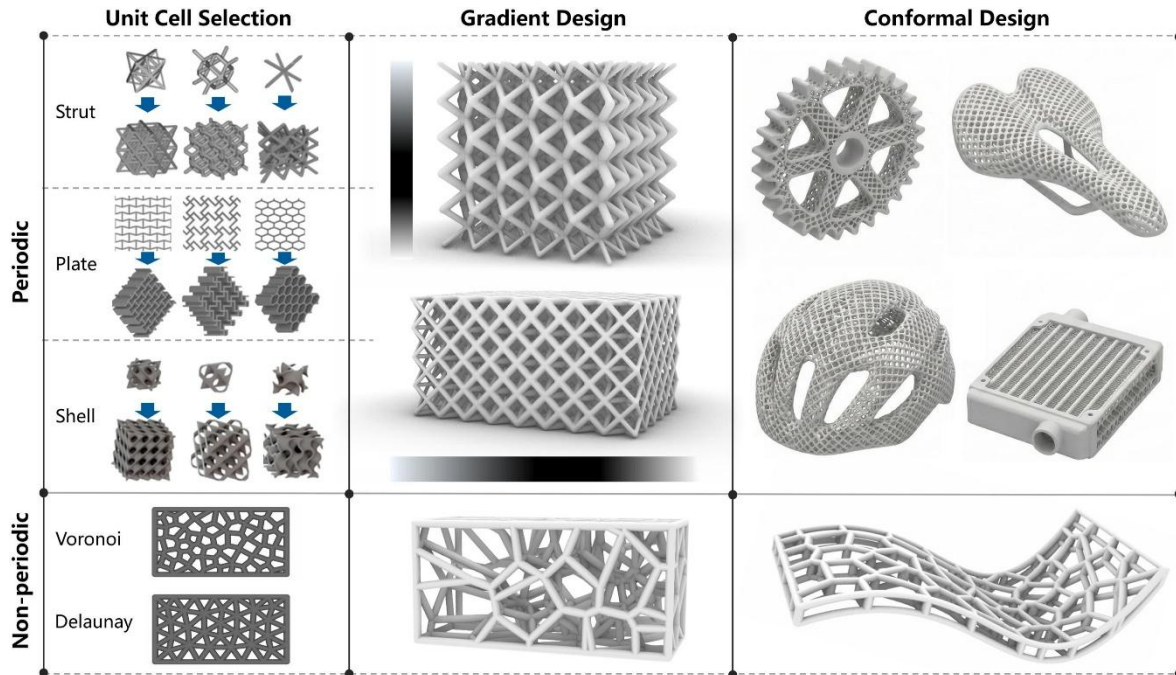


Figure 1.8. Incorporation of internally modelled lattice architectures for stiffness-to-weight optimisation [35].

These explanations of an optimised FE model could be considered as initial steps of a digital workflow. Such a model demonstrates structural performance. However, it may not account for the part's manufacturability. Therefore, the next step, Process Simulation (section 3.2), is required to analyse the thermal and physical stresses of the build itself, while Validation (section 3.3) is the subsequent step to confirm that the final part meets the required safety factors [25,31,34]. Such models are essential for linking process parameters to structural performance in aerospace applications.

1.3.2. Process Simulation

Once the geometry of a component has been structurally improved, a process simulation becomes the next step to determine how to build the part reliably and to ensure its manufacturability [25]. The primary goal of process simulation is to model the part's response to the intense, localized, and high thermal gradients [31] and to transient heat conduction [24] from the moving heat source. This temperature history [24,25] directly affects the final part quality. Uncontrolled residual stresses can induce part deformation (warping) [31], while improper thermal conditions can lead to a lack of fusion [25]. These pores are critical, as they act as stress concentrators and can initiate crack formation [25].

To model these multi-faceted issues, multiphysics simulation tools are used [22,26]. The simulation workflow typically combines different numerical methods [22,24,36]:

- Thermo-Mechanical FE analysis: This is one of the most common methods. It uses FEA to model the temperature and stress fields in the part as it is built [22,24,31] like "quiet elements" or "inactive elements" [24].
- CFD: For more detailed prediction of melt pool shape and size [22,24,36], CFD is used to model the complex fluid convection and "Marangoni convections" within the molten material. This is often coupled with the FE model to improve the accuracy of thermal history prediction.
- Phase & Microstructure Models: For predicting final material properties, especially for novel alloys, CALPHAD-based simulations (phase diagram calculations) are used to model transition temperatures and phase changes, and to assess the risk of crack formation or segregation [26,36]. More advanced Cellular Automaton (CA) and Phase-field models can then be combined with the thermal data from FE analysis to predict the grain structure [24].
- Dedicated Software: In addition to general-purpose FE/CFD, standalone software such as 3DSIM can simulate AM processes and predict the resulting properties [26].

The practical application of these simulations helps test and optimise the build strategy before committing to costly, time-consuming builds [25,31]. This includes simulating key process parameters such as laser power, scan velocity, hatch spacing, and powder size/shape [22,24,26,31]. One of the most critical simulation goals is to determine the optimal build orientation. By simulating different orientations (e.g., different degrees of placement), one can identify the orientation that minimises residual stress and reduces the required support volume [25,31]. These capabilities support the development of predictive digital manufacturing methodologies.

The outputs of these simulations, including predicted maps of distortion or locations with high probability of residual stress, are not just theoretical. They can be considered part of a DT framework and are carried forward to the next step, validation (section 3.3). These predictions are then compared against physical experimental or in-situ measurements [22,24,25,31].

1.3.3. Validation of Models and Simulations

Validation is another critical step in digital workflows for aerospace component production. It is the process of verifying that the digital models are sufficiently accurate and that the final physical part is reliable, safe, and meets the required performance expectations [24-26]. Compared to traditional methods, AM remains less extensively studied and characterised, making validation a key challenge for certification [24]. First, the optimized FE model must be validated virtually. Subsequently, the physical part and the process simulation must be validated experimentally.

Before printing, the optimized design from section 3.1 must be structurally verified. This is accomplished by taking the final, redesigned part (the output of the TO) and re-analyzing it using the FE method [22,31,34]. This virtual validation would follow a workflow:

1. The redesigned, optimized model is imported back into the FE software [31,34].

2. The original loads and boundary conditions are applied to this new geometry [31,34].
3. A final, high-fidelity FE analysis is performed (often with a refined mesh) to validate the results [34].

The validation is considered successful if the optimized part meets or exceeds the performance of the original. A case study of this was the Alcoa aerospace bracket, which had an original Factor of Safety (FOS) of 1.54. After optimisation and re-analysis, the new lightweight part demonstrated improved FOS, thereby validating the optimised FE model [31].

Once the virtual model is validated and the part is manufactured, it must be tested to validate both the process simulation and its structural performance [24-26]. This is essential to meet the stringent regulatory frameworks of bodies such as the European Union Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA) [24,25].

This physical validation involves three main stages:

1. Statistical Process Validation: To ensure the reliability of the build process, "test coupons" or "witness specimens" are fabricated concurrently with the fabrication of parts [25,26]. These coupons are then destructively tested to validate the material properties of that specific build. This provides a statistical basis for the part's quality, with a recommended minimum of five samples for tensile, fatigue, and other tests per build [26].
2. Non-Destructive Testing (NDT): NDT is prescribed for all critical flight components [25] to find internal flaws predicted by the process simulation. X-ray computed tomography (CT) is usually a powerful NDT method for this task [25]. It is used to find internal cracks, pores, trapped powders, deviation from design geometry, and warping [25]. Ultrasonic Inspection is also used to find internal flaws in limited applications [23].
3. Post-Processing (defect correction): If NDT validates the simulation's prediction of defects such as significant porosity [26], a corrective post-processing step is needed. Hot Isostatic Pressing (HIP) is a common step used to close pores, homogenise the microstructure, and improve ductility, thereby greatly improving fatigue performance [25,26]. Similarly, an annealing process (heat treatment) could often be used to achieve a desired grain structure and help ensure consistent, predictable mechanical properties [26,27,35].

At the end, a validated component undergoes functional testing to certify it for flight. This could include ground-based engine testing of the General Electric (GE) fuel nozzle and hot-fire tests to validate the National Aeronautics and Space Administration (NASA)'s rocket injectors [23,26,37].

1.3.4. Print Preparation and Slicing (Pre-Printing)

After the model is designed and verified, the final stage before physical production is preparing the model geometry and generating the machine instructions, often referred to as pre-printing or slicing. This process involves crucial conversions, planning decisions, and

simulations to ensure the part is manufacturable, especially when using complex outputs such as those from TO.

1.3.4.1. Geometric Conversion and Data Exchange

CAD systems primarily use B-rep (vector graphics), whereas AM machines require layer-by-layer instructions based on mesh data (raster graphics). The process of converting B-rep data into triangles or meshes is called tessellation, which is necessary both for displaying the geometry on a computer (GPUs only display mesh data) and for exporting the file for printing (**Figure 1.9**) [38].

Although the STL format is one of the oldest and most widely used 3D-printing mesh formats, it is strongly recommended to use modern alternatives. STLs should be avoided whenever possible because they do not store critical information such as unit, material, or colour data, thereby increasing the risk of errors. The 3D Manufacturing Format (3MF) is the modern replacement for STL and can contain all necessary information for manufacturing [38]. For exchanging technical B-rep data with a manufacturer, a solid file format such as STEP is highly preferred, as it is universally accepted and serves as the "PDF of the CAD world" [39].

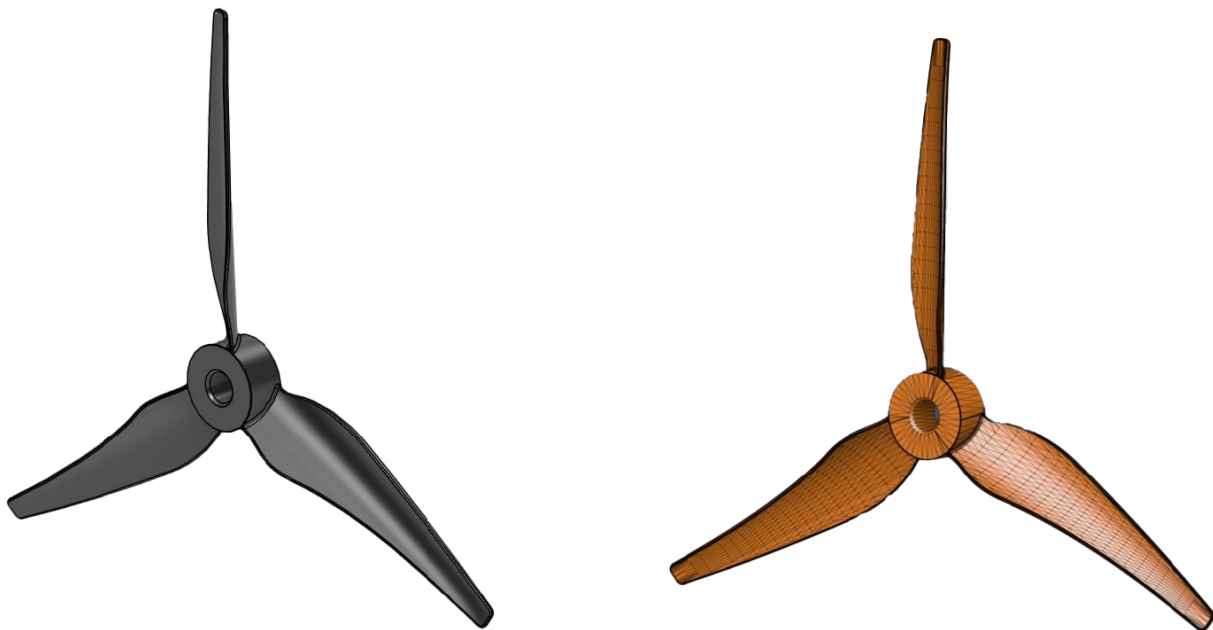


Figure 1.9. Left image: original solid part; right image: the mesh converted into triangles (.stl format) for 3D printing.

Before slicing, raw mesh models, especially those resulting from topology optimisation, frequently contain deficiencies that must be addressed, such as discontinuities or incorrect triangle orientations. Specialized tools such as MeshMixer and MeshLab are used during this 3D mesh treatment phase to review and repair files, ensuring the surfaces are closed and normals are correctly oriented, which is essential for successful printing.

1.3.4.2. Process Planning and Simulation

Process planning encompasses the critical operations executed after the AM technology has been selected. A key decision is part orientation within the build chamber, as this profoundly influences factors such as surface quality, mechanical properties, material consumption, and production time. Optimal orientation generally aims to minimise the part's height (for speed) and minimise the required supported area or support volume.

If the AM technology requires them, support structures must be generated, particularly for overhanging features. In metal AM, supports are especially crucial, as they serve as essential heat-transfer structures to mitigate excessive distortions and residual stresses that arise during printing [5]. Commercial software such as Netfabb Premium and Magics is widely used for this preliminary process planning, part orientation, and support generation.

Furthermore, process simulation is a vital digital tool that predicts potential issues, such as residual stress and geometric distortion, that occur during the AM build process, helping to avoid costly experimental trials. By simulating these effects, designers can intentionally compensate the CAD model geometry beforehand to achieve the desired dimensional specifications post-printing [40,41].

1.3.4.3. Slicing and Toolpath Generation

The final step is using slicing software, specialised applications that transform the processed geometric models into machine-specific code that details layer-by-layer material deposition. Popular slicers, including Cura and Simplify3D, offer designers extensive control over crucial process variables, such as layer height, printing speed, and temperature. Advanced slicers enable the virtual recreation of the 3D printing process, aiding early detection and prevention of potential printing errors. The most important parameters to consider during slicing and toolpath generation include decisions made during the process planning stage, fundamental geometric variables, and specific machine execution controls.

1.3.4.3.1. Process Planning and Geometric Constraints

Slicers incorporate and execute decisions made during process planning, which are critical because they define the geometric relationship between the part and the machine (**Figure 1.10**).

- **Part Orientation:** This is a paramount decision that influences nearly every aspect of the build and must be finalised in the slicer environment.
 - **Production Time:** Orienting the part to achieve the lowest height (minimum build height) is essential for faster printing.
 - **Support Minimisation:** Orientation directly impacts the volume of support structures required. Optimal orientation seeks to minimise the supported area or support volume.

- Surface Quality and Accuracy: Orientation affects the surface texture and the dimensional and geometrical accuracy of functional surfaces.
- Support Generation: If the AM technology requires them, supports must be generated and their parameters defined (e.g., density, type, contact area). In metal AM, supports are particularly crucial as heat-transfer structures needed to mitigate distortions and residual stresses.

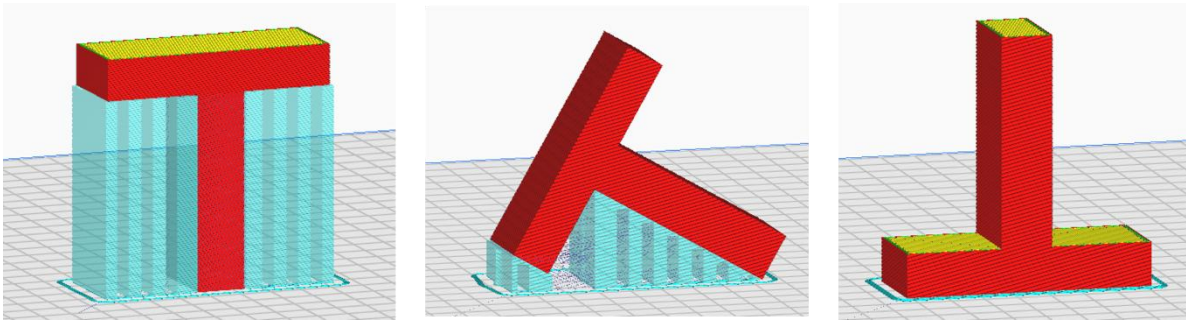


Figure 1.10. The same part is positioned in different ways to demonstrate the importance of part orientation in 3D printing. The orientation on the right saves not only on material, since it does not require any support, but also on printing time.

1.3.4.3.2. Machine Execution and Layer Parameters

Slicers offer extensive control over the variables that dictate how the material is deposited:

- Layer Height: This variable defines the vertical thickness of each deposited layer. Layer height directly affects print resolution and total build time. A smaller layer height increases resolution but lengthens the build time.
- Temperature Controls: Slicers manage crucial thermal parameters, including the extruder and build platform temperatures. These controls are vital for ensuring proper material flow and layer adhesion, as well as mitigating thermal stress and warping in the printed part.
- Printing Speed: Defining the speed of material deposition is a key control that balances total build time with final part quality and dimensional accuracy.
- Part Positioning and Scaling: Slicers allow designers to control the part's final position, size, and orientation within the build chamber.

1.3.4.3.3. Toolpath Strategy

The slicer transforms the geometric data into a print path strategy, or toolpath, which is the machine-specific code (G-code) detailing the material deposition sequence (**Figure 1.11**).

- Impact on Mechanical Properties: The generated toolpath is highly consequential. For instance, in FFF, the filament orientation along the principal stress directions must be accounted for, as the layer direction profoundly influences the mechanical behaviour

and material anisotropy of the final part. Predicting the final mechanical behaviour often requires a simplified FEA that accounts for this filament orientation.

- **Topology Integration:** Research has focused on incorporating AM constraints, such as the deposition path/toolpath constraints, during the topology optimisation phase itself, particularly when using Level-set Methods (LSMs). This integration aims to control sharp angles, deposition gaps, and minimum strut sizes, and can even generate paths that follow principal stress trajectories, potentially increasing overall performance.

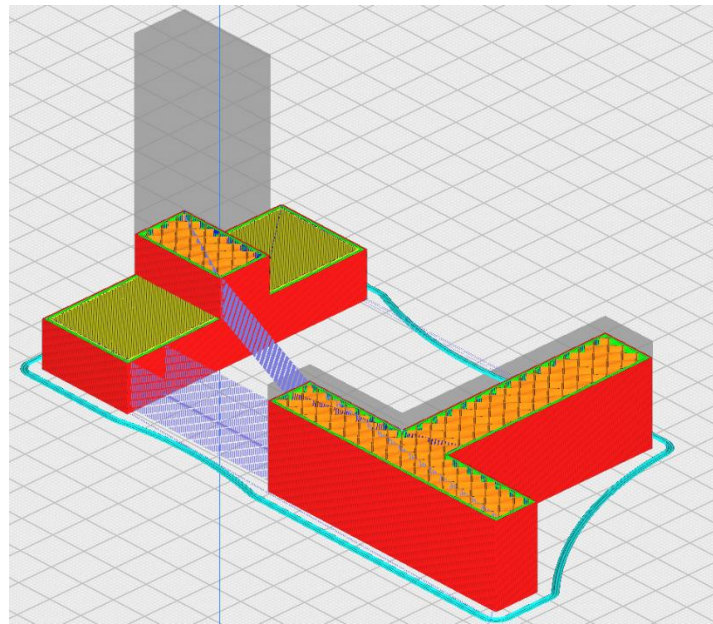


Figure 1.11. The same part oriented in two different ways. This difference will result in parts with different mechanical properties.

1.4. Digital Design Methodologies

AM has transformed traditional design and production paradigms by enabling the direct fabrication of complex geometries from digital models. As this technology has evolved from a prototyping tool to a production-ready process, it has prompted the development of new design philosophies collectively referred to as DfAM. These address both the opportunities and constraints inherent to layer-by-layer fabrication, leveraging AM's unique capabilities while accounting for manufacturing challenges, cost considerations, and performance requirements [40].

In traditional Design for Manufacturing (DfM), the primary objective is to ensure that parts can be efficiently produced using subtractive or formative processes such as machining, casting, or injection moulding. These processes impose strict geometric limitations, often requiring a compromise between performance requirements and production constraints. In contrast, DfAM shifts the design emphasis toward functional optimisation, customization, and

part consolidation [40]. With many conventional geometric constraints removed, the design process can prioritize performance-driven structures rather than those dictated by manufacturing limitations.

Moreover, digital design plays a pivotal role in this transformation. Every AM component begins as a digital model, and its quality, performance, and cost efficiency are directly influenced by the digital design methodology used [40]. Consequently, understanding and mastering DfAM is not merely about adjusting geometries for printability. It involves adopting a comprehensive digital-first approach to product development.

1.4.1. The Digital Design Workflow in Additive Manufacturing

The digital workflow in AM represents the sequence of processes through which an idea evolves into a tangible product. This workflow typically includes concept development, digital modelling, design optimisation, build preparation, fabrication, and post-processing (Figure 1.12). Each stage relies on digital tools and requires feedback between design, analysis, and production:

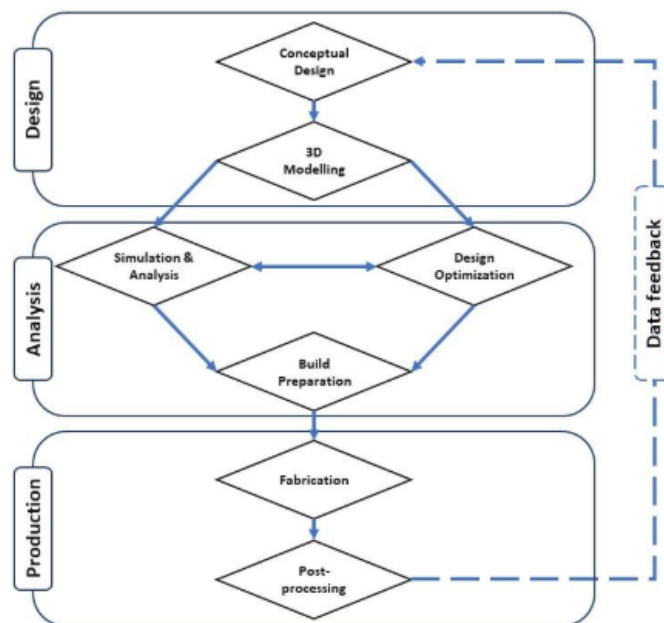


Figure 1.12. Workflow for digital design for AM.

The process begins with problem definition and conceptualization, during which digital sketching or direct modelling is used to explore potential forms and functions. At this stage, flexibility and creativity are prioritized, allowing multiple iterations without the need for physical prototyping [4].

The next step is to create detailed geometry using CAD software. Parametric design tools (e.g., SolidWorks, Autodesk Fusion 360) enable dynamic relationships between features,

allowing for dimensions and parameters to be quickly adjusted. This approach is particularly beneficial for customization and design iteration.

Before fabrication, designs are digitally tested for performance, structural integrity, and production feasibility. FEA and CFD simulations are commonly used to predict stresses, heat dissipation, or deformation under load. For example, in metal AM, thermal simulation is crucial for predicting warping and residual stresses [41].

Design optimization typically involves applying TO and generative design. These computational methods refine geometry based on defined performance criteria such as stiffness, strength, and weight reduction. Optimisation tools generate material-efficient shapes that would be impossible to produce using traditional manufacturing processes [40]. Because these optimisation techniques require validation, the newly developed designs are typically looped back to the previous step, where simulations are rerun. This creates a direct feedback loop between the two stages, ensuring continuous design refinement.

The finalized design is then imported into slicing software (e.g., Cura, Materialise Magics, and EOSPRINT), where it is digitally “sliced” into layers corresponding to the machine’s layer thickness. Support structures, orientation, and infill patterns are also defined here. These decisions directly affect surface finish, print time, and structural quality.

Fabrication and post-processing involve executing the print, often with real-time sensing and process control. After printing, the part may require cleaning, support removal, thermal treatment, or surface finishing. Importantly, digital data generated during this phase, such as print feedback and deformation scans, can be fed back into earlier design stages to enhance future iterations. This iterative feedback mechanism illustrates the continuous integration between design and production stages in AM.

Unlike traditional design methodologies, which often follow a linear “design–manufacture–evaluate” sequence, DfAM is inherently iterative and data-driven. The integration of digital simulation, in-process monitoring, and post-process scanning enables continuous feedback between virtual and physical models. The resulting datasets are analysed to identify defects or deviations, and the findings are used to inform subsequent design refinements. This closed-loop approach not only enhances part quality but also enables the development of a DT, a virtual representation that accurately reflects the physical behaviour of the manufactured component [42].

1.4.2. Core principles of DfAM

DfAM represents a paradigm shift in how the relationship between form, function, and production is approached. Traditional manufacturing techniques, such as casting, milling, and injection moulding, impose clear constraints on part geometry, draft angles, and assembly requirements. In contrast, AM enables the creation of geometries defined primarily by functional performance rather than process limitations [40].

As highlighted by Gibson et al. [43], DfAM seeks to leverage the freedoms of AM while mitigating its process-specific constraints. This dual focus implies that DfAM is not simply a matter of making parts “printable”. Instead, it involves strategic use of digital tools to unlock new design spaces while simultaneously optimizing production feasibility, cost, and performance.

1.4.2.1. Part consolidation and functional integration

One of the most transformative principles in DfAM is part consolidation, the process of combining multiple components into a single, solid structure. This approach eliminates the need for fasteners, welds, or adhesives, reducing both assembly time and inventory costs. It can also increase functionality and improve performance [40].

In traditional manufacturing, complex assemblies are often unavoidable due to geometric and tooling limitations. In contrast, AM eliminates many of these constraints, enabling the direct fabrication of intricate, interconnected structures. For example, in aerospace applications, an aircraft duct originally composed of sixteen machined components can be re-engineered into a single unit [43], reducing mass and simplifying logistics.

Beyond reducing part count, consolidation supports functional integration, embedding multiple functions into a single design. Examples include components that simultaneously serve as structural supports, fluid channels, and heat exchangers [44]. The ability to integrate functionality at the design stage is one of the defining advantages of DfAM, promoting designs that are both lighter and more reliable.

1.4.2.2. Weight reduction

Weight reduction has always been a central goal in industries such as aerospace, automotive, and robotics, where minimizing mass improves energy efficiency and performance. AM enables lightweighting through computational design techniques such as topology optimisation and lattice structure generation.

TO is an iterative structural design method in which non-critical material is algorithmically removed from a defined design space while preserving essential load paths and mechanical integrity. The process uses techniques such as FEA and sensitivity calculations to evaluate stress distributions and to reshape the model so that stiffness-to-weight ratios remain within target limits [45]. The resulting organic geometries can be manufactured efficiently only through additive methods.

Complementing topology optimisation, lattice and cellular structures enable the replacement of solid regions with periodic internal frameworks (**Figure 1.13**). These structures significantly reduce material use while maintaining mechanical performance and can be tuned to achieve specific stiffness or energy-absorption characteristics [46].

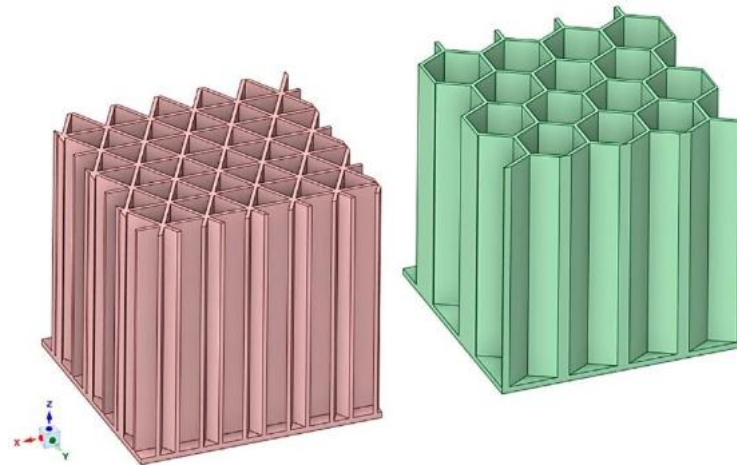


Figure 1.13. Example of two types of 3D-printed 2D lattice structures with different cross-sections [46].

As noted by Hague et al. [47], this capability is often characterized as the ability to incorporate geometric complexity without substantial increases in cost or production time, meaning that AM performance remains relatively unaffected by intricate geometries. This freedom allows prioritising performance-driven structures over simplified geometries optimized for subtractive manufacturing.

1.4.3. Process-Driven Design Strategies

Beyond geometric considerations, effective DfAM requires a detailed understanding of material behaviour and performance optimisation. Additive processes not only shape form but also influence the intrinsic microstructure, anisotropy, and functional properties of materials. Consequently, material-aware design represents a critical methodological layer in digital workflows, ensuring that the physical performance of a printed component aligns with its digital intent. ASTM 52900 organizes AM technologies into seven distinct process categories: binder jetting, directed energy deposition, material extrusion (MEX), material jetting, powder bed fusion (PBF), sheet lamination, and vat photopolymerization (VP). This classification is directly relevant to material selection, as each process category defines specific limitations on material form, chemical composition, and processing requirements. The relationship between material and process is bidirectional: material characteristics determine feasible process parameters, while process variables such as temperature, energy input, and layer orientation directly modify material properties. This integration of design, material science, and digital control constitutes one of the most distinctive features of AM compared to conventional methods.

The layer-by-layer nature of AM leads to mechanical anisotropy and microstructural heterogeneity. As previously discussed, in FDM processes, weak interlayer bonding results in reduced tensile strength along the Z-axis. Similarly, in Selective Laser Melting (SLM), rapid cooling rates produce fine microstructures accompanied by high residual stresses, which

influence fatigue and creep behaviour. Understanding these process–structure–property relationships is essential to DfAM. Design parameters, such as layer height, build orientation, and scanning strategy, directly affect grain orientation, porosity, and the distribution of residual stresses [48]. A key opportunity in AM lies in the ability to locally tailor material properties through precise control of process parameters.

As noted by Bikas et al. [49], a process-driven design strategy ensures that digital models are not only functionally optimized but also manufacturable within the parameters of a chosen technology. This approach requires integrating process knowledge early in the design phase, aligning geometric intent with the characteristics of layer-by-layer fabrication. The following sections outline key design considerations for the most widely used AM methodologies.

1.4.3.1. Design for Material Extrusion

MEX includes FDM, Fused Granulate Fabrication (FGF), and Robocasting (or Direct Ink Writing), which involve the processing of thermoplastic or thermoplastic-based composite filaments [50-52], thermoplastic or thermoplastic-based composite granulates, and a wide range of pastes, respectively. FGF offers key advantages over FDM, including lower material costs, broader compatibility with industrial and recycled polymer feedstocks, and higher deposition rates enabled by the direct use of granulated materials instead of pre-processed filaments. PLA and ABS are typically the most processed thermoplastic filaments. On the other hand, robocasting typically processes highly concentrated, rheologically tailored pastes, such as ceramic suspensions, hydrogel-based (bio)inks, and cementitious or geopolymer formulations, among others [50-52]. These materials are engineered to exhibit shear-thinning behaviour and sufficient yield stress, enabling extrusion through a nozzle while maintaining shape fidelity after deposition.

Typical layer thicknesses for MEX techniques range from 50 to 400 μm , which influences the mechanical performance and aesthetics of the printed parts [53]. The extruded materials can be deposited in a molten state or at room temperature onto a build platform that can be either heated or unheated. When a heated bed is used, thermal gradients within the part are reduced, helping to limit distortion phenomena such as warping and decreasing the formation of residual stress concentrations. Additionally, designing filleted corners, rounded transitions, and gradual cross-section changes minimizes these thermal gradients [54]. For geometrically complex components, support structures are often necessary. In particular, overhang features—defined as horizontal or near-horizontal extensions without underlying support—constitute a key design limitation in AM. Overhangs exceeding approximately 45° from the vertical axis typically require additional support material (**Figure 1.14**), which in turn increases material usage and extends post-processing time. Strategies to mitigate this include designing self-supporting angles, chamfers, or curved surfaces [55,56].

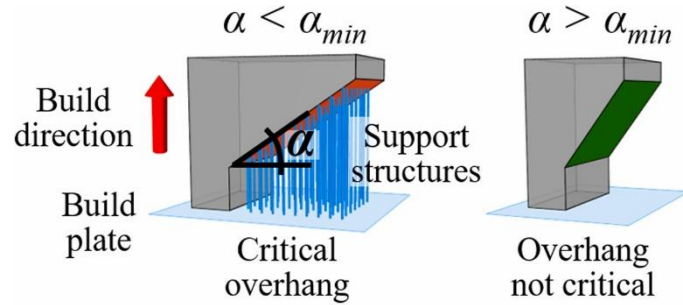


Figure 1.14. Support structure requirement for inclined angle [57].

In single-nozzle systems, these supports are fabricated from the same material as the part itself, whereas in dual- or multi-nozzle configurations, dissolvable support materials can be employed. These are commonly based on materials such as polyvinyl alcohol (PVA), high-impact polystyrene (HIPS), or PLA, which can later be removed through immersion in water or appropriate solvents. Despite their broad applicability, MEX techniques are associated with several intrinsic limitations, including pronounced anisotropy, internal porosity, limited interlayer bonding, and limited geometric resolution. The mechanical anisotropy introduced during layer-by-layer construction is closely linked to layer thickness and can significantly reduce overall structural performance. According to Kuznetsov et al. [58], when the layer height is kept constant, using a larger nozzle diameter can lead to greater flexural strength. Their findings also indicate that reducing the layer height further improves strength. As a result, increasing the nozzle diameter-to-layer height ratio enlarges the interlayer contact area, thereby contributing to a higher ultimate flexural strength. Consequently, critical load paths should be oriented parallel to the build plane, and geometries that rely on Z-direction strength should be avoided. Moreover, a range of processing parameters, such as raster orientation, inter-layer spacing (air gap), build orientation, and infill pattern, play a decisive role in determining the final mechanical response of printed parts. For example, Letcher et al. [59] observed that PLA samples achieved maximum tensile strength at a raster angle of 45°, while Chacón et al. [50] reported that flat and on-edge build configurations yielded the highest tensile strength and stiffness among the tested orientations. Infill patterns and wall thickness also influence performance and print time. For instance, a honeycomb or gyroid infill can provide superior stiffness-to-weight ratios while reducing material usage. Parametric control of infill density enables the balancing of mechanical strength and printing efficiency [60].

Improvements in MEX have significantly expanded its process capabilities beyond conventional 3-axis systems. These advancements include the integration of 5-axis printing strategies [61] enabling improved geometric freedom and reduced need for support structures, as well as the incorporation of FDF into hybrid manufacturing systems that combine additive and subtractive operations within a single platform [62]. Additional innovations involve the direct deposition of continuous filaments onto pre-existing substrates, which enhances process flexibility and enables the fabrication of large-scale or functionally graded structures [63,64].

For aerospace applications, high-performance thermoplastics processed via MEX techniques are increasingly adopted for their superior strength-to-weight ratio, thermal stability, and resistance to demanding environmental conditions, including vacuum, radiation, and extreme temperature fluctuations. Polymers such as polyether ether ketone (PEEK) and polyetherimide (PEI) are particularly attractive, as they enable the fabrication of lightweight yet mechanically robust components with excellent chemical resistance. However, their processing requires advanced MEX systems capable of operating at elevated extrusion temperatures (typically above 300 °C) and controlled heated chambers (approximately 70–200 °C), which are essential to ensure adequate interlayer bonding and to reduce residual stresses. These materials are widely used in applications including structural brackets, interior cabin components, cable management systems, ducting, and satellite housings, where dimensional stability and long-term reliability are critical [65,66]. More recently, emerging research has explored 3D-printed PEEK combined with cork to develop reusable, sustainable, high-performance thermal protection systems for spacecraft.

1.4.3.2. Design for Vat Photopolymerization

Originally patented in 1986, stereolithography (SLA) was the first AM technology ever developed. Today, it remains one of the most cost-effective processes for producing components with outstanding dimensional accuracy and superior surface quality. Vat photopolymerization refers to a family of processes that rely on the selective curing of liquid photopolymer resins through controlled light exposure. According to the exposure strategy, VP technologies can be classified into three main subgroups: (i) SLA, (ii) digital light processing (DLP), and (iii) volumetric AM. SLA operates through point-by-point UV laser scanning, whereas DLP simultaneously cures entire layers using projected light patterns. In contrast, volumetric approaches generate a complete 3D object through a single light field projected into a rotating (tomographic) resin vat [67]. Although still at an early stage of development and currently largely restricted to biomedical applications, volumetric VP offers key advantages over SLA and DLP by enabling the fabrication of full 3D geometries in a single exposure, thereby eliminating layer-wise construction and significantly reducing build time and anisotropic effects. Continuous Liquid Interface Production further enhances SLA by introducing a controlled photochemical mechanism that maintains a continuous liquid interface, enabling layerless fabrication, achieving build speeds approximately 25-100 times faster than conventional SLA, and improving overall part quality and performance [69]. Another important advancement is two-photon polymerization (2PP), a micro- and nanoscale manufacturing technique capable of producing highly complex three-dimensional architectures with sub-micron resolution through localized polymerization driven by nonlinear light-matter interactions. Unlike conventional VP processes, where a single photon initiates polymerization, 2PP relies on the simultaneous absorption of two photons, typically generated by femtosecond or picosecond laser pulses [68].

In contrast to MEX systems, VP is generally not well-suited for multi-material printing, as it requires replacing or separating photopolymer vats for different materials. Nevertheless,

efforts are being made to overcome this constraint [70]. Typical layer thicknesses in VP range from approximately 25 to 100 μm , enabling high-resolution fabrication and fine feature definition compared to MEX processes. VP systems may operate in either top-down or bottom-up configurations, which directly influence process parameters such as peel forces, build speed, and scalability. In bottom-up VP systems, the light source is located beneath a transparent resin vat, and the part is built upside down, with each layer cured and then detached from a coated vat window through a peeling step. This configuration is common in desktop printers due to its simplicity and low cost, but it is limited in build size because higher peeling forces reduce process reliability for larger cross-sections. In contrast, top-down systems cure layers from above and are typically used in industrial equipment, offering greater scalability and larger build volumes while maintaining high accuracy, although with higher system complexity and cost [53,71].

Despite its ability to produce highly detailed components with excellent surface finish, VP exhibits several inherent limitations, including material brittleness, limited long-term environmental stability, and sensitivity to UV-induced degradation. Although mechanical behaviour is more isotropic than in MEX processes, it remains dependent on parameters such as layer thickness, exposure conditions, and build orientation. Process variables, including exposure time, light intensity, and layer height, significantly influence the degree of polymerization and, consequently, the final mechanical properties. Design guidelines for VP must carefully address key process limitations, including support structures, curling effects, and interlayer adhesion, to ensure optimal part performance and quality. Due to the liquid nature of the photopolymer resin, support structures for overhangs and intricate features are always fabricated, with the same material as the final part. These supports must be manually removed after printing and can leave surface marks [55]. Consequently, appropriate part orientation plays a critical role in minimizing support requirements, particularly in functionally or visually sensitive regions. In top-down SLA systems, support requirements are similar to those in FDM, with support mainly needed for overhangs and bridges, and a critical overhang angle of approximately 30° [53]. Parts can be oriented more freely and are often positioned to minimize layer count and support volume. In bottom-up systems, support design becomes more critical due to additional peeling forces acting on the part. Minimizing the cross-sectional area per layer is essential to reduce detachment forces from the build platform. As a result, parts are typically oriented at an angle that prioritizes process stability rather than minimizing support material usage. Curling is one of the most common accuracy-related defects in SLA, analogous to warping in FDM. It occurs due to resin shrinkage during UV exposure, which induces internal stresses that lead to deformation or edge lifting. Preventive strategies include optimizing support placement, adjusting part orientation to avoid large flat surfaces, and limiting excessive post-curing or UV exposure that may intensify residual stress development. Another important consideration is resin drainage. Enclosed cavities may trap uncured resin, leading to contamination or deformation. To prevent this, drainage holes must be incorporated into the design to allow excess resin to escape. The placement and diameter of these holes depend on the resin's viscosity and the geometry of the part. Wall thickness and cross-section transitions should also be uniform to ensure consistent curing and reduce

internal stresses [57]. In digital workflows, simulation tools can predict over-cure regions and optimize exposure parameters, linking digital design decisions directly to print fidelity. VP workflows must also account for shrinkage and post-curing distortion. Parts are typically oversized slightly in the CAD model to compensate for these effects. Such corrections are incorporated into slicer settings or applied through digital scaling algorithms [57]. Following fabrication, post-processing steps are required, such as solvent cleaning and UV post-curing to achieve the desired mechanical properties and surface quality. However, the post-curing stage increases material hardness while reducing ductility, often resulting in brittle parts.

VP materials have evolved significantly from conventional low-viscosity acrylate and epoxy resins to highly engineered ceramic-filled systems designed for functional applications. Recent developments in high-load ceramic resins, as demonstrated in advanced studies on VP-based ceramic AM, show that it is possible to incorporate very high solid loadings of ceramic precursors while maintaining adequate photopolymerization and printability, enabling the fabrication of complex ceramic green bodies with improved mechanical integrity and controlled shrinkage after sintering. These formulations typically consist of photosensitive monomer systems combined with finely dispersed ceramic powders or reactive precursors, which are subsequently converted into dense ceramic structures through debinding and high-temperature sintering [72,73]. For aerospace applications, these material systems are particularly advantageous due to their ability to produce lightweight, geometrically complex components with high thermal stability, excellent wear resistance, and improved performance in extreme environments. The development of high-loading ceramic resins further enhances the potential of vat photopolymerization for manufacturing thermal protection systems, structural brackets, and other high-performance ceramic components where precision, material efficiency, and multifunctionality are critical [73]. Additionally, volumetric VP represents a promising approach for in-space manufacturing due to its ability to rapidly produce complex 3D geometries without layer-by-layer construction, making it particularly suitable for microgravity and resource-constrained environments. This technology enables on-demand fabrication of lightweight structural components, optical (transparent) devices, microfluidic devices, and other functional parts for space systems. In addition, it holds emerging potential for biomedical applications, including the production of tissue-like structures and biologically relevant constructs, supporting future long-duration space missions where in situ resource utilization and medical autonomy are relevant [74].

1.4.3.3. Design for Powder Bed Fusion

PBF encompasses AM techniques such as Selective Laser Sintering (SLS), SLM, Multi Jet Fusion (MJF), and Electron Beam Melting (EBM), all of which rely on the selective consolidation of powder materials using a thermal energy source. These processes typically involve the use of thermoplastic powders (usually polyamide 12, but also PP, PEEK, TPU, among others [75]) or metallic powders (e.g., titanium alloys, aluminium alloys, stainless steels [76]). More recently, ceramic powders have also been processed directly using PBF techniques [77], providing an

alternative to the conventional indirect SLS approach [78]. In contrast to MEX and VP processes, PBF benefits from the surrounding powder bed, which acts as support for overhangs and complex geometries, significantly reducing or even eliminating the need for additional support structures, particularly in polymer-based systems. Typical layer thicknesses in PBF range from approximately 20 to 100 μm , depending on the material and process, enabling a good balance between resolution, surface quality, and mechanical performance. The process is carried out within a controlled environment—often under inert gas or vacuum conditions—to prevent oxidation and ensure material integrity, especially for metals [76]. Thermal gradients generated during selective melting or sintering can lead to residual stresses, distortion, and potential cracking; therefore, careful control of process parameters such as laser power, scan speed, hatch spacing, and preheating temperature is essential [79]. Design guidelines for PBF techniques must respect minimum feature sizes and wall thicknesses (typically around 0.7–2 mm), ensure adequate hole diameters (generally above 1.5 mm), and include escape holes to remove trapped powder in hollow structures. Additionally, uniform wall thickness and smooth geometric transitions are recommended to minimize residual defects resulting from thermal gradients during processing. Large flat surfaces should be avoided or reinforced with ribs to improve stiffness and dimensional stability [53]. Simulation tools such as Ansys Additive Suite and Simufact Additive can predict residual stresses and distortions, enabling compensation directly within the CAD model before printing. Chen et al. [80] pointed out that, with respect to thermal behaviour, predictive modelling is critical for analysing dimensional variations and enabling adjustments to maintain dimensional accuracy. PBF technologies are known for producing parts with high density and excellent mechanical properties, often approaching those of conventionally manufactured components. Although anisotropy is generally lower than in MEX processes, mechanical performance still depends on build orientation and scan strategy [76,81]. In metal PBF systems, support structures may still be required, not only for overhang stabilisation but also for heat dissipation and anchoring parts to the build platform [82]. These supports must be removed after fabrication, typically through machining or other post-processing methods. Parts produced by PBF commonly exhibit defects such as porosity, incomplete fusion holes, residual stresses, and surface roughness, which can compromise mechanical performance, dimensional accuracy, and surface finishing [76]. To minimise such defects, post-processing steps are often applied, typically including stress relief through heat treatments, hot isostatic pressing, and surface finishing. Recent advancements in PBF include the development of multi-laser systems [83], improved in situ monitoring and process control [84], and the integration of PBF into hybrid manufacturing platforms that combine additive and subtractive processes [85,86]. For aerospace applications, PBF is particularly attractive due to its ability to produce lightweight, high-strength components with complex, topology-optimised geometries and, in some cases, to integrate multimaterial architectures within a single build [87]. Metallic materials, such as titanium, Inconel, and aluminium alloys, are used for critical components, including structural brackets, turbine parts, heat exchangers, and satellite structures [88-90].

1.4.4. AI-Driven Design Tools

Artificial Intelligence (AI) and Machine Learning (ML) are emerging as powerful accelerators of AM design. Unlike classical optimisation, which relies on explicit mathematical formulations, AI-based approaches learn patterns from datasets of past designs, simulations, and manufacturing outcomes [91,92].

Key applications include:

- Performance prediction models: ML algorithms that predict stress distribution, thermal distortion, or surface quality prior to fabrication [93].
- Support-generation optimisation: AI systems that minimise support volume and improve surface finish [94].
- Process parameter optimisation: Algorithms that recommend scan strategies, laser power settings, or infill patterns based on target material properties [95].
- Cost estimation: Printing cost and time are critical in AM, but are difficult to estimate accurately using simple volume-based methods. ML models and simulation-based predictions can provide more accurate and adaptive cost estimates [95].

These tools shorten design cycles, enable rapid exploration of alternative geometries, and facilitate the integration of DTs into AM workflows.

1.4.5. Sustainability in DfAM

Sustainability has become a central concern in modern engineering practice, driven by global efforts to reduce material waste, energy consumption, and environmental impact. It is both an opportunity and a design imperative in DfAM. Unlike conventional subtractive processes, which often generate significant material waste, AM constructs components by depositing material only where it is required. Sustainability in DfAM arises from two complementary mechanisms:

1. Intrinsic sustainability of AM processes, including reduced scrap generation and the ability to fabricate lightweight geometries [96].
2. Digital design methodologies that enable optimisation of energy use, material efficiency, product longevity, and end-of-life product manufacturing processes [44].

1.4.5.1. Material efficiency through DfAM

Material efficiency represents one of the most significant sustainability advantages of AM. Traditional machining can waste up to 70% of the initial stock material [91], particularly in aerospace and tooling applications. In contrast, AM employs near-net-shape production, depositing only the material required to achieve the final geometry. Therefore, DfAM can enhance this efficiency, and thus sustainability, by enabling the incorporation of:

- Topology-optimized geometries, which remove unnecessary mass and align material with load paths.
- Lattice and cellular structures, which reduce weight while maintaining performance.
- Hollow internal channels or variable-density infills, which decrease material volume without compromising functionality.
- Minimal support structures are achieved through orientation optimisation and self-supporting geometry, which reduces material usage and post-processing requirements.
- Design features that facilitate powder removal and efficient support detachment, which reduce post-processing waste.
- A reduced number of unique components in assemblies through functional integration and part consolidation, which lowers inventory demands and spare-part requirements.

Furthermore, lightweighting reduces operational energy consumption over the lifecycle of manufactured components. Huang et al. [92] highlighted that lightweight AM components can significantly lower fuel usage in aircraft, generating long-term environmental benefits. Aeronautical parts optimized for AM can reduce aircraft mass, thereby decreasing fuel consumption and emissions.

1.4.5.2. Digital design for circular manufacturing

Digital design tools within AM workflows increasingly support circular manufacturing principles (reduce, reuse, and recycle). DfAM contributes to circularity by incorporating design-for-disassembly strategies, enabling components to be easily repaired, replaced, or reused. It also supports design-for-recycling approaches through material-selection tools that prioritize recyclable polymers and metal powders. Moreover, lifecycle simulation capabilities allow environmental impact assessments to be integrated into the early stages of product development, ensuring that sustainability considerations guide decision-making from the outset [40].

1.4.5.3. Environmental limitations and challenges

Despite its potential, AM is not universally sustainable. Several challenges must be acknowledged [97]:

- Cost and speed of production
- Changing the way that designers think about and approach the use of AM.
- Development and standardization of new materials.
- Validation of the mechanical and thermal properties of existing materials and AM technologies.
- Automation of AM systems and process planning to improve manufacturing efficiency.
- Post-processing is often required.

- Support structure materials cannot be recycled, and as such, they need to be minimized through a good build-up orientation.
- High energy consumption, particularly in metal AM.
- Material recyclability limitations, including polymer degradation after repeated processing and powder contamination in metal systems.
- Lifecycle assessment complexity, as AM's environmental impact varies significantly with material type, machine architecture, and operational conditions.
- Limited and uncertain performance due to the low maturity of certain technologies for large-scale structures.

Sustainability profits depend on applying AM in contexts where it provides genuine added value, rather than using it as a direct substitute for conventional manufacturing. Achieving sustainability, therefore, requires careful consideration of energy consumption, material selection, and the broader manufacturing context. As the field continues to evolve, digital tools and data-driven design approaches will play an increasingly central role in assessing and maximizing the ecological benefits of AM.

1.5. Integration of 3D Printing in Digital Production Systems

DPS are defined as integrated ecosystems that connect product definition, process planning, manufacturing execution, inspection, and lifecycle management through computable models and data. In practice, a DPS integrates the digital thread, ensuring traceable continuity from design intent to qualification data. In addition, the DPS integrates a DT, a virtual representation of parts, assets, or processes that mirrors the behaviour of the physical system [98-100]. These elements operate within the context of smart factories (Industry 4.0) [99], facilitating communication between machines, sensors, and platforms. In the context of AM, this involves integrating design models, machine and sensor logs, inspection data, and service usage data, thereby enhancing prediction and feedback throughout the lifecycle. This approach is now central to modern manufacturing digitalisation, providing the foundation for data reliability and computability within and across organisations [98,99].

The integration of 3D printing into digital production ecosystems represents a fundamental shift from isolated design and fabrication stages towards continuous, data-driven development workflows. Within this framework, geometric, material, or process-related objects are transformed into a digital asset that can be simulated, validated, and iteratively improved before and after fabrication [99-101]. The resulting closed-loop feedback between virtual and physical domains has been demonstrated to accelerate innovation, reduce waste, and strengthen traceability, particularly in sectors that demand rigorous quality assurance, such as aerospace and aeronautics [100,101]. The following sections will detail the enabling concepts of digital threads, DT, Industry 4.0 connectivity, and model-based systems engineering (MBSE), which collectively form the foundation of this transformation.

1.5.1. Digital Concepts for Additive Manufacturing Integration

1.5.1.1. Digital Thread

The digital thread is a foundational element of modern DPS, serving as the comprehensive framework that integrates all phases of a product's lifecycle. It enables the integration of design, analysis, manufacturing, inspection, and maintenance data into a traceable, continuously updated information flow [98]. Singh and Willcox [102] defined the digital thread as "data-driven architecture that links together information from all stages of the product life", encompassing the conceptual, structural design, testing, manufacturing, service, and disposal phases. Rather than a single software platform, the digital thread constitutes an operational integration of multiple digital tools, such as CAD, CAE, and CAM [103].

In AM, the digital thread is particularly relevant due to the high data intensity and process variability of layer-by-layer fabrication. Each AM build generates extensive datasets involving geometric design, material parameters, machine settings, and sensor measurements. Without a structured framework, such information frequently remains fragmented, impeding traceability and reproducibility. The integration of AM within a digital thread enables engineers to ensure that design intent, process execution, and inspection evidence are captured in an unbroken digital sequence [103-106].

The role of the digital thread in AM also extends to model-based certification, an emerging approach in the aerospace and aeronautical industries [106]. In conventional manufacturing, certification relies on rigorous physical testing and documentation. Conversely, a digital thread workflow can automate the collection of evidence, establishing a connection between each element of the digital design and production chain and its verified data source [101,106]. Such a system of traceability is fundamental to the airworthiness certification process, where every geometric modification or process parameter must be justified. Therefore, this integration has been demonstrated to reduce documentation redundancy and accelerate regulatory approval cycles [107,108].

However, implementing digital threads raises technical and organizational challenges, including diverse data formats, proprietary machine interfaces, and non-standardised terminologies [109]. Efforts led by NIST and ISO/ASTM aim to address these gaps by defining standardized data schemas for AM workflows, such as ISO/ASTM 52920 for site-level quality management [110] and ISO/ASTM 52915:2020 for the specification of the AM file format [111]. Another challenge is ensuring data security and intellectual property protection across collaborative supply chains. However, despite these challenges, the digital thread emerges as the key catalyst for ensuring digital continuity in the AM domain.

1.5.1.2. Digital Twin

The DT is the dynamic virtual counterpart of a physical product, process, or system that uses real-time data exchange and physics-based simulation to mirror the behaviour and condition of its physical counterpart. According to Tao et al. [112] DT can be defined as a "multiphysics,

multiscale, probabilistic, ultra fidelity simulation that reflects, promptly, the state of a corresponding twin based on the historical data, real-time sensor data, and physical model", thereby highlighting its role between the physical and digital domains. Although it was not its first appearance, the concept was articulated in NASA's aerospace research programs, where Glaessgen and Stargel [113] envisioned DTs as virtual surrogates for airframes and engines, capable of predicting performance degradation and guiding maintenance decisions.

In AM, DTs exist at multiple levels (process, product, and system), corresponding respectively to the manufacturing process, the produced o, and the production environment. Process twins are a method of replicating the physics of material deposition, thermal gradients, and residual stress evolution. They are used for real-time control or optimisation of AM process parameters [114]. Product twins represent the geometry and microstructure of the built part, enabling virtual testing under realistic loading conditions [115,116]. System twins that monitor and optimise factory operations, machine health, and production scheduling [117].

Nevertheless, implementing robust AM DTs presents considerable challenges. Firstly, the fidelity and validation of physics-based process models remain limited, especially for metallic alloys used in aerospace [118-120]. High-resolution simulations require computationally intensive solvers, which are not yet feasible for real-time control [121,122]. Secondly, the process of assimilating data, which involves integrating simulation and sensor data, is challenging due to noise, temporal misalignment, and incomplete measurements [123]. ML techniques are increasingly being explored to address these issues by enabling models that accelerate computation while preserving accuracy [124,125]. Thirdly, regulatory acceptance of DTs as part of certification evidence is still emerging. While aerospace agencies such as the EASA, the FAA, and NASA recognise the potential of DTs for verification and validation, there is a paucity of research on standardised frameworks for their use in safety certification.

Finally, the DT complements the digital thread: the thread provides traceability, while the twin provides predictability. Together, these elements establish a closed-loop manufacturing ecosystem in which each physical event is mirrored, analysed, and optimised in the digital domain.

1.5.1.3. Industry 4.0 and Smart Factories

The emergence of Industry 4.0 corresponds to the transition from isolated production chains to cyber-physical manufacturing systems, in which data from machines, sensors, and digital models are integrated across the enterprise [126]. In such systems, automation is enabled by the convergence of industrial Internet of Things (IoT) connectivity, big data analytics, AI, and cloud computing, resulting in factories that become self-aware, self-optimising, and self-configuring entities. AM aligns with this approach due to its connection to digital models, layer-wise data, and machine feedback. Unlike conventional operations, AM integrates design, process planning, and production in a fully digital workflow, thus defining it as a native Industry 4.0 technology.

As mentioned, in a smart factory, AM serves as both a digital node and a data generator. Each printing system can be integrated into a cyber-physical loop in which sensor networks monitor process variables, such as temperature, laser power, layer morphology, and acoustic emissions, which are then transmitted to manufacturing execution systems (MES) and DT platforms for real-time analysis [31]. The resulting feedback enables adaptive control and predictive maintenance while updating product- and process-level digital twins [117,127].

Table 1.1 illustrates the conceptual differences between traditional and Industry 4.0 factories by comparing key data sources, attributes, and technologies at the component, machine, and production-system levels. In this context, AM machines transition from conventional condition-based monitoring to self-predictive, self-comparing entities capable of estimating remaining useful life and automatically adjusting process parameters.

Table 1.1. Comparison of most of today's factories and an Industry 4.0 factory [126].

	Data Source	INDUSTRY 3.0		INDUSTRY 4.0	
		Key Attributes	Key Technologies	Key Attributes	Key Technologies
COMPONENT	Sensor	Precision	Smart Sensors and Fault Detection	Self-Aware Self-Predict	Degradation Monitoring & Remaining Useful Life Prediction
MACHINE	Controller	Producibility & Performance (Quality and throughput)	Condition-based Monitoring & Diagnostics	Self-Aware Self-Predict Self-Compare	Up Time with Predictive Health Monitoring
PRODUCTION SYSTEM	Networked manufacturing system	Productivity	Lean Operations: Work and Waste Reduction	Self-Configure Self-Maintain Self-Organize	Worry-free Productivity

In an Industry 4.0 environment, AM equipment is connected through industrial IoT gateways that collect high-frequency data streams. These data are aggregated in cloud or edge computing infrastructures, where analytics modules extract performance indicators, including energy consumption, deposition stability, and build success probability [128,129]. The integration of AM with enterprise resource planning (ERP) and MES software enables dynamic scheduling, part traceability, and automated generation of certification records. In aerospace manufacturing, this capability is critical because integrating smart factory connectivity supports the extensive documentation trails required by EASA and FAA for quality assurance and airworthiness compliance. The DT functions as the coordinating element within this

network. For instance, process twins use real-time sensor data to adjust scanning strategies. Product twins validate part performance through simulation updates. System twins process shop-floor information to optimise global throughput, including machine health, job queues, and environmental conditions [112,117]. The outcome of this process is a fully closed-loop manufacturing cycle in which design and production are in continuous communication.

1.5.1.4. Data, Model and Process Integration

The integration of AM within DPS depends on the interoperability of heterogeneous models (geometric, analytical, process-based, and data-driven) and on the efficient exchange of information among them [103-105]. In a digital thread framework, models serve as computable representations of both physical artefacts and manufacturing behaviour, ensuring that every design or process decision is recorded, validated, and traceable throughout the product life cycle [102,109]. These models extend beyond conventional CAD to CAE, build-process simulation, material and sensor models, and the DT. Collectively, these elements establish a complex system of interconnected representations that facilitate data-driven design, fabrication, inspection, and operational monitoring [101,112].

The foundation of the digital thread is composed of CAD and CAE models. CAD defines the nominal geometry, tolerances, and metadata required for manufacturing, while CAE provides the structural and thermal analyses that guide topology optimisation and performance verification. In AM, these design representations must incorporate build-orientation constraints, support strategies, and material-dependent anisotropy [118,130]. In model-based design environments such as STEP AP242 or ISO/ASTM 52915 (AMF), this information can be embedded directly within the part file, thus linking geometry to process metadata, ensuring that the digital model is not merely a visual reference, but a complete definition of design intent, forming the first element of the digital thread [103,111]. The outputs of CAE analysis, such as stress fields and thermal gradients, are transferred to AM process models. In these models, they inform scan-path optimisation and distortion compensation. For instance, residual-stress predictions from FE simulations can be used to modify layer-wise strategies before printing, thereby achieving DfAM convergence between virtual and physical domains [120-122,130].

Process AM models depend on two main components: physics-based solvers and data-driven approaches. These are used to predict layer quality, porosity formation, and dimensional accuracy [118,122]. In smart factories, integrating sensor models that convert raw signals into measurable quality indicators significantly extends this framework, including optical, thermal, acoustic, and electrical signals [117,123]. The utilisation of machine vision and infrared thermography enables spatially resolved data concerning layer morphology. Concurrently, photodiodes and pyrometers are used to monitor laser power stability [118,119,123-125]. Sensor fusion models can combine these heterogeneous data streams, applying filtering or ML algorithms to reconstruct the state of the building in real time. The calibrated relationships between sensor output and predicted defect probability are then re-fed into the DT, allowing automated anomaly detection and closed-loop control [124,125].

1.5.1.5. Certification and Quality Assurance

Certification and quality assurance are among the most critical challenges in integrating AM within DPS. The aerospace industry is subject to several rigorous regulatory requirements, including those established by the EASA, FAA, and NASA. Conventional certification approaches, which rely heavily on destructive testing, manual documentation, and fixed qualification procedures, are increasingly incompatible with the agile, data-driven nature of AM. The transition to model-based and digitally traceable certification processes represents a paradigm shift that aligns manufacturing assurance with the principles of the digital thread and DT [101,106-109].

In traditional manufacturing, certification evidence is typically produced through isolated documentation stored in disconnected systems, including drawings, material test reports, and inspection records. As previously stated, the digital thread replaces this with a continuous certification record that connects design, process parameters, and inspection results through standardised identifiers. Each manufacturing dataset, whether it be CAD/CAE or process monitoring, is referenced within a unified model, forming a digital certification dossier that can be automatically queried [105,106,109]. The FAA is also exploring this approach by applying model-based systems engineering (MBSE) methods to support airworthiness certification, transitioning from traditional certification to model-based certification workflows, and capturing system requirements, verification data, and compliance evidence within interconnected digital models [131].

DPS also enables traceability at an incredibly high level of detail. Each layer of an AM build can be associated with its precise scan path, laser power, and environmental conditions. This information is linked to corresponding simulation and inspection data via the digital thread, ensuring that any deviations from the design specification can be traced back to their origin [118-120]. However, AM also introduces challenges regarding data integrity and authenticity. As digital workflows become increasingly automated, it is crucial to ensure that data remains tamper-proof and verifiable for regulatory acceptance. Therefore, initiatives within NIST and ISO/ASTM have emphasised the development of standardised schemas and secure data protocols, such as ISO/ASTM 52920:2023, which define the qualification and quality management requirements for industrial AM processes [110].

DTs extend the qualification process by incorporating lifecycle data. Once a component enters service, its operational performance, such as temperature, strain, and vibration, is monitored and compared against predictions made by the DT. This closed-loop verification process strengthens confidence in the digital model and the manufacturing process, thereby supporting continuous airworthiness [110, 9, 115,117]. For example, fatigue life assessment is a crucial certification parameter for metallic AM components. The layer-wise nature of AM introduces process-induced features, such as residual stresses, anisotropic microstructures, and surface roughness, that influence crack initiation and propagation. DTs coupled with high-fidelity process models can estimate the impact of these factors on fatigue before physical testing. Furthermore, inspection data, such as computed tomography porosity maps, can be

incorporated into FE models to perform virtual fatigue testing on the as-built geometry [118-120,125].

Quality assurance in AM depends on multi-scale inspection methods that feed verification data back into process control systems. X-ray CT, ultrasonic testing, and optical metrology generate volumetric and surface data that are automatically compared with the nominal CAD definition. Any discrepancies trigger updates to process parameters or machine calibration routines via the DT feedback loop. In advanced DPS implementations, this feedback loop operates autonomously; defect detection during one build can prompt real-time compensation in subsequent builds. ML models trained on historical inspection data have demonstrated the ability to classify defect types and predict their root causes, effectively functioning as self-auditing systems [105,106,123-125].

In this landscape, DTs and digital threads are not just optional tools but regulatory enablers, providing verifiable evidence of conformity by integrating material pedigree, process conditions, inspection results, and operational history. This digital certification package can then be exchanged between manufacturers and authorities, eliminating the need for manual transcription and significantly reducing lead times and administrative overheads.

1.6. Conclusions

AM in the aerospace industry has evolved into a fundamentally digital-driven paradigm in which performance, reliability, and sustainability are established by the coherence of the entire digital pipeline rather than individual process choices. The successful implementation of AM requires the convergence of advanced digital tooling, physics-based modelling and simulation, design techniques tailored to process-specific constraints, and seamless integration within DPS. In this perspective, AM should not be regarded as a mere alternative manufacturing route, but as a continuous digital workflow in which design intent, process behaviour, and production outputs are intrinsically connected. The alignment of these digital elements is especially important in aerospace applications, where stringent certification requirements, high material and processing costs, and environmental considerations demand a high level of predictability and traceability throughout the manufacturing lifecycle.

Modelling, simulation, and digital print preparation are essential aspects of this digital manufacturing framework, rather than auxiliary validation steps. Their importance extends beyond performance prediction, enabling early detection and mitigation of process-induced problems, such as distortion and residual stresses, which are particularly critical in high-value aerospace components. These digital stages greatly reduce the need for costly physical iterations and experimental trial-and-error by providing early insights into the process behaviour. As a result, simulation-driven preparation promotes a first-time-right manufacturing strategy by increasing decision-making confidence, shortening development cycles, and improving the utilisation of materials, energy, and production resources. In this regard, modelling and simulation serve as a critical link between design intent and the actual reality of AM processes.

In this setting, design takes on a fundamental and distinguishing role, positioning DfAM not as a late-stage adaptation of conventional solutions, but as a strategic driver from the very beginning of component development. Methodologies such as topological optimisation, generative design, and lattice structures enable designers to leverage AM's inherent geometric freedom while addressing structural performance, weight reduction, and functional integration. Importantly, these techniques should be viewed as enabling mechanisms rather than goals in and of themselves, with their effectiveness ultimately determined by how well they comply with production restrictions, certification requirements, and qualification criteria. In aerospace applications, where performance margins are tight and economic and environmental pressures are high, design decisions are key determinants of component efficiency, cost-effectiveness, and sustainability.

The true potential of AM in aerospace applications is shown when it is embedded within digitally integrated production systems rather than considered as an independent manufacturing technique. Concepts like digital twins and the digital thread provide the basis for connecting design data, process parameters, in-situ monitoring, and post-process information throughout the component lifecycle. This connection promotes greater traceability, data-driven decision-making, and improved process control in smart industrial environments, all of which are necessary to achieve aerospace certification criteria and sustainability goals. Furthermore, the capacity to manage complex data flows and feedback loops is particularly well-suited to the aerospace industry's low-volume, high-value production paradigms, which emphasise flexibility, reliability, and lifecycle transparency.

Looking ahead, the ongoing growth of AM in the aerospace industry will be driven less by incremental breakthroughs in specific machines or materials than by the consolidation and interoperability of the surrounding digital ecosystem. The ability to effectively organise, exchange, and validate data throughout design, simulation, manufacturing, and quality assurance phases will be critical to developing robust, certifiable, and sustainable production workflows. In this regard, data integration, model validation, and standardisation challenges are strategically important because they directly affect confidence in digital decision-making and lifecycle traceability. Finally, the long-term development of aerospace AM will be determined by the extent to which these digital infrastructures can be integrated into coherent, end-to-end systems that promote technological innovation and industrial reliability.

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CHAPTER 2

Materials in 3D Printing for Aerospace Applications

Mehmet Alper Sofuoğlu^{1,*}, Turgay Urla², and Selim Gürgen²

¹Department of Mechanical Engineering, Eskişehir Osmangazi University, Eskişehir, Türkiye

²Department of Aeronautical Engineering, Eskişehir Osmangazi University, Eskişehir, Türkiye

*Corresponding author: asofuoglu@ogu.edu.tr

2.1. Polymeric Materials for 3D Printing

Over the past thirty years, Additive Manufacturing (AM), also known as 3D printing, has drawn significant attention due to its ability to rapidly produce complex geometries. Its advantages over traditional manufacturing such as reduced lead time, customization capabilities, minimal material waste, and high design flexibility have accelerated its use across many sectors. These include medicine, construction, architecture, education, food, fashion, and especially engineering, where it is now utilized in automotive, aerospace, energy, electronics, and maritime applications. Despite its growth, one of the key obstacles to widespread adoption has been the lack of standardized procedures [1–3]. AM encompasses a variety of techniques, each with distinct benefits. Fused Deposition Modeling (FDM) extrudes heated thermoplastic material through a nozzle and is favored for its affordability and adaptability to various material properties. PolyJet printing, which mimics inkjet technology, allows for high-resolution prints with smooth finishes, making it ideal for aesthetic and medical uses. Stereolithography (SLA) uses lasers to cure resin-based materials, with recent enhancements such as Continuous Liquid Interface Production (CLIP) improving speed and accuracy. Selective Laser Sintering (SLS) fuses powdered materials without needing support structures, offering freedom in geometry. Laminated Object Manufacturing (LOM), which bonds layers of material, remains popular for its simplicity in prototyping [4–6].

The emergence of AM has transformed polymer synthesis by enabling precise fabrication of diverse polymers and composites. Thermoplastic polymers are widely used for their ability to form intricate structures and enable rapid prototyping. AM techniques allow accurate placement of reinforcing materials like fibers or particles in polymer matrix composites, enhancing strength and performance. Thermoresponsive polymers, which react to temperature changes, can be engineered through AM for specific applications. Likewise, AM supports the production of thermoplastic elastomers (TPEs) and facilitates the fabrication of multi-material components that combine polymers with metals or ceramics [7,8]. Industries widely adopt polymer-based AM techniques for prototyping and manufacturing. Prototyping accelerates design iterations, cutting both time and cost. Customization is a major benefit,

especially for medical implants and consumer goods. The quick production of tools and fixtures improves manufacturing efficiency, and the ability to perform low-volume production without molds makes it cost-effective. Lightweight polymer components are especially valued in aerospace and automotive fields for improving performance and fuel economy. The flexibility to fabricate designs previously unachievable using conventional methods is a significant advantage.

Polymers produced via AM bring revolutionary benefits. Design flexibility allows for intricate, previously impossible geometries. AM reduces material waste through layer-by-layer fabrication, supporting sustainability. The resulting lightweight parts are especially beneficial in aircraft and vehicles. AM also enables embedding complex functionalities, such as sensors and electronics, within structures. High customization meets the needs of applications ranging from implants to industrial parts [9,10]. The performance and quality of AM polymers are assessed through various characterization methods. Differential Scanning Calorimetry (DSC) determines thermal transitions like melting and glass transition temperatures. Thermogravimetric Analysis (TGA) measures material degradation and thermal stability. Dynamic Mechanical Analysis (DMA) evaluates stiffness and damping properties. Scanning Electron Microscopy (SEM) provides insight into the microstructure and surface morphology of printed polymers. These tools are essential for optimizing materials and ensuring consistent quality [11,12].

Despite significant advances, polymer AM faces ongoing challenges. Key concerns include scaling production to meet growing industrial demand, improving speed, cost-effectiveness, and quality control for large-scale use. Material selection remains a constraint, particularly in tailoring polymers for specific applications while maintaining consistent mechanical and thermal behavior. Balancing performance, sustainability, and cost is essential for broader adoption [13]. Looking ahead, the future of polymer-based AM appears highly promising. Advances in materials science are expected to expand the polymer selection available for AM, opening new avenues across industries. Automation and optimization of production will enhance efficiency and reduce costs, making AM more accessible. Integrating artificial intelligence and machine learning into design workflows will further streamline customization. Furthermore, hybrid manufacturing—combining AM with traditional techniques—is anticipated to gain momentum, enhancing the strengths of both methods. Overall, polymer AM is poised to evolve continually, driving innovation across engineering, healthcare, and beyond [14,15].

2.1.1. 3D Printing of Polymers

Thermoplastics are a class of plastics known for their ability to soften when heated and solidify upon cooling, a process that can be repeated without degrading their essential properties. Traditionally, techniques such as injection molding and material extrusion have been employed to shape thermoplastic parts. However, advancements in AM technologies—particularly FDM and SLS—have enabled the fabrication of intricate thermoplastic structures

through 3D printing. These methods involve heating thermoplastics to a pliable state, followed by extrusion and solidification on a build platform. Thermoplastics are widely used in AM due to their favorable mechanical characteristics, including rigidity, high strength, and stability at elevated temperatures. Commonly utilized thermoplastics in this context include acrylic, acrylonitrile butadiene styrene (ABS), nylon, polylactic acid (PLA), polycarbonate (PC), and polyethylene (PE), as shown in relevant material selection tables [16,17].

A range of AM techniques—such as SLA, SLS, and FDM—has been applied to produce thermoplastic components for both general and specialized applications. These include engineering parts and biomedical devices. For example, Gkartzou et al. [18] investigated FDM-based processing of bio-based PLA blends, focusing on parameters like extrusion temperature, print speed, and fiber width that influence shear stress and melt behavior. Similarly, Childs et al. [19] developed thermal and densification models for PC processed via SLS, while Lee et al. [20] investigated porous polypropylene fumarate (PPF) scaffolds for tissue engineering. Further research has shown the potential of thermoplastics in biomedical microfluidics. Matellan et al. [21] fabricated microfluidic devices using polymethylmethacrylate (PMMA), while PDMS-based water-soluble scaffolds were also printed using specialized microfluidic chambers [22]. Other studies demonstrated the successful use of polymer scaffolds in dental and craniofacial applications [23], and Valtonen et al. [24] replicated nasal cavities for clinical airflow studies. These applications highlight the capability of thermoplastics to enable affordable and complex biomedical solutions through 3D printing. Beyond biomedical uses, thermoplastics are crucial in prototype development and functional part production. Their mechanical performance can be further enhanced by incorporating various reinforcements.

In addition to conventional polymers and composites, responsive polymers are materials that can modify their chemical and physical behavior when exposed to external stimuli such as temperature, pressure, pH levels, ion concentrations, or the presence of specific molecules. Among these, temperature-triggered responses are the most commonly studied. Certain thermo-responsive polymers exhibit a phenomenon known as the lower critical solution temperature (LCST). Below this temperature, the polymer chains mix uniformly with the solvent, forming a homogeneous phase. However, when the temperature rises above the LCST, the mixture undergoes phase separation, leading to distinct structural or functional changes. Notable examples of thermo-responsive polymers include poly[N-[2-(diethyl amino)ethyl acrylamide]] (PDEAEAM), poly(N,N-diethylaminoethyl methacrylate) (PDEAEMA), poly(2-(N-morpholine)ethyl methacrylate) (PMEMA), poly(N,N-dimethylaminoethyl methacrylate) (PDMAEMA), poly(oligo(ethylene glycol)methacrylate), and poly(N,N-diethylacrylamide) (PDEAAM) [25]. These materials are increasingly used in biomedical and smart material applications, such as controlled drug and gene delivery, tissue engineering scaffolds, biosensors, and responsive coatings. Depending on their morphology and architecture, thermo-responsive polymers are categorized into hydrogels, interpenetrating networks, micelles, polymersomes, particles, and films. Recent advancements in AM have facilitated the fabrication of such polymers into complex functional structures. Zhou et al. [26] employed material extrusion AM to process polyvinyl alcohol (PVOH), a heat-sensitive

polymer. They developed a process that combined compounding, extrusion, and 3D printing at minimal processing temperatures. Yuan et al. [27] focused on producing carbon nanotube (CNT) composite powders, which were fabricated using SLS to achieve thermally and electrically conductive properties. Du et al. [28] explored AM of a thermoelectric composite made from carbon black and B12Te3 alloy within a PLA matrix. Their analysis showed satisfactory thermoelectric behavior within the temperature range of 300–360 K. In the biomedical field, Shimizu et al. [29] developed a cell sheet-polymer film complex with good mechanical strength, which could be detached post-transplantation by lowering the temperature. However, these materials faced long-term stability issues due to the presence of extracellular matrix (ECM) proteins. To mitigate this, oxygen plasma treatment was applied to the thermo-responsive polymer poly-N-isopropylacrylamide. In another study, Constantine et al. [30] fabricated copper/diamond composites through AM, demonstrating excellent thermal performance. This further highlights the potential of AM technologies in enhancing the functional capabilities of thermo-responsive and heat-conductive polymer-based composites.

Polymers are also widely favored in AM due to their flexibility, ease of processing, and ability to be shaped into intricate geometries with high precision. Despite these advantages, their relatively weak mechanical properties make them unsuitable for load-bearing or high-strength applications. To address this limitation, researchers have focused on enhancing polymers through reinforcement, resulting in the development of polymer matrix composites. These composites are typically composed of short or continuous fibers embedded in a polymer matrix, which can be derived from both synthetic and biopolymer sources [31]. These reinforcements significantly improve mechanical performance, enabling the use of polymers in structurally demanding contexts. Common reinforcement materials used in AM include carbon nanofibers, TiO₂, montmorillonite clay, and graphene, especially in FDM. In SLA, additives such as carbon nanotubes, graphene oxide, and BaTiO₃ are more commonly used. Sanchez et al. [32] demonstrated that adding 20 wt% carbon fiber to acrylonitrile styrene acrylate (ASA) resulted in a 350% increase in flexural modulus and a 500% boost in thermal conductivity. Glass fiber is another widely used reinforcement. Its orientation within the polymer matrix can be controlled to improve load-bearing capacity, and its mechanical properties can rival those of steel while offering higher stiffness than aluminum [33]. Carneiro et al. [34] investigated the effects of layer orientation and thickness in glass fiber-reinforced composites produced via FDM. Their findings confirmed that FDM is suitable for creating small structural components. One critical factor in composite performance is the interfacial adhesion between the fiber and the polymer matrix. Strong interfacial bonding enhances the mechanical strength and durability of the final material. To improve this adhesion, coupling agents are introduced to chemically bond fibers to the matrix [35]. Fernandes et al. [36] explored the use of short sisal fibers in polyethylene-graft-maleic anhydride composites. They applied alkali treatment to enhance fiber-matrix adhesion and found that 10 wt% sisal fiber combined with 2 wt% coupling agent significantly improved the tensile and flexural properties of the resulting composite. Lastly, Turk et al. [37] proposed four AM-specific design strategies to facilitate better composite fabrication: position and fixation elements, structural handling

aids, layup and handling supports, and post-processing aids. These principles aim to optimize the AM process for reinforced polymer systems.

AM is not only renowned for its ability to fabricate complex three-dimensional structures but also for its growing potential to produce multi-material components within a single manufacturing platform. The incorporation of multiple materials into a single build process has led to enhanced functionality and weight reduction, resulting in improved overall performance of fabricated components [38]. Despite these advantages, multi-material AM still faces technical challenges, including dimensional inaccuracies, the need for post-processing, and difficulties in processing dissimilar materials under uniform conditions. Technologies such as FDM and PolyJet printing are among the most commonly used methods for multi-material AM [39]. Recent research has explored the use of multicomponent bioinks, which combine two or more biomaterials to improve printability, biological functionality, and shape fidelity [40]. Bahr et al. [41] demonstrated the use of SLA for multi-material processing by integrating silver nanoparticle inkjet printing while Bruyas et al. [42] utilized multimaterial AM to develop compliant joints for unibody robotic mechanisms. In electronic applications, researchers have employed multi-material AM to develop functional components. For instance, Pa et al. [43] combined standard FDM with conductive microdispensing to fabricate robust antenna systems featuring dielectric properties and embedded 3D conducting networks. Similarly, Mirotznik et al. [44] used FDM for antenna fabrication, and Nassar et al. [45] designed bendable smart sensing structures using printed strain sensors with excellent electrical conductivity. Taylor et al. [46] used PolyJet technology to create a miniature diaphragm pump composed of multiple materials, while Gheisari [47] developed sensors and communication components through slurry-based multi-material AM coupled with selective laser burnout. Further innovations include Gómez [48]’s hybrid printer, which merges digital light processing (DLP) with drop-on-demand inkjet printing for multi-material electronic device fabrication. Singh et al. [49] conducted a comparative analysis using ABS, PLA, and high-impact polystyrene in FDM-based AM, concluding that these thermoplastics are suitable for load-bearing applications. Altogether, multi-material AM is enabling the fabrication of advanced structures in fields ranging from biomedicine to electronics. However, the process remains constrained by challenges in material compatibility, precision control, and the complexity of managing multiple material flows, requiring continued research and technological refinement.

Apart from other groups of polymers, elastomers are a class of polymers characterized by their weak intermolecular forces, allowing them to deform significantly under stress and return to their original shape when the stress is removed [50]. This reversible behavior under high strain makes them ideal for applications requiring flexibility and resilience. TPEs are a type of elastomer that can be processed using AM techniques to produce rubber-like components. These materials combine the processability of thermoplastics with the elasticity of rubber, offering desirable properties such as softness, flexibility, and durability. TPEs are categorized into six major types: multiblock copolymers, ionomers, hard polymer-elastomer combinations, styrenic TPEs, graft copolymers, and core-shell morphologies. Styrenic TPEs are structured as A–B–A block copolymers, where “A” represents polystyrene (the hard segment)

and “B” is the elastomeric component. Multiblock copolymers, on the other hand, consist of repeating A–B units in sequences like A–B–A–B or $(A-B)_n$. In these structures, segment A is typically a hard thermoplastic such as polyester, polyurethane, or polyamide, while segment B is a soft, amorphous polymer like polyether or polyester. Hard polymer-elastomer combinations are blends in which thermoplastic polymers are finely dispersed within an elastomeric matrix. Graft copolymers represent another class where elastomeric backbones (B) are grafted with thermoplastic side chains (A). For these to function effectively as elastomers, the grafts must be numerous and well-distributed, forming an interlinked network. If the B chains contain fewer than two A blocks, they will fail to form a cohesive structure, diminishing the elastic properties of the material [51]. Moreover, TPEs find significant application in fields like electronics and biomedical engineering due to their processability and mechanical performance. The development of novel elastomeric formulations compatible with AM is expected to accelerate the production of innovative, high-performance products in these domains [52].

2.1.2. 3D Printing Technologies with Polymers in Engineering Applications

AM has revolutionized product development by enabling intricate and highly customized designs that were once impossible using conventional methods. Industries such as automotive and aerospace benefit significantly from AM, particularly through the use of lightweight polymer structures that improve overall system performance. Polymer-based AM provides rapid prototyping and design customization, efficient tooling solutions, and lightweight, high-strength structures. As a result, AM has become a key transformative technology across several industrial sectors. **Figure 2.1** illustrates the diverse range of polymer AM applications.

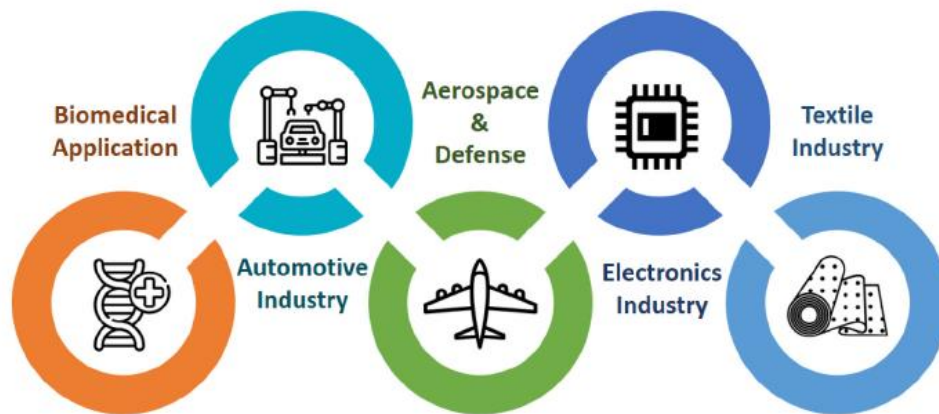


Figure 2.1. Polymer applications in 3D printing technologies [53].

AM plays a pivotal role across multiple advanced technological domains, particularly in healthcare, electronics, textiles, aerospace, and automotive industries, due to its versatility, precision, and ability to create complex, customized structures. In personalized medicine, AM enables the fabrication of patient-specific drug delivery systems by allowing precise adjustment of pharmaceutical dosages and designs. Its capacity to produce intricate geometries makes it especially valuable for manufacturing implants, prosthetics, and tissue-engineering scaffolds that are difficult or impossible to fabricate using conventional methods. Moreover, AM facilitates accurate replication of anatomical structures, offering enhanced control over scaffold porosity, surface characteristics, and overall architecture. When integrated with complementary techniques such as nanofiber fabrication and porous structure generation, AM can yield biomimetic hybrid constructs. For example, wet spinning has been successfully used to process medical polymers—including poly(L-lactic acid), polycaprolactone, and chitosan—into fibrous assemblies often loaded with bioactive agents for regenerative applications. Although AM techniques were initially developed for metals, processes such as Electron Beam Melting (EBM) have demonstrated significant potential in producing anatomically precise, patient-specific implants, thereby improving comfort, functionality, and clinical outcomes [54].

Advanced materials further expand the biomedical applications of AM. Shape-memory polymers (SMPs), particularly biodegradable variants, have gained attention for their ability to undergo remotely triggered shape changes, making them suitable for minimally invasive procedures such as endovascular aneurysm treatments and other smart therapeutic interventions. In bone regeneration, bioactive glass and calcium phosphate-based ceramics are widely employed due to their strong bonding capability with natural bone. These materials are frequently combined with polymers to form composite scaffolds that provide both mechanical stability and osteogenic stimulation, aiding fracture healing and the correction of skeletal deformities. Moreover, Ti–Nb–Zr alloys have emerged as promising materials for orthopedic implants, owing to their excellent biocompatibility, corrosion resistance, low stiffness, high strength, and ductility, with elongation at break values closely matching the mechanical requirements of bone and joint replacements [55]. Beyond biomedical uses, AM has significantly influenced electronics manufacturing by enabling the integration of embedded circuitry through either the transfer of prefabricated components using laser-based methods or the direct printing of functional elements such as interconnects and sensors. Recent advances include the 3D printing of carbon nanotube-based devices, hybrid supercapacitors, flexible pressure sensors, stretchable strain sensors, and flexible antennas using conductive polymers like ABS and various nanocomposites [56]. The textile industry has also benefited from AM through the creation of customized apparel, functional footwear, and smart textiles that combine mechanical performance with aesthetic and responsive functionalities. Research has highlighted improved polymer adhesion on fabrics, with PLA demonstrating superior bonding characteristics, while other studies have explored wear resistance, shape-memory behavior, and the development of conductive, flexible textile structures using polymer-based materials [57,58].

In aerospace and defense, AM has become a standard manufacturing tool for producing both structural and electronic components, enabling rapid, localized production and enhancing strategic autonomy. Initiatives such as the U.S. National Additive Manufacturing Innovation Institute (NAMII) underscore its importance in defense applications. SLA techniques are often preferred over FDM due to their superior durability and suitability for casting. In aerospace applications, AM supports the fabrication of lightweight, customizable polymer composites, reducing fuel consumption and costs while enabling complex geometries and efficient material usage [59]. Similarly, the automotive sector increasingly relies on polymer-based AM to produce lightweight components such as brackets, dashboard elements, air vents, interior trims, and custom fixtures. Materials like PA6 are favored for their thermal stability and mechanical strength, enabling the production of high-performance parts including gears, engine components, and structural supports. AM also enhances precision and quality control through CAD-driven design, ensuring dimensional accuracy and compatibility in components such as mirror holders and other precision parts [60].

2.1.3. Limitations and Opportunities in 3D Printing of Polymers

AM continues to transform various industries by offering advantages like complex geometry creation, cost savings, faster prototyping, and consumer involvement during design. Despite these benefits, AM still faces multiple challenges in terms of production speed, material diversity, cost, quality assurance, standardization, workflow efficiency, and scalability. **Figure 2.2** shows future research directions in several kinds of materials.

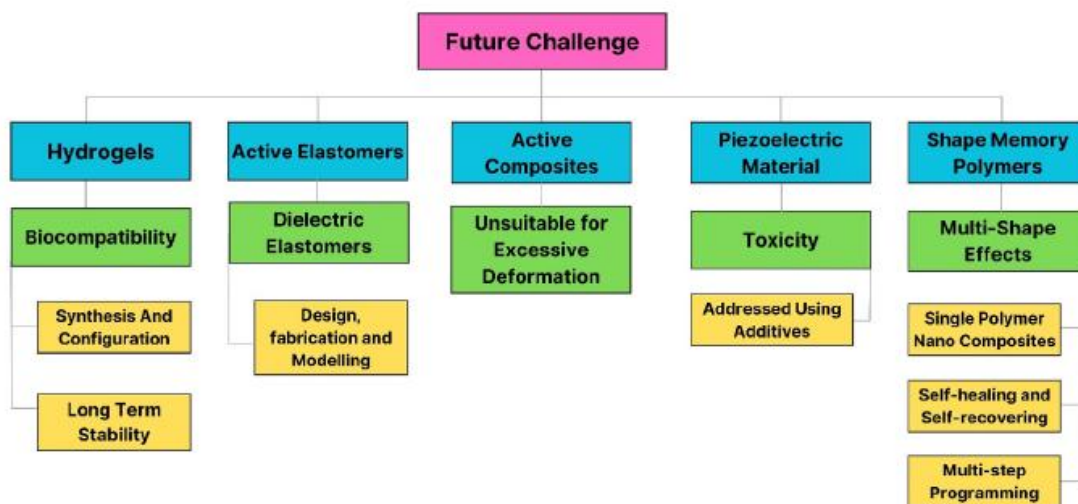


Figure 2.2. Emerging challenges in using and processing various polymers [53].

Although rapid prototyping is becoming more popular in industrial applications, the full potential of AM in final product manufacturing is yet to be realized. A recent survey revealed that only a small number of companies utilize AM for end-use parts, indicating a limited adoption rate. Efforts to scale up production include innovations like robotic arm-based

printing with minimal support structures, and the growing shift towards biodegradable and thermally conductive polymers, which are essential for electronics applications. AM holds promise for reducing production costs and minimizing material waste (by up to 90%) compared to subtractive methods. However, successful large-scale implementation requires ongoing improvements in materials, processes, and learning from prior limitations [61].

Material choice is a critical factor after the AM process is completed. Performance indicators such as durability and mechanical strength must be balanced against cost. A key hurdle is the limited variety of polymers currently compatible with AM, restricting broader applications. There is a growing need to deepen understanding of how polymers behave during AM, expand the range of printable polymers, and translate these materials to practical uses. Post-processing is also essential to enhance the mechanical, aesthetic, and functional properties of AM components. Techniques such as heat treatment, surface finishing, cleaning, and sterilization are vital to finalize parts for application-specific use. Modern research emphasizes the impact of post-processing on performance, especially in reducing residual stresses, preserving ductility, and improving surface quality. This is particularly important for applications requiring precision or unique geometries that are hard to achieve with conventional manufacturing. For example, Dizon et al. [62,63] highlight how post-processing significantly influences the mechanical integrity of both metal and polymer AM parts, making it a critical phase in AM workflows. Common technical challenges in polymer AM include warping, irregular filament diameter, extrusion difficulties, nozzle clogging, and layer separation. To overcome these, parameters such as temperature, printing speed, infill density, flow rate, and cooling rates must be optimized. While AM remains promising for customized, low-volume polymer part production, its success depends on addressing challenges in quality control, material compatibility, post-processing efficiency, and scalability [64].

AM, or 3D printing, is poised to replace conventional manufacturing for rapid prototyping and customized production. Advances in polymer chemistry and technology are enabling more sustainable AM processes, including eco-friendly raw material sourcing, green synthesis, and end-of-life recycling. This shift is expected to support a decentralized production model, where distributed manufacturing hubs replace centralized facilities. As a result, on-demand production will reduce the need to transport finished goods, with only raw materials needing shipment. This will enhance supply chain efficiency and reduce resource consumption and waste. Moreover, open-source design software is making complex digital models widely accessible, democratizing production. Though it may take time to mature fully, this simplified, efficient, and adaptable production model has the potential to revolutionize the industrial landscape. AM in polymer science offers unmatched design flexibility, enabling complex geometries and tailored parts through layer-by-layer fabrication. Compared to traditional methods, AM significantly reduces material waste and energy consumption, aligning with sustainability goals. However, several challenges remain with it. Some of the common drawbacks are limited material compatibility, difficulties in achieving uniform mechanical properties, post-processing requirements, low production speeds, and complexity. To address

these challenges, recent studies are focused on developing new AM-specific polymers, optimizing post-processing techniques, and refining printing parameters.

2.2. Metallic Materials for 3D Printing

Metal AM has undergone substantial advancement in recent decades, driven by the maturation of both research-grade and commercial equipment, and an expanding range of feedstock materials. Key 3D metal printing methods include powder beds, powder jets propelled by gas, and wire-fed systems. These typically use lasers or electron beams as energy sources, along with precision automation to direct material and energy during layer-by-layer fabrication. A major benefit of metal AM is its ability to fabricate complex parts directly from digital designs without the need for molds or tooling. This enables faster and more cost-effective production, particularly for prototypes, customized components, or small-lot production runs. Components with advanced geometries and tailored material properties often unachievable with conventional methods can be produced efficiently. As a result, 3D metal printing is already being adopted across industries and research organizations globally. Despite its advantages, several challenges hinder broader implementation. First, the microstructures and textures created through additive techniques differ significantly from those formed by casting or deformation processing. Second, the complexity of the AM process due to variations in materials, machines, and parameters leads to inconsistencies in microstructure and mechanical properties. Lastly, a deep understanding of defects and the effectiveness of post-processing techniques such as heat treatment or Hot Isostatic Pressing (HIP) is still limited, and remains a key area of ongoing research [65].

2.2.1. 3D Printing of Metals

2.2.1.1. Laminated Object Manufacturing

Laminated Object Manufacturing (LOM), also known as Sheet Lamination, uses stacked metallic sheets as feedstock and bonds them using a localized energy source such as ultrasonic vibration or laser. The most widely used variant is Ultrasonic Additive Manufacturing (UAM), also called ultrasonic consolidation, patented by White. In UAM, ultrasonic vibrations combined with mechanical pressure at room temperature bond metal sheets through diffusion without melting. Layers are pre-cut to the desired geometry and optionally polished during or after consolidation for surface finishing [66]. **Figure 2.3** shows a schematic illustration of UAM method.

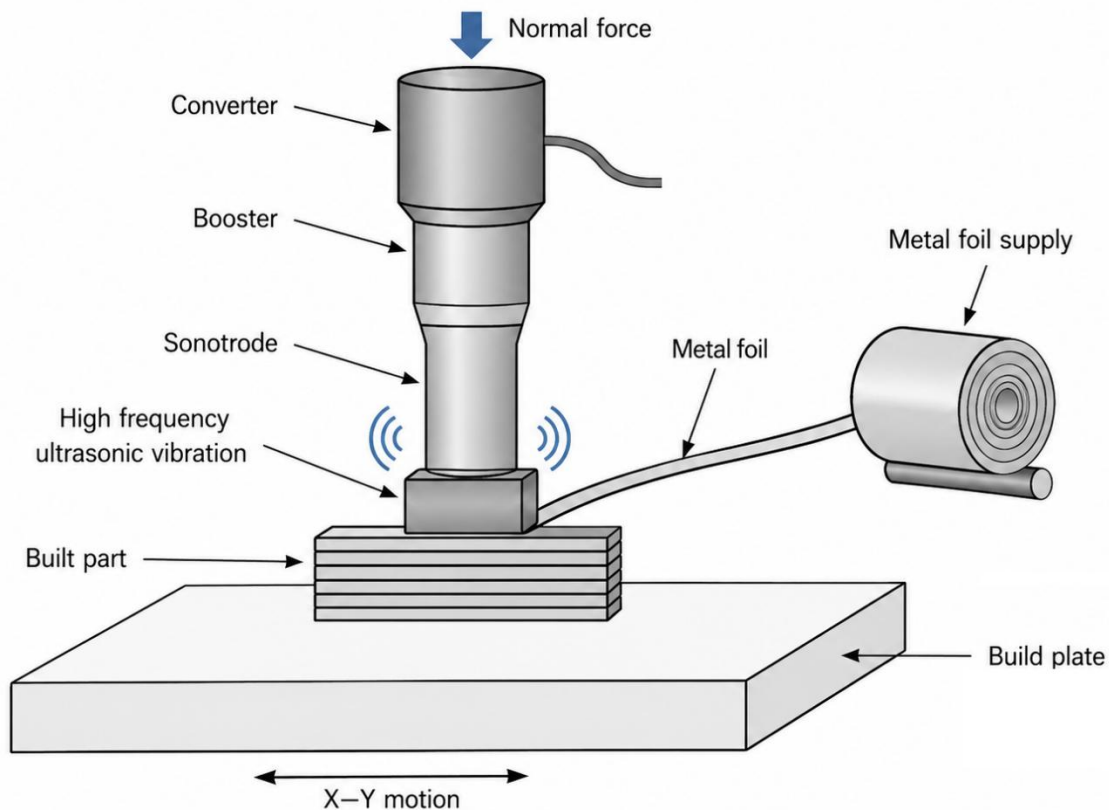


Figure 2.3. Visual representation of the UAM method.

In UAM, metallic sheets are stacked on a base plate, and a digitally controlled sonotrode moves along the rolling direction to apply ultrasonic vibrations and pressure. The vibration causes frictional heat and shear deformation at the interface, promoting bonding. A short cooling period between layers helps avoid residual thermal stresses. Once all layers are built, the part is cut from the base plate and polished [66]. Bonding occurs through asperity formation on the metal surface under ultrasonic vibration and mechanical load. When a new sheet is placed, shear deformation and compression cause asperities to interlock, creating equiaxed grain structures at the interface. Dynamic recrystallization occurs due to localized temperature rise, which is strongly influenced by vibration amplitude. Higher-strength metals tend to produce higher peak bonding temperatures than softer metals [67,68].

Parts made by sheet lamination exhibit anisotropic mechanical properties, with the build (Z) direction being weakest due to interface delamination and pre-existing shear band migration. For example, UAM-fabricated AA6061 can fracture at only one-fourth of the bulk material's yield strength in the Z-direction. Heat treatments and optimized processing parameters, such as sonotrode surface roughness and tape overlap techniques, can significantly improve Z-direction properties [69]. Alternating different aluminum alloys (e.g., AA1050A/AA5005) improves fatigue life compared to pure alloys. Laminated carbon steel composites can resist

higher impact energy in the direction normal to the sheet surface due to delamination effects such as notch blunting. For composites, tensile strength often follows the mixing rule when component ductilities are similar, but large ductility differences make the rule invalid. Sheet lamination offers advantages such as faster production rates, lower costs (since metal sheets are cheaper than fine powders), and the ability to fabricate layered composites from dissimilar metals a challenge for most other AM processes [54]. It also enables high geometric accuracy in the rolling and vibration directions due to precision sheet cutting. However, in the Z-direction, dimensional accuracy is harder to control because layer thickness changes under consolidation pressure [70].

2.2.1.2. Powder Bed Fusion

Powder Bed Fusion (PBF) is an AM technique that uses a high-energy heat source to selectively melt or sinter metal powders on a powder bed. Two major PBF technologies are Selective Laser Melting (SLM) and EBM, which use lasers and electron beams, respectively. Despite their similar underlying principles, their equipment setup and processing conditions differ significantly. **Figure 2.4** shows the layouts for SLM and EBM techniques. In the SLM process, a laser beam is guided using mirrors and lenses across the powder bed, selectively melting powder based on the design. After each layer is completed, the platform moves downward and a fresh layer of powder is spread, repeating the cycle in an inert gas environment usually argon to prevent oxidation. In contrast, EBM uses a powerful electron beam and requires a vacuum environment. The electron beam, controlled via a lens system, melts the powder layer-by-layer, with powder delivered via a rake from a hopper [71].

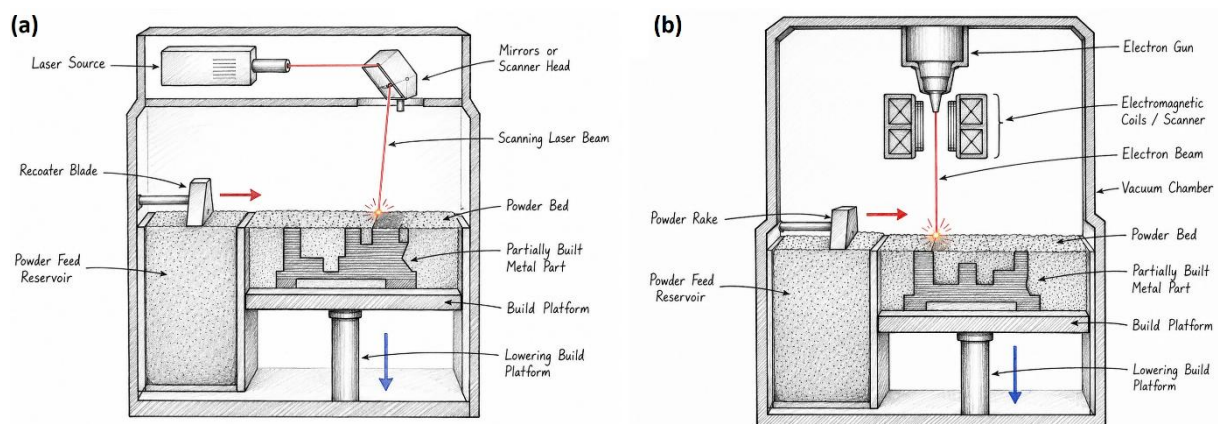


Figure 2.4. Visual layouts of PBF techniques: (a) SLM, and (b) EBM.

The microstructure of PBF parts is influenced by thermal gradients and solidification dynamics. In SLM-fabricated Ti-6Al-4V, grains are elongated and columnar in shape, aligned with the scan direction, due to rapid heating and cooling. Pores often form due to trapped gas or insufficient

melting, especially near edges. The grain structure is governed by the temperature gradient and solidification interface velocity. High temperature gradients with low interface velocity promote columnar grain growth, while equiaxed grains form under opposite conditions. These phenomena can be predicted by models such as the Hunt dendrite growth model. Grain structures and growth in alloys like Inconel 718 can be tailored by adjusting processing parameters such as scan speed and beam power [72]. The mechanical behavior of PBF-manufactured parts, including elastic modulus, ductility, and fatigue resistance, is critical to their industrial use. Binding mechanisms during processing ranging from solid-state sintering to full melting strongly affect these properties. Anisotropy is a common issue, with weaker properties in the build (vertical) direction due to inadequate fusion between layers [73].

Ti-6Al-4V is widely studied due to its importance in aerospace and biomedical fields and its difficulty to machine using traditional techniques. In PBF-fabricated Ti-6Al-4V, SLM parts generally show superior yield and ultimate strength compared to wrought material, attributed to the use of fine powder. However, these parts tend to be brittle with low elongation. Post-process treatments like HIP can significantly enhance ductility while slightly reducing strength. EBM parts show less elongation in the vertical direction but similar strengths across orientations. Machining can improve modulus and strength but does not affect elongation [74]. Although other metals like aluminum alloys and stainless steels have also been studied (e.g., AlSi10Mg and 316L), the volume of data is much lower than for Ti-6Al-4V. Common issues in PBF parts include poor interlayer bonding, high residual stresses from steep thermal gradients, part distortion, warping, delamination, and cracking. These challenges arise due to complex thermal histories during the build process and must be addressed to improve part quality and reliability.

2.2.1.3. Direct Energy Deposition

Direct Energy Deposition (DED) is an advanced AM process that builds parts by melting and depositing metal feedstock directly onto a substrate. Unlike PBF, which spreads powder across a bed, DED systems feed either metal powder or wire into a localized melt pool generated by a focused energy source such as a laser or electron beam. DED techniques are generally categorized by their feedstock type: wire-based methods, derived from traditional welding practices, and powder-based methods like Laser Engineered Net Shaping (LENS), developed by Sandia National Laboratories in 1996 [75]. **Figure 2.5** shows a visual representation of LENS technique. In a typical LENS system, a Nd:YAG laser beam is focused onto the build platform while metal powder is simultaneously injected into the melt pool through a nozzle. The platform or laser head moves to build up layers of solidified material. This process is repeated layer-by-layer until the part is complete. In contrast, NASA's Electron Beam Freeform Fabrication (EBF3) uses a metal wire and an electron beam in a vacuum environment. The beam melts the wire tip, depositing material layer-by-layer. EBF3 is primarily used in space-related applications due to its precision and surface quality, despite slower deposition rates [76].

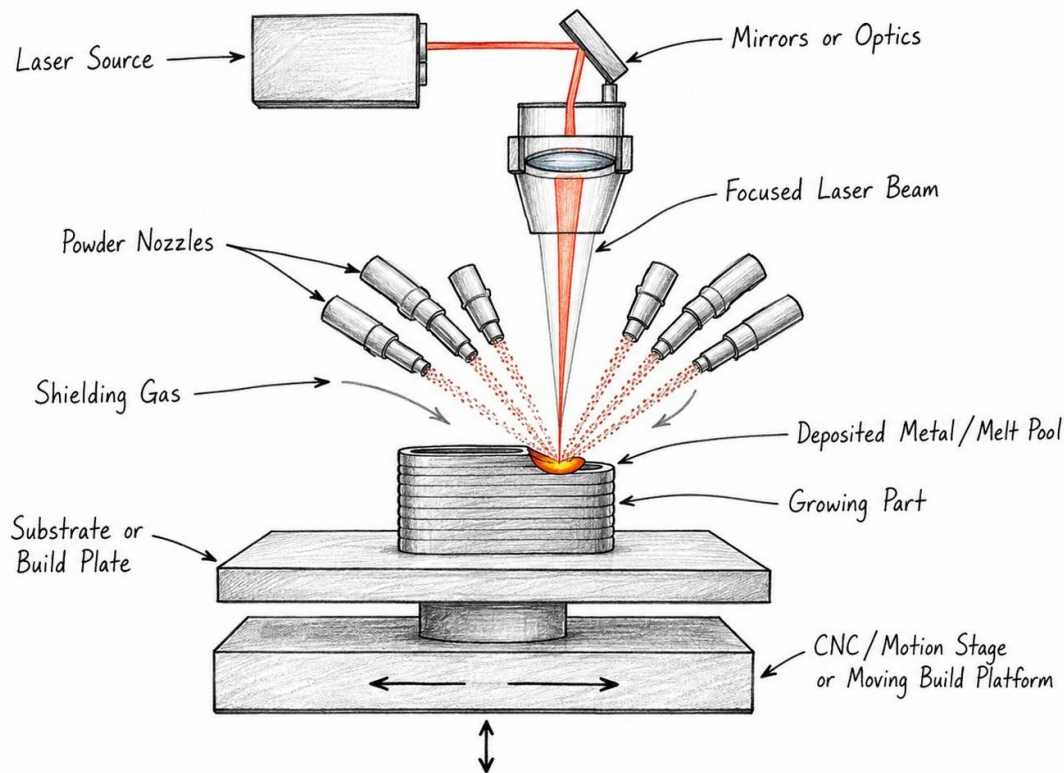


Figure 2.5. Visual representation of LENS technique.

Microstructural studies on LENS-fabricated components reveal that grain morphology is heavily influenced by process parameters such as laser power and scanning speed. Griffith et al. first reported that the mechanical properties especially yield strength of LENS parts are comparable to those of wrought materials and can be tuned by modifying process parameters. Wu et al. confirmed that grain shape and size vary with processing conditions, and Wang et al. identified two solidification mechanisms: epitaxial growth (resulting in columnar grains) and heterogeneous nucleation (leading to equiaxed grains), which compete during deposition. These two grain structures form distinct layers in the part: equiaxed grains form at the top, near the melt pool surface, while columnar grains develop beneath. This creates a layered microstructure, clearly visible in both transverse and longitudinal cross-sections, with Heat-Affected Zones (HAZ) and penetration depths in microscopy images.

In terms of mechanical performance, DED-produced Ti6Al4V and Inconel 718 parts show Young's modulus values similar to wrought materials, but with reduced failure strain in their as-built states. Post-processing with HIP can significantly increase ductility often doubling elongation though it also reduces yield and ultimate strengths due to microstructural changes such as decreased alpha-platelet thickness. A notable characteristic of DED parts is their high anisotropy, which is more pronounced than in PBF parts. This is attributed to the thicker layer heights in DED, resulting in less fusion between layers and therefore weaker bonding in the build direction. Tests on wire-fed EBF3 parts also show variation in mechanical behavior depending on in-plane orientation. Heat treatment can improve bonding between adjacent

wires, enhancing strength, though it does not affect all planar orientations equally. Similar trends have been observed in 316L stainless steel, with reported differences of up to 16% in ultimate strength and 53% in elongation depending on print orientation. Surface properties such as hardness and roughness also vary significantly. For example, microhardness differences exceeding 25% were noted between horizontally (0°) and vertically (90°) printed samples [77].

DED, like PBF, suffers from thermal residual stresses, warping, and distortion due to steep thermal gradients. However, some DED machines utilize 5-axis or more movement systems instead of the traditional 3-axis setups, allowing for larger and more complex parts to be produced with optimized deposition paths. Additionally, unlike PBF systems that require inert or vacuum environments throughout the build, DED systems typically use local shielding gas flow around the melt pool. This enables processing of non-reactive metals without a full inert atmosphere [77].

2.2.1.4. Binder Jetting

Binder Jetting (BJ) is an AM technique that builds parts by depositing a liquid binder onto a bed of metal powder to selectively bond the material. Often referred to as "powder bed and inkjet head 3D printing," this process was first developed and patented by Sachs et al. [78]. The method extends traditional 2D inkjet printing into the third dimension by using one or more nozzles to trace and solidify thin layers of powder. After each layer is bonded, a new layer of powder is spread, and the process is repeated to create a full 3D object, known at this stage as the "green body". **Figure 2.6** shows a visual representation of BJ method.

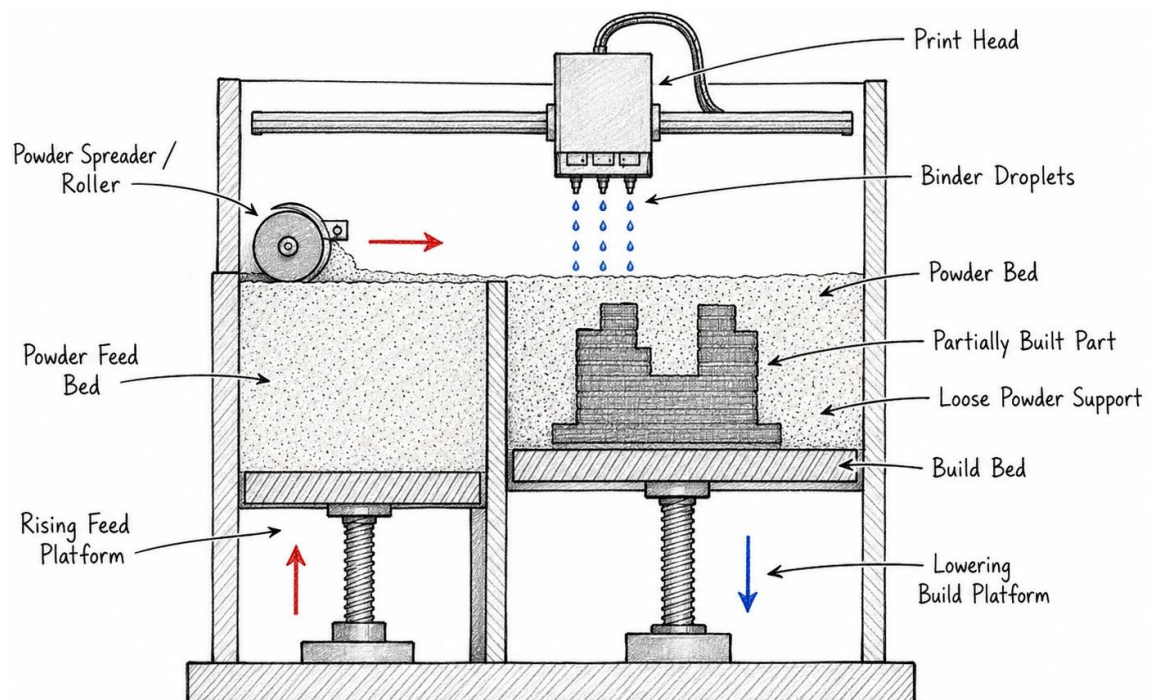


Figure 2.6. Visual representation of BJ method.

The equipment typically includes a build platform and a powder reservoir. A leveling roller spreads a thin layer of powder onto the platform, after which the binder is injected in the X-Y directions. Once a layer is completed, the platform is lowered (Z direction), and another layer of powder is spread and bonded. Upon completion, the green body is removed for post-processing. Post-processing is essential for BJ, particularly when working with metals. To achieve mechanical integrity, the green body must undergo curing for 6–12 hours followed by sintering at temperatures above 1000 °C for 24–36 hours. This stage may include densification, infiltration, and binder burnout. During sintering, loosely packed powders bond to increase density and strength. In some cases, a low-melting metal such as bronze is used to infiltrate a higher-melting material to enhance ductility [79]. The final microstructure and mechanical properties depend heavily on post-processing parameters. Powder size, layer thickness, and thermal treatment affect the final density and mechanical performance. While finer powders improve density, they present spreading challenges. Thicker layers reduce build time but can increase porosity. Heat treatment techniques like sintering, solutionizing, and aging also significantly influence outcomes. Studies by Mostafaei et al. [80] demonstrated that aging treatments yield higher tensile strength, elongation, and hardness compared to basic sintering. More recently, reactive sintering has been introduced, allowing for the formation of new alloy compositions during post-processing. For example, Dilip et al. [81] fabricated TiAl intermetallics using a mixture of Ti6Al4V and Al powders. For nickel-based alloy 625, different heat treatments were compared using SEM imaging. All methods produced near fully dense structures, but varied alloy phases influenced mechanical performance. Aged and solution-treated samples showed superior hardness and toughness due to carbide dissolution and intermetallic precipitation.

An important characteristic of BJ is that identical green bodies can yield drastically different final properties based on the heat treatment used. For example, bronze parts can show ultimate tensile strengths ranging from 8 to 117 MPa after sintering. Meanwhile, Inconel 625 samples—even when nearly fully dense—showed reduced hardness and strength at higher sintering temperatures. This decline was attributed to grain coarsening, element segregation, Laves phase formation (due to Nb and Mo enrichment), and the presence of niobium carbides. While the printing phase of BJ is typically faster than other AM processes thanks to low-temperature operation and multi-nozzle printing the overall production time becomes longer due to extensive post-processing. Each layer can be printed in just seconds, but the sintering phase significantly slows down the total build time. Moreover, dimensional shrinkage during sintering affects the geometric accuracy of the final product [82].

2.2.2. Limitations and Opportunities in 3D Printing of Metals

Although metal-based AM shows promise, widespread industrial adoption is hindered by challenges in qualifying both the process and final components. Qualification involves detailed tracking and analysis of process parameters, such as using Fast Fourier Transform (FFT) to identify signatures of successful or problematic builds over long production cycles. In situ

monitoring such as optical and thermal imaging for each layer can be combined with logged process data to inform computational models. These models help predict defects and microstructural inconsistencies. Furthermore, sacrificial test samples are inspected non-destructively using techniques like ultrasound, X-ray or neutron tomography, and residual stress analysis. To qualify components, datasets are created by integrating multiple types of monitoring data. For instance, Schwalbach et al. conducted a study where a cylindrical part was manufactured alongside others. Process data revealed a change in build layer time below 15 mm, which tomography correlated with fewer pores, linking geometric variations to material quality.

Metal 3D printing is currently used mainly in aerospace and biomedical industries due to its high cost, which stems from expensive equipment and feedstock. These costs make it economically viable only for small batches of parts with complex geometries. However, as adoption increases, production costs are expected to decrease, allowing expansion into other sectors, especially tooling. Current research focuses on overcoming challenges such as machine and feedstock costs, surface finish, certification, and part size. While machine costs are unlikely to drop soon owing to the need for high-powered lasers and electron beams increasing build speed by raising beam power has limits due to its effect on cooling rates and microstructure. Using multiple beams is possible but further increases machine cost. Feedstock costs are expected to decline as competition and production volume increase; for instance, Alcoa has invested in a new metal powder production facility. Surface finish remains a key challenge, but hybrid machines that combine additive and subtractive processes (like milling during build) offer promising solutions, though they come with geometric constraints. For large parts, technologies like Sciaky's wire-fed electron-beam AM and Oak Ridge's BAAM system (currently for plastics) are under development for metals. Additionally, Alcoa's Ampliforge process which combines 3D printing with forging improves mechanical properties, although it has some geometric limitations.

2.3. Ceramic and Hybrid Materials for 3D Printing

Ceramic materials are highly regarded for their mechanical strength, thermal stability, corrosion resistance, and biocompatibility in some biomedical applications. These characteristics make ceramics ideal for both structural and functional components. However, one significant limitation is their inherent brittleness, which makes them prone to failure under impact or dynamic loads. This brittleness remains an issue even in 3D printed ceramics, whether dense or porous. To mitigate this challenge, ceramic matrix composites are used. These consist of a ceramic matrix combined with ductile reinforcements, helping to enhance toughness and damage tolerance. AM—commonly known as 3D printing—includes seven categories defined by ISO/ASTM 52900, such as: Vat Photopolymerization (VPP), Material Extrusion (MEX), Material Jetting (MJT), Binder Jetting (BJ), Sheet Lamination (SHL), Powder Bed Fusion (PBF), and Directed Energy Deposition (DED). These techniques have evolved rapidly over the past 30 years and can now process a wide range of materials including

polymers, metals, ceramics, and composites. Different 3D printing methods are used for fabricating ceramic matrix composites, with specific techniques suited for different composite types, such as MEX, especially Direct Ink Writing (DIW), enables structured designs like woodpile geometries, PBF, such as SLS, and BJ naturally create porous parts due to larger particle sizes, and VPP, often called ceramic SLA, is increasingly used for SiC and SiOC composites due to its ability to fabricate dense and complex parts [83,84]. **Figure 2.7** illustrates the process details of MEX, and VPP techniques.

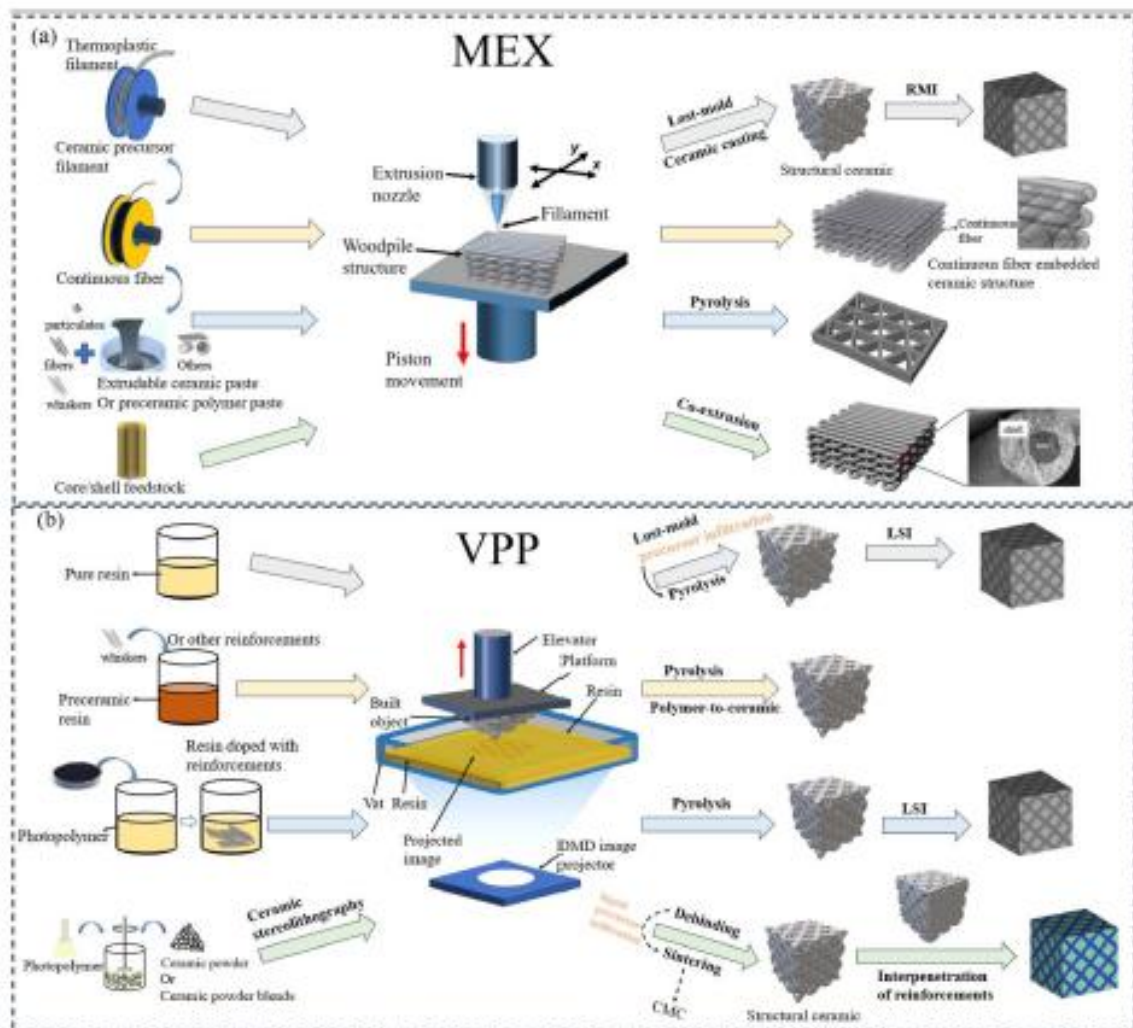


Figure 2.7. 3D printing methods for ceramic composites: (a) MEX, and (b) VPP [84].

2.3.1. 3D Printing of Ceramic and Hybrid Materials

2.3.1.1. Fused Deposition Modeling

FDM is a widely used 3D printing method that works by extruding molten thermoplastic materials mixed with ceramic powder through a nozzle at temperatures above the polymer's melting point. Once extruded, the material cools and solidifies layer by layer to form the final structure. FDM is known for its low material cost, high utilization rate, and compatibility with a wide range of materials. However, it has some notable drawbacks, including limited precision, slow printing speed, and poor mechanical strength perpendicular to the print layers, making it difficult to produce complex or highly detailed structures [85].

Warping caused by shrinkage stress is a common issue in FDM products made from polyamide-6 (PA6) due to its crystallization behavior. To address this, Jia et al. [86] modified PA6 by incorporating maleic anhydride grafted polyethylene-octene (POE-g-MAH), which disrupts crystallization and reduces stress. Moreover, they added polystyrene (PS) to enhance flow properties and maintain printability. This approach led to the development of a toughened PA6 filament with improved shape stability and reduced warping. Achieving high trans-surface thermal conductivity (TPTC) using boron nitride (BN) is difficult through traditional methods due to poor control over BN sheet alignment. Geng et al. [87] explored three FDM-based printing strategies to align BN sheets vertically in PA6/BN composites, achieving a TPTC of 2.03 W/m·K. This research highlights how smart filler alignment during FDM printing can significantly improve thermal performance with efficient material usage. Another limitation in developing continuous fiber-reinforced ceramic composites using AM is the lack of proper fiber-matrix interfaces and difficulty in resin or slurry penetration into fiber bundles. To overcome this, Cheng et al. [88] applied a prepreg-coating method using polycaprolactone (PCL) to coat continuous carbon fibers, combined with a hydrothermal carbon interface derived from sugar. The flexible filaments enabled smooth FDM processing. They also used ultrasonic treatment to enhance slurry impregnation. The resulting Cf/ZrB₂-SiC composite, formed via pyrolysis and densification, achieved a flexural strength of 218.1 ± 21.3 MPa and a fracture toughness of 9.40 ± 1.45 MPa·m^{1/2}, showing strong potential for high-performance applications.

FDM has been in use for nearly three decades and is now a well-established technology. It constructs 3D objects layer by layer by building cross-sections and increasing height with each pass of the nozzle. Because of its mature development, ease of use, and adaptability, many manufacturing enterprises use FDM to rapidly prototype, develop new products, and shorten innovation cycles, thereby enhancing their market competitiveness [89]. The main stages of FDM are given in **Figure 2.8**.

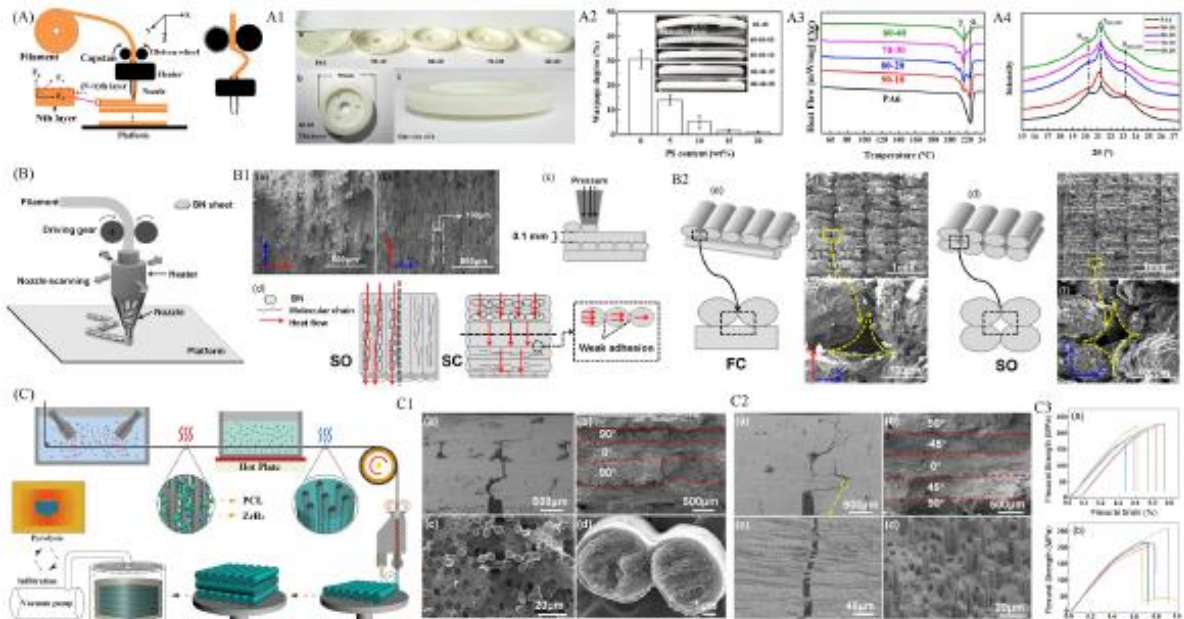


Figure 2.8. Process diagram of FDM method [84].

2.3.1.2. Selective Laser Sintering

SLS is a layer-by-layer AM technique where ceramic powder is spread onto a powder bed and selectively fused using a laser along a programmed path. A low-melting-point binder in the powder helps bond the ceramic particles when melted by the laser. After each layer is processed, the build platform lowers incrementally to allow stacking of layers. SLS provides advantages such as fast printing speeds and the ability to handle larger and more complex structures. However, due to the high binder content, initial parts (green bodies) tend to be low-density and porous, requiring post-processing techniques like isostatic pressing or infiltration to improve quality. Wang et al. [90] demonstrated an advanced approach for fabricating high-performance SiC ceramics by combining SLS, precursor impregnation pyrolysis (PIP), and liquid-phase sintering (LPS). They used a multi-material powder blend including SiC, Al_2O_3 , Y_2O_3 , and phenolic resin. Through this process, they achieved SiC ceramics with a relative density of 98.2% and a flexural strength of 150 MPa. The multistep approach involved initial laser sintering of porous green bodies, followed by PIP and LPS to produce ceramics with a dense microstructure and enhanced performance, suitable for structural applications [91].

In aerospace applications, ceramic cores are crucial for forming hollow turbine blades. Zheng et al. [92] fabricated B_4C -reinforced silicon-based ceramic cores using SLS and $\text{SiO}_2/\text{Al}_2\text{O}_3$ sol infiltration. They investigated the effects of B_4C content and the sol composition on mechanical properties. An increase in B_4C (up to 2 wt%) improved room-temperature flexural strength from 3.39 MPa to 27.35 MPa due to B_4C oxidation. Adjusting the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio optimized mullite formation, leading to enhanced high-temperature strength and reduced linear shrinkage. These outcomes fulfilled performance criteria for ceramic cores used in precision investment casting. Deng et al. [93] developed $\text{Fe}_3\text{O}_4/\text{NFG}$ -based ceramic

composites using SLS and vacuum impregnation. A powder mix of flake graphite, phenolic resin, Fe_3O_4 , and mullite was laser-sintered and later infiltrated with epoxy resin. Mechanical tests revealed that increasing laser power improved flexural strength, reaching 8.03 MPa—a 27-fold increase compared to the unsintered green body. The study also explored microwave absorption performance, achieving -41.81 dB reflection loss and a 6.56 GHz absorption bandwidth at 20 W laser power and 2 mm thickness. The result was a multi-functional composite with both mechanical robustness and EM wave attenuation capability, ideal for EM interference shielding and stealth technologies [94]. **Figure 2.9** shows the main stages of SLS.

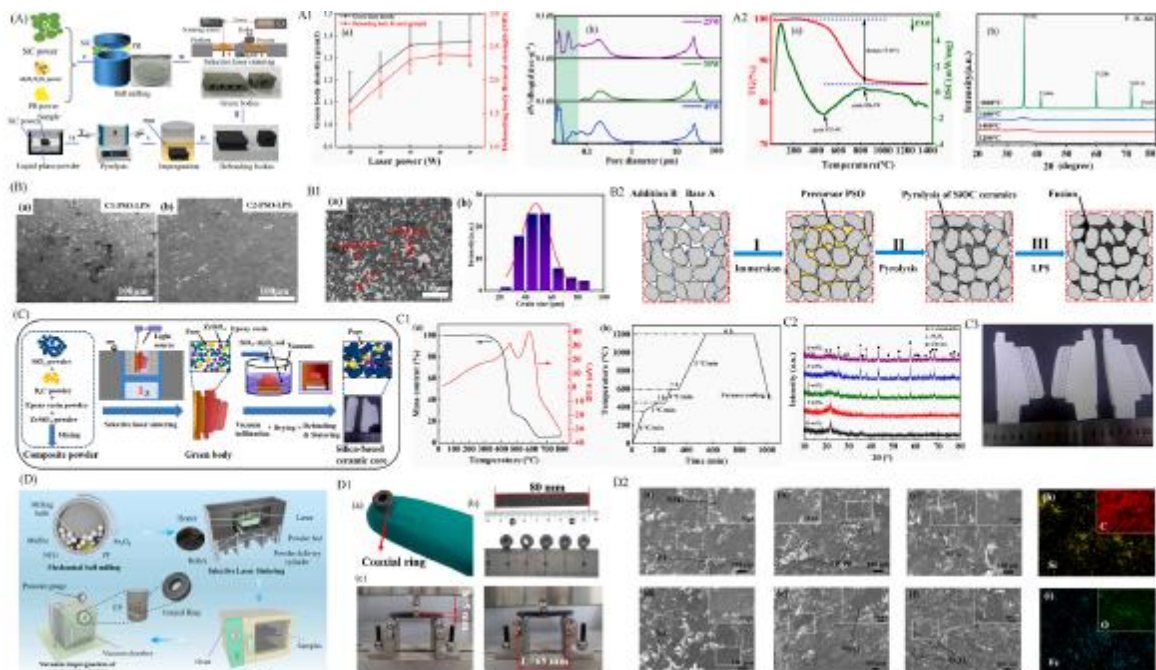


Figure 2.9. Process diagram of SLS method [84].

2.3.1.3. Direct Ink Writing

DIW is a 3D printing technique where ceramic powders are mixed with organic compounds to form a printable ceramic ink, which is extruded onto a substrate to form a green body. The formulation of this ink is critical requiring uniform dispersion, optimal viscosity, surface tension, conductivity, and rapid drying, while maintaining high solid content. After printing, the parts must undergo degreasing and high-temperature sintering. While DIW allows for rapid fabrication and the use of diverse materials, it typically results in parts with lower density and surface precision. Chen et al. [95] used DIW to print polycarbosilane (PCS)/n-hexane-based inks for producing 3D SiC structures with feature sizes ranging from 100 to 400 μm . Tuning the rheological behavior of the PCS ink enabled effective printing and self-supporting structures. Upon oxidative crosslinking and pyrolysis, the printed shapes were converted into SiC, preserving their original 3D form despite significant shrinkage. The viscoelastic properties of the ink and uniform shrinkage were vital in ensuring structural integrity during transformation into ceramics.

DIW ceramics often exhibit variability in mechanical properties, necessitating large-scale testing. To address this, Thiraux et al. [96] introduced a high-throughput method to evaluate Weibull parameters by fabricating multiple small bending specimens. Their multiscale approach showed that porous DIW-printed alumina structures could even surpass dense parts in strength. This framework provides a rapid way to assess the strength distribution of ceramics across different formulations. In the petrochemical sector, DIW has been used to fabricate monolithic catalysts with improved flow, heat, and mass transfer properties. Chen et al. [97] optimized catalyst inks for oxidative desulfurization (ODS) of diesel by analyzing their rheological behavior. By incorporating ionic liquids and mordenite, they produced $\text{MoO}_3/\text{BT-MOR}$ catalysts that achieved 100% removal efficiency of dibenzothiophene. These monolithic catalysts offer recyclability and industrial viability, with potential applications in other oxidation-based reactions.

DIW is praised for its low-cost setup, material flexibility, customizability, and accuracy. However, it requires post-processing, such as curing and sintering, to achieve desired properties. The final product's quality depends on ink formulation, rheological properties, and printing parameters [98]. To overcome limitations, researchers are experimenting with external-field-assisted DIW, incorporating light, heat, vibration, or magnetic fields during printing. These approaches expand the scope of DIW-compatible materials and enhance functionality, establishing DIW as a mature, versatile technology used across microelectronics, energy, photovoltaics, and biomedical engineering. **Figure 2.10** shows the main stages of DIW.

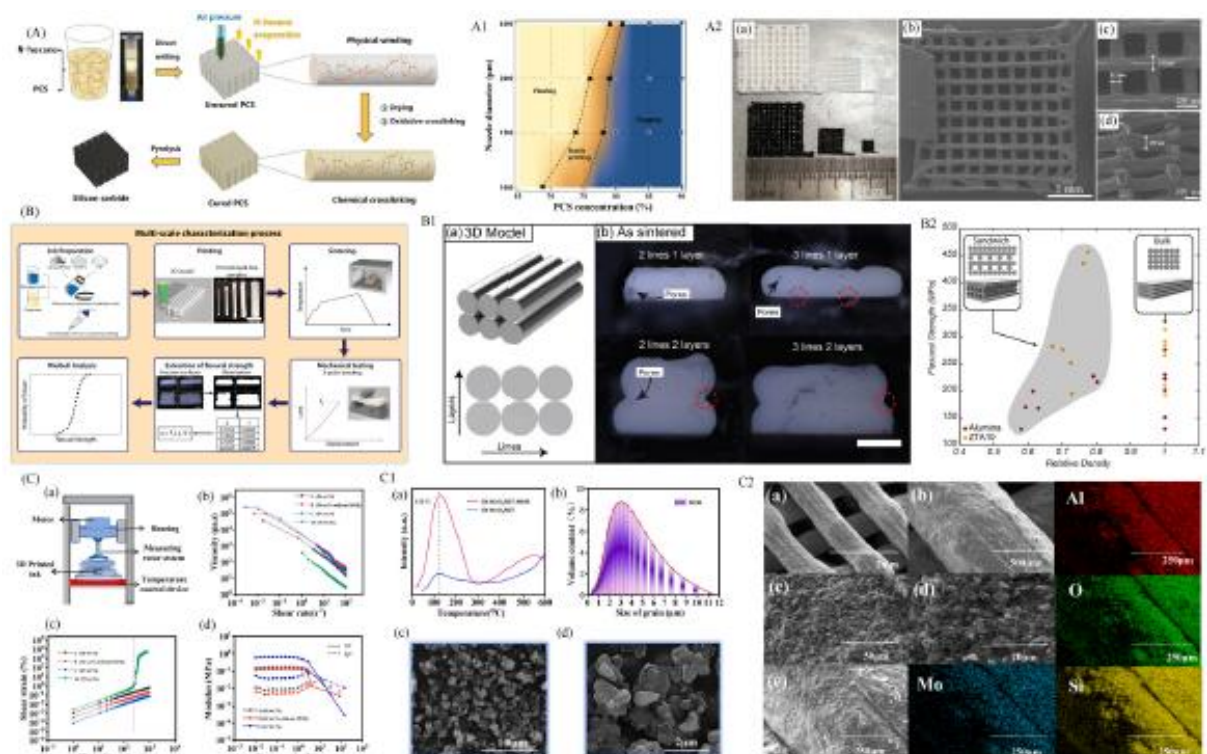


Figure 2.10. Process diagram of DIW method [84].

2.3.1.4. Stereolithography

SLA is a popular 3D printing technique that involves curing a photosensitive ceramic slurry composed of ceramic powder, UV-curable resin, and additives. The slurry is solidified layer by layer through exposure to ultraviolet light. After each layer cures, the platform lowers, allowing new slurry to flow in, continuing the process. Once printing is complete, the ceramic green part undergoes degreasing and sintering to yield the final ceramic object. SLA stands out for its high precision, excellent surface quality, and suitability for small and intricate components, such as those made from Al_2O_3 , ZrO_2 , and calcium phosphate, with densification reaching up to 96% [99]. A notable application of SLA is in fabricating structural electrolyte supports for monolithic SOFC stacks using 8 mol% yttria-stabilized zirconia (8YSZ). Jia et al. [100] developed a photocurable 8YSZ slurry with a 43 vol% solid content and excellent stability. The printed parts displayed an activation energy of 0.87 eV and a peak power density of 230 mW/cm^2 at 850°C , comparable to materials formed via dry pressing. This demonstrates SLA's potential for high-performance ceramic energy devices. Xing et al. [101] used SLA to fabricate ZrO_2 rods of varying dimensions. Post-sintering evaluation revealed anisotropy in surface roughness, with horizontal surfaces smoother ($<0.41 \mu\text{m}$) than vertical ones ($\sim 1.07 \mu\text{m}$). Even for rods as large as $3 \times 4 \times 80 \text{ mm}$, warpage and flatness deviations were under $40 \mu\text{m}$ and $27 \mu\text{m}$, respectively. The final ceramics had exceptional mechanical properties, including 1154 MPa flexural strength, $6.37 \text{ MPa}\cdot\text{m}^{1/2}$ fracture toughness, and 99.3% density. The study also emphasized how scanning paths and part sizes influence accuracy and performance. Zhao et al. [102] investigated the creep resistance of SLA-printed silicon ceramics, particularly when ZrSiO_4 was added. Under temperatures between $1400\text{--}1500^\circ\text{C}$ and stresses from $5\text{--}20 \text{ MPa}$, the creep rate initially increased and then decreased with rising ZrSiO_4 content, peaking at 15%. This behavior was explained using the Norton–Bailey Arrhenius equation, and SEM analysis revealed layer delamination. While moderate ZrSiO_4 worsened creep resistance by hindering silica flow, higher concentrations improved interlayer densification and reduced creep. Sua et al. [103] fabricated SiOC microlattices via SLA by incorporating a light absorber (Sudan III), improving resolution for truss diameters between $52\text{--}220 \mu\text{m}$. These lattices showed enhanced oxidation resistance, mechanical strength, and high-temperature stability. Similarly, Wang et al. [104] used SLA combined with PIP to produce carbon fiber-reinforced SiC composites, achieving high fracture toughness and flexural strength, contributing to the advancement of fiber-reinforced ceramic matrix composites.

High-performance SLA printing of ceramics often requires high solid loading slurries, which introduces issues like layering defects, slurry sedimentation, and uneven green body formation. Hu et al. [105] addressed this by implementing a bottom-up digital light processing (DLP) system with a custom coating-storage-stirring recoating mechanism, effectively tackling sedimentation and ultra-thin layer control. SLA technology continues to lead in terms of resolution, detail fidelity, and surface finish, outperforming other plastic 3D printing methods. Its core strength lies in the ability to support complex geometries and fine features. Moreover, innovative resin formulations now offer a broad spectrum of optical, mechanical, and thermal properties, rivaling standard thermoplastics. SLA is also a preferred platform for creating

biocompatible materials, supporting its growth in medical and engineering applications. The main stages of SLA are shown in **Figure 2.11**.

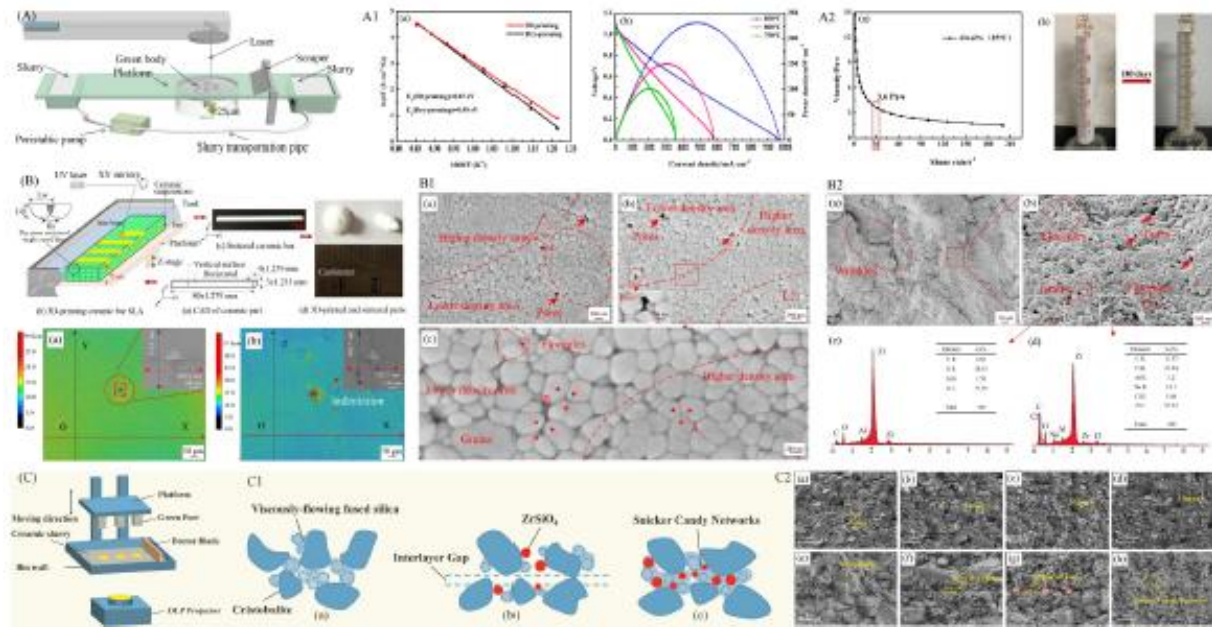


Figure 2.11. Process diagram of SLA method [84].

2.4. 3D Printing Technologies in Aerospace Applications

3D printing technologies have emerged as a transformative technology in the aerospace sector due to its ability to fabricate complex geometries, reduce material waste, shorten production cycles, and enable unprecedented design freedom. Unlike conventional subtractive manufacturing, AM builds components layer by layer directly from digital models, allowing engineers to optimize structures for weight, performance, and functionality—key drivers in aerospace engineering. One of the most significant advantages of 3D printing in aerospace applications is the ability to produce lightweight, topology-optimized components. Weight reduction directly translates to improved fuel efficiency, increased payload capacity, and reduced emissions. Using advanced computational design tools, engineers can integrate lattice structures, internal channels, and functionally graded materials that are impractical or impossible to manufacture using traditional methods. These capabilities have been widely exploited in the production of brackets, supports, housings, and structural reinforcements for both aircraft and spacecraft.

Metal AM technologies such as SLM, EBM, and DED are increasingly used to fabricate load-bearing aerospace components. Titanium alloys, nickel-based superalloys, and aluminum alloys are particularly attractive due to their high strength-to-weight ratios, corrosion resistance, and thermal stability. Aerospace manufacturers have successfully qualified AM-

produced parts for use in airframes, engine components, and satellite structures, demonstrating mechanical performance comparable to or exceeding that of conventionally manufactured counterparts. In addition to metallic materials, ceramic-based structures are also efficiently produced by using AM technologies. Ceramic 3D printing is already used in manufacturing micro-components of aviation engines, such as crankshafts, valves, and flywheels, demonstrating its integration into critical aerospace systems [106]. Honeycomb ceramic structures, known for their outstanding mechanical and thermal properties, are another innovation. Zhang et al. [107] employed DLP technology to fabricate cellular ceramic structures (CCSs) with varying configurations to study compressive performance, offering insight into their structural integrity. AM plays a critical role in the production of propulsion system components, especially in rocket engines and gas turbines. Complex internal cooling channels, optimized fuel injectors, and integrated assemblies can be fabricated as single parts, reducing assembly complexity and failure points. In high-temperature environments, ceramic matrix composites and hybrid material systems produced through additive techniques offer enhanced thermal resistance and durability, making them suitable for nozzles, combustors, and heat shields. In space exploration, 3D printing offers unique advantages for reducing launch mass and enabling in-situ manufacturing. Components for satellites, space stations, and planetary exploration systems can be fabricated with minimal material waste. Research into in-space and extraterrestrial additive manufacturing, including the use of lunar or Martian regolith as feedstock, highlights the long-term potential of AM for sustainable space missions and deep-space exploration.

Beyond end-use parts, 3D printing is extensively used for rapid prototyping, tooling, and fixtures in aerospace manufacturing. Polymer-based AM allows for fast iteration of designs during the development phase, significantly reducing time and cost. Additively manufactured tooling, including molds, jigs, and inspection fixtures, can be customized for specific components and produced on demand, increasing manufacturing flexibility and efficiency. Bae et al. [108] developed a fused quartz core/shell mold using ceramic SLA, while Shi et al. [109] introduced a hybrid method using photopolymeric 3D printing and gel injection molding. These approaches eliminate the need for metal molds or assembly, offering improved formability, reduced defects, and higher design freedom. Chen et al. [110] used PBF to produce alumina-based core/shell molds with enhanced density and minimized shrinkage. AM has also gained attention in maintenance, repair, and overhaul (MRO) operations. The ability to produce spare parts on demand is particularly valuable for aging aircraft fleets, remote operations, and space missions where logistics are constrained. Directed energy deposition and other repair-oriented AM processes enable the restoration of high-value components by adding material only where needed, extending service life and reducing downtime.

Despite its advantages, the adoption of 3D printing in aerospace applications faces challenges related to certification, quality assurance, and process repeatability. Aerospace standards require strict control over material properties, microstructure, and defect tolerance. Ongoing research focuses on process monitoring, non-destructive evaluation, and the development of standardized qualification frameworks to ensure reliability and safety of additively

manufactured aerospace components. As materials science, process control, and digital manufacturing technologies continue to advance, the role of AM in aerospace applications is expected to expand further. The integration of multi-material printing, smart materials, and digital twins will enable next-generation aerospace systems with enhanced performance, adaptability, and sustainability. Consequently, 3D printing is poised to remain a cornerstone technology in the future of aerospace design and manufacturing.

2.5. Conclusions

AM has established itself as a disruptive and enabling technology in the aerospace sector, fundamentally reshaping how components are designed, manufactured, and deployed. The layer-by-layer fabrication approach intrinsic to 3D printing offers unparalleled design freedom, enabling the production of geometrically complex, lightweight, and functionally optimized components that meet the stringent performance requirements of aerospace applications. This chapter has highlighted the critical role of material selection in the successful implementation of 3D printing technologies. Polymeric materials provide cost-effective solutions for prototyping, tooling, and non-structural components, while high-performance thermoplastics extend their applicability to demanding operational environments. Metallic materials, particularly titanium, aluminum, and nickel-based alloys, dominate load-bearing and high-temperature aerospace applications due to their superior mechanical strength, corrosion resistance, and thermal stability. Ceramic and hybrid materials further expand the design space, offering exceptional thermal resistance and multifunctional capabilities for extreme environments encountered in propulsion systems and space applications. The integration of AM into aerospace production workflows has demonstrated significant benefits, including reduced material waste, shortened development cycles, part consolidation, and enhanced supply chain flexibility. Applications ranging from structural components and propulsion systems to maintenance, repair, and in-situ space manufacturing illustrate the versatility and transformative potential of this technology. However, challenges related to process repeatability, material qualification, and certification remain critical barriers to widespread adoption, particularly for safety-critical components.

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CHAPTER 3

3D Printing Processes in Aerospace Components and Maintenance

Virginija Leonavičiūtė*, Giedrius Jočbalis, Arnoldas Novikevičius

Department of Aeronautical Engineering, Antanas Gustaitis' Aviation Institute, Vilnius
Gediminas technical university, Vilnius, Lithuania

*Corresponding author: virginija.leonaviciute@vilniustech.lt

3.1. Introduction

Advanced technology aimed at producing three-dimensional (3D) shapes by joining the smallest parts of materials is commonly referred to as additive manufacturing (AM). The term additive manufacturing is used to characterize direct digital manufacturing, 3D printing, and related technologies, and it is broadly applicable to the production of all classes of materials, including metals, ceramics, polymers, composites, concrete, and even biological tissues. Early technological developments in AM have been reviewed by Wong and Hernandez [1] and Huang et al. [2]. Three-dimensional printing is an additive manufacturing process in which products are formed through the sequential deposition of material layers.

The design of materials with desired properties is a challenging issue for most industries, particularly in the aerospace sector. In 2021, additive manufacturing accounted for approximately 1% of the aerospace industry [3], while the aerospace sector is expected to represent up to 20% of the additive manufacturing market by 2026 [4]. In aerospace applications, reducing mass relative to strength is a critical requirement. Different AM processes employ technology-specific materials, including various metal powders. Recent developments in 3D printing technology [5] enable the manufacture of materials with tailored micro-scale structures and final products with highly complex macro-scale topologies. An example of laser metal deposition (LMD) used in turbo engine manufacture and repair is presented by Gasser et al. [6].

3.2. Additive Manufacturing Technologies

3.2.1. Overview of Additive Manufacturing for Aerospace Applications

Additive Manufacturing (AM), also known as layered manufacturing technologies, has become widely used in the aviation industry in recent years. It is used for producing components with complex geometries that require high performance. AM plays a crucial role in aviation. One of its most important functions is the reduction of component weight, which affects fuel

efficiency. Additive Manufacturing offers advantages such as producing parts in a single piece and increasing material efficiency [7]. This reduces the risk of errors and maintenance costs [8]. Furthermore, this positively impacts aerodynamic performance, significantly increasing operational efficiency, particularly for unmanned aerial vehicles. This technology also significantly reduces production time. Unlike traditional production methods, time and cost constraints are reduced, and new designs can be tested as rapidly as possible [9]. Furthermore, every production process is meticulously controlled because reliability and continuity are crucial in aviation [10]. AM also provides ease and flexibility in spare parts production. It allows aircraft to be maintained without being grounded for extended periods and without increasing costs. With all the features mentioned, AM offers numerous benefits. Its applicability in aviation is significant due to its ease of use and efficiency [7].

3.2.2. Comparison of FDM, SLA, SLS, and Other Relevant Methods

Among AM technologies, the most prominent ones used in aerospace are Fused Deposition Modelling (FDM), also referred to as Fused Filament Fabrication (FFF) (**Figure 3.1**), Stereolithography (SLA) (**Figure 3.2**), of which the most commonly used is Digital Light Processing (DLP) method; and Selective Laser Sintering (SLS) (**Figure 3.3**). Each of these methods has its own advantages and disadvantages [11]. FDM allows for low-cost and rapid prototyping and, in UAVs, is used for lighter load-carrying parts. However, more advanced techniques are used for high-performance aerospace components, where FDM may not provide sufficient strength. Therefore, it is most often used during design validation [9].

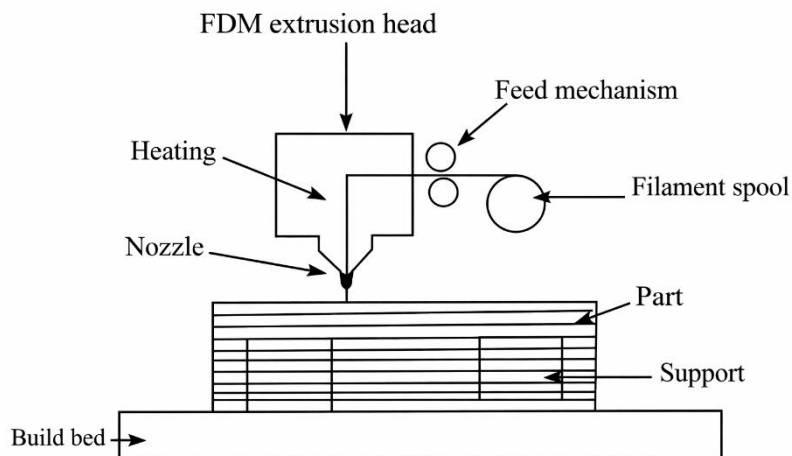


Figure 3.1. Schematic of FDM/FFF extrusion-based 3D printing

SLA, on the other hand, is a suitable technology for precision parts because it offers high-quality prints and smooth surfaces. It can be used for aerodynamic and aesthetic reasons. However, SLA has limited use in engines and load-bearing components because it provides limited resistance to high temperatures. Most of the photopolymer resins used are not very

durable [9]; however, SLA-printed material exhibits isotropic properties (which is not the case for FDM-printed material).

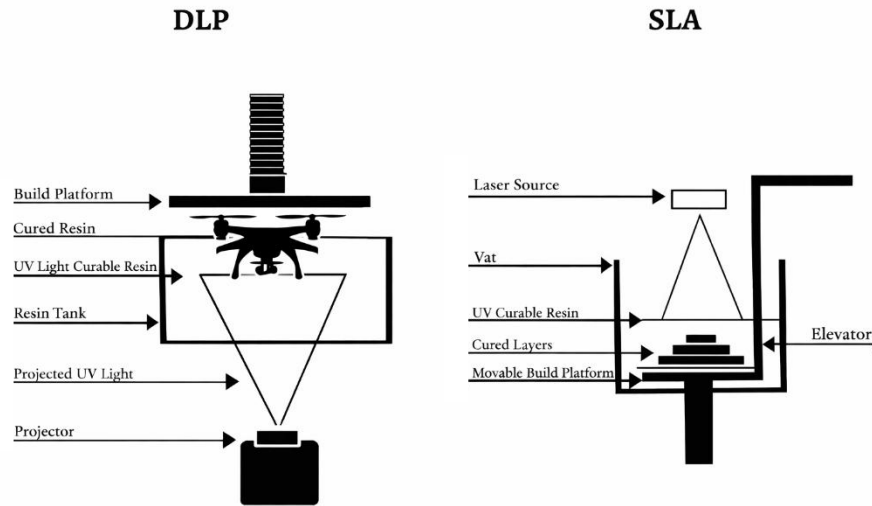


Figure 3.2. Difference between DLP and SLA printing

SLS is one of the most commonly used methods for structural applications in aviation. It can produce useful and durable parts from polymer and metal materials. However, these advantages are accompanied by several limitations. Large equipment requirements, long production times, and high costs are among the negative characteristics of this technology [7].

There are metal-based AM methods such as Direct Metal Laser Sintering (DMLS), Laser Metal Deposition (LMD) and Electron Beam Melting (EBM). These are used for critical parts requiring high density and durability, typically in specific cases of UAV manufacturing. However, they also consume significant energy and are costly.

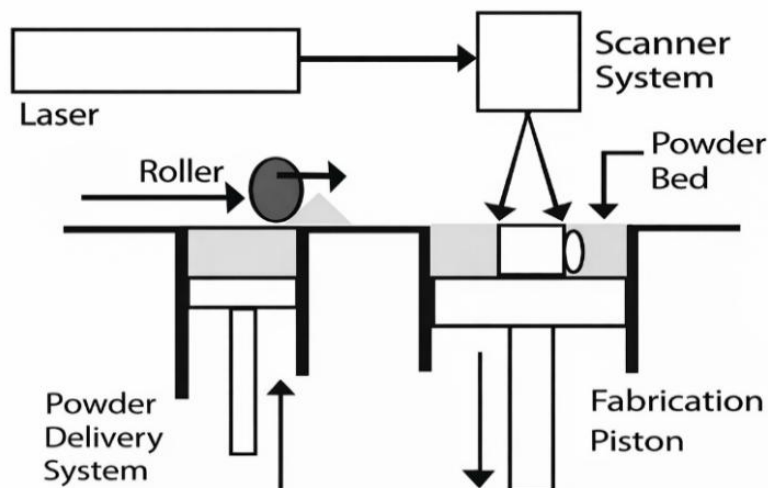


Figure 3.3. Schematic of SLS printing

Each technology must be evaluated against specific requirements. Features such as part requirements, material type, cost, and speed should be considered. Using these methods together provides the greatest benefits for an optimal solution. This improves performance and production efficiency [10]. **Table 3.1** presents a comparison between main printing technologies.

Table 3.1. Comparison between main printing technologies [12].

Feature	FDM (Fused Deposition Modelling)	SLS (Selective Laser Sintering)	SLA (Stereolithography)
Working principle	Thermoplastic filament is heated to a semi-solid state and extruded layer by layer onto the print bed.	Polymeric powder is selectively fused/sintered by a laser layer by layer in a powder bed.	Liquid photosensitive resin is cured layer by layer by light/UV-induced photopolymerization.
Material options	Thermoplastic filament; wide range of materials such as PLA, ABS, PEEK, Nylon, ULTEM, etc.	Thermoplastic powder; commonly PA12, PA11, TPU, TPE, PP and related polymer powders.	Photosensitive liquid resins; e.g., standard, castable, biocompatible, flexible, clear, and other resin families.
Resolution	Lower than SLA and SLS; around up to 40 μm as a guide.	Intermediate; around 20 μm minimum layer resolution as a guide.	Highest among the three; around up to 10 μm as a guide.
Ease of use / process simplicity	Simplest process; most suitable in terms of printing simplicity.	More complex; requires coordinated powder handling and laser scanning.	More complex than FDM due to resin handling and curing/post-curing steps.
Printing time	Fast printing process in general; slower than SLS but faster than SLA.	Fastest of the three, shortens overall time because it does not require support structures.	Longest total time, especially because post-processing/post-curing is usually required.
Cost	Generally, the most economical and widely available option.	Most expensive equipment among the three; high maintenance cost also noted.	Usually cheaper than SLS in terms of machine cost, but resin and post-processing remain important cost considerations.

3.2.3. Integration of 3D Printing into Composite Structures

Additive manufacturing can be integrated in composite structures, and this integration offers opportunities in component design by providing strength in areas requiring high durability. It enables the reduction of overall weight by increasing structural integrity [7]. In addition, 3D-printed parts can be directly integrated, reducing the number of assembly elements.

However, many technical challenges remain to be considered in this process. There are important factors that directly affect the functionality of the composite structure. Some of these factors include adhesion quality between layers, fibre orientation, and material homogeneity [13]. Furthermore, detailed testing is required for every new design because meeting aviation safety standards is imperative and cannot be ignored. Optimizing combinations, parameters, and design strategies maximizes performance. This also ensures process reliability. In particular, 3D-printed reinforced composite structures offer critical

benefits in terms of cost and performance compared to those produced using traditional methods [13]. The fast prototyping and spare part manufacturing enable the use of 3D printing technologies in the development of modular UAVs. The modular UAV design allows easy maintenance by replacing modular components, as well as an experimental design approach by changing individual modules to experimental ones.

3.3. Limitations of Technologies and Common Defects in Products

3.3.1. Technological Constraints of 3D Printing in Composite Applications

When composite structures are produced using additive manufacturing, they can present various challenges in the aerospace industry. The process under consideration is based on layer-by-layer manufacturing, which can lead to problems such as weakness and high porosity between fibre layers. The presence of such issues results in lower performance and reduced reliability compared to traditional composites [14]. In carbon fibre-reinforced filaments, inadequate fibre orientation reduces the structure's load-carrying capacity. Furthermore, the weak bond between the polymer matrix and the fibre poses a risk of premature delamination of the part. Limited material options prevent the desired mechanical and thermal properties from being achieved [15].

3.3.2. Common Defects: Layer Adhesion Failure, Warping, Porosity, Dimensional Inaccuracy

Layer adhesion failure: improper surface preparation or insufficient printer temperature can lead to defects. These defects result in poor bonding between layers and loss of structural integrity [16].

Warping: When polymer parts cool layer by layer, thermomechanical stresses can occur, causing warping at the corners of parts with wide, thin bases. This may occur due to inadequate thermal control, insufficient adhesion, or improper build surface conditions.

Porosity: Porosity in metal or composite prints creates micro-voids within the part. These can lead to inconsistent mechanical performance and reduced durability. Porosity can be reduced by using appropriate process parameters or post-processing techniques [17].

Dimensional inaccuracy: layered systems exhibit deficiencies that negatively impact part functionality. Thermal distortion, mechanical vibrations, and inadequate hardware calibration can lead to inconsistencies between the design and the output [17].

3.3.3. Strategies for Defect Prevention and Quality Control in UAV Part Production: Unavoidable Defects

Quality control, as well as error prevention methods, are crucial for the reliability of unmanned aerial vehicle components. First, a real-time parameter monitoring and

optimization system connected to sensors should be implemented during production. This system identifies and corrects deviations during printing. Second, non-destructive testing (NDT) methods (such as ultrasonic testing and thermography) are effective tools for identifying interlayer and internal defects. These techniques play a significant role in part certification. It is difficult for any comprehensive testing method to completely eliminate micro-defects. Therefore, processes such as improving the safety of UAV components, maintaining spare parts, and implementing final testing procedures are of great importance [17].

3.4. Mechanical Strength and Performance Characteristics

3.4.1. Evaluation of Static and Dynamic Mechanical Strength of Printed Components

A thorough understanding of the static and dynamic strength of 3D-printed parts is crucial for their use in aircraft and unmanned aerial vehicle applications. Studies have shown that factors such as layer thickness, print orientation, and infill ratio directly affect strength [18]. Dynamic mechanical analysis (DMA) studies have shown that materials such as PLA, PETG, ABS, and ASA exhibit viscoelastic behaviour influenced by temperature. This is important for vibrations encountered during flight [19].

3.4.2. Impact Resistance and Toughness of Materials Used in UAV Applications

Impact strength is crucial in areas such as the UAV's fuselage, landing gear, and propeller mounting points. Research shows that the infill ratio significantly affects impact resistance [20]. Parts reinforced with carbon and aramid fibres better absorb energy during impacts and exhibit increased toughness [21]. The impact resistance of polyamide parts produced using SLS technology is related to properties such as processing temperature and powder quality. PA12 parts produced with the correct parameters provide good flexibility and impact resistance [22]. Recent research shows that composite filaments such as fibre-reinforced PLA and PETG provide greater impact resistance in UAV parts compared to pure polymer.

3.4.3. Influence of Printing Parameters on Strength and Structural Integrity

The mechanical strength of parts is highly sensitive to printing settings. For example, if the printing direction is parallel to the load, the parts are stronger and more durable. If the layer thickness is reduced and the printing temperature is increased, the bond between the layers is enhanced [18]. When considering the infill percentage in terms of fatigue, the layer thickness and the number of outer walls is important. If these are determined correctly and appropriately, the durability of the parts can also be increased. Fatigue tests have shown that print orientation and infill structure significantly affect durability. For example, high infill ratios with the raster direction parallel to the load increase fatigue strength, but weaknesses may occur in other directions [23]. The infill shape of the internal structure is also a factor affecting durability. Patterns such as triangles and hexagons are preferred to provide better load

distribution and enhance impact resistance [20]. The strength of PA12 parts produced with SLS technology generally depends on porosity. Reusing the powder can increase porosity and reduce strength. High porosity reduces part durability. At the same time, stronger parts can be obtained by maintaining powder quality and using appropriate energy settings [22].

3.5. Lightweight PLA Printing for UAV Structures

3.5.1. Lightweight Polymers in UAV Manufacturing

In the development of small unmanned aerial vehicles (UAVs), weight optimization is a primary design constraint. Additive manufacturing using lightweight PLA and ASA (LW-PLA, LW-ASA) has become increasingly popular for producing UAV components such as wings and fuselages due to their reduced density [24], [25]. LW-PLA is a polylactic acid (PLA)-based filament. Active foaming technology increases its volume during the printing process, reducing its density. This feature is particularly preferred for weight reduction in the UAV industry. Research has shown that LW-PLA expands up to three times its volume during printing, and its density drops to approximately 0.54 g/cm^3 [26]. In terms of mechanical properties, LW-PLA provides a softer and rougher finish. However, because its impact resistance is higher than that of conventional PLA, it can be used to mitigate impact [25]. Furthermore, the glass transition temperature of LW-PLA is generally around $60\text{--}65^\circ\text{C}$, making it suitable for low-temperature conditions [26].

LW-ASA is an acrylonitrile-styrene-acrylate (ASA)-based filament. Like LW-PLA, it uses active foaming technology; however, there are differences. The density of LW-ASA can drop to as low as 0.43 g/cm^3 during printing, making it lighter than LW-PLA. The printing temperature for LW-ASA is between $240\text{--}260^\circ\text{C}$, at which foaming begins. LW-ASA has greater impact resistance than LW-PLA, making it more durable. Furthermore, LW-ASA offers an advantage due to its higher UV resistance. Additionally, it is more suitable for high-temperature applications because its glass transition temperature is around 100°C .

3.5.2. Parameter Selection Based on Weight, Strength, and Printability Criteria

When printing with LW-PLA, there are parameters that affect the material's density and the rate of delamination. Examples include printing temperature and flow rate [26]. These settings are important for achieving lightweight structures. Printing parameters should be selected according to mechanical requirements, and care must be taken to avoid a reduction in mechanical properties. For example, to achieve denser parts, higher flow rates and lower printing temperatures are required [26].

The print quality of most LW-PLA and LW-ASA materials is both manufacturer- and printer-specific. Therefore, it is recommended to perform test prints to determine the optimal temperature and flow rate for a given printer. This is typically done by printing samples at different temperatures to determine the maximum expansion temperature, followed by

printing samples at different flow rates (at the optimal temperature) to determine the rate at which the line thickness approximates the nozzle diameter (a slight overflow is recommended for improved bonding). Additionally, the filament degrades over time; therefore, recalibration is required if the filament has been exposed to air for extended periods. For these test prints, a 20x20x20 mm cube with a single outer wall and zero infill can be used.

However, owing to their high expansion rates, LW-PLA filaments tend to ooze during non-printing travel movements (**Figure 3.4a**). This oozing reduces the gaps between structures, making supports difficult to remove (**Figure 3.4d**), and produces weak walls immediately after travel due to a decrease in extrusion pressure (**Figure 3.4b**, **Figure 3.4c**). Traditional mitigation methods are largely ineffective for lightweight polymers: retraction frequently leads to nozzle clogging, the required retraction length depends on travel distance, and options such as “avoid crossing perimeters” merely limit oozing outside the part without addressing internal defects.

In some cases where low mass is not required, surface defects can be partially concealed by printing a second external perimeter (**Figure 3.5**), but oozing both inside and outside the part during travel movements cannot be fully avoided. Therefore, although component geometry may require more effort during model preparation, printing in vase mode (also referred to as single-contour or spiralized printing (**Figure 3.6**) is optimal for expanding filaments, as it completely eliminates non-printing travel movements.

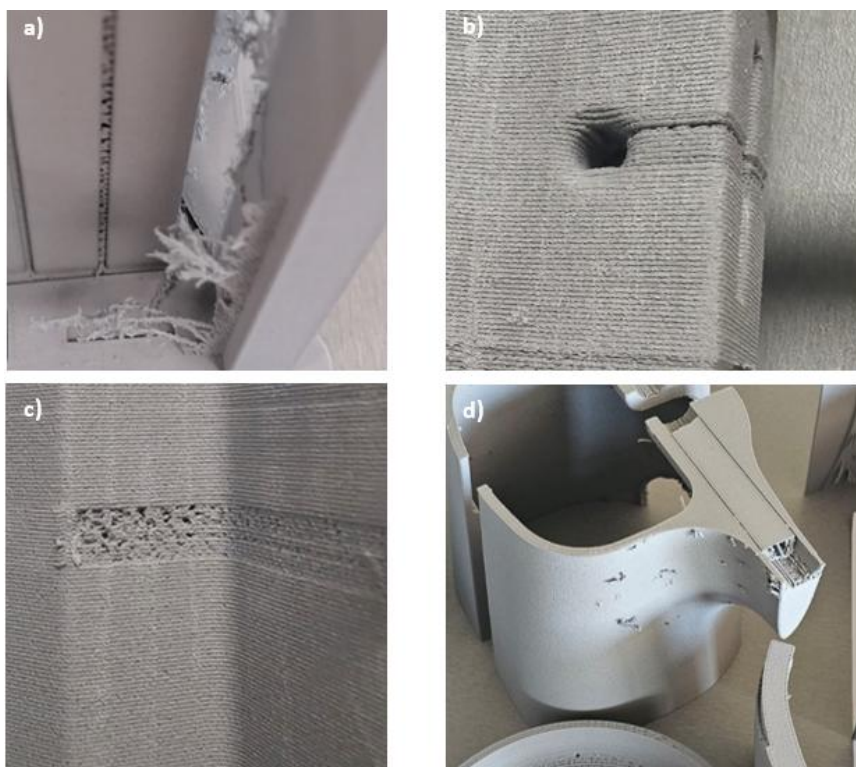


Figure 3.4. Difficulties in printing with expanding materials: a) oozing, b) weak perimeters, c) weak walls, d) stuck supports

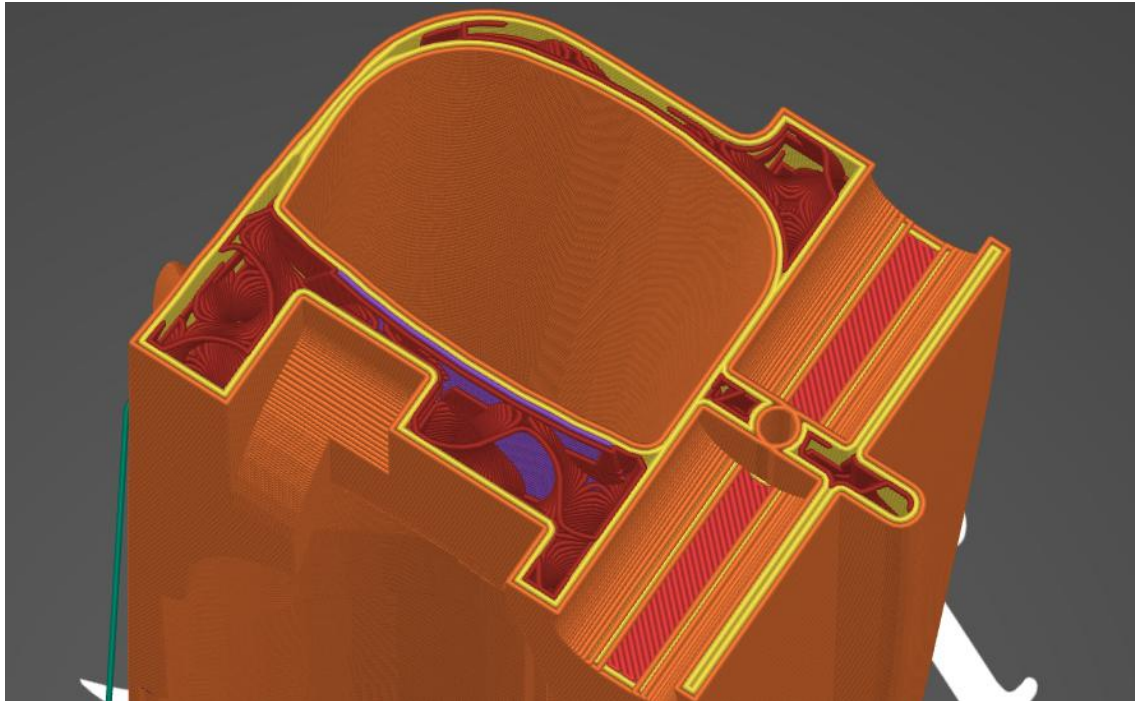


Figure 3.5. Double-shelled drone fuselage element (rendered in PrusaSlicer)

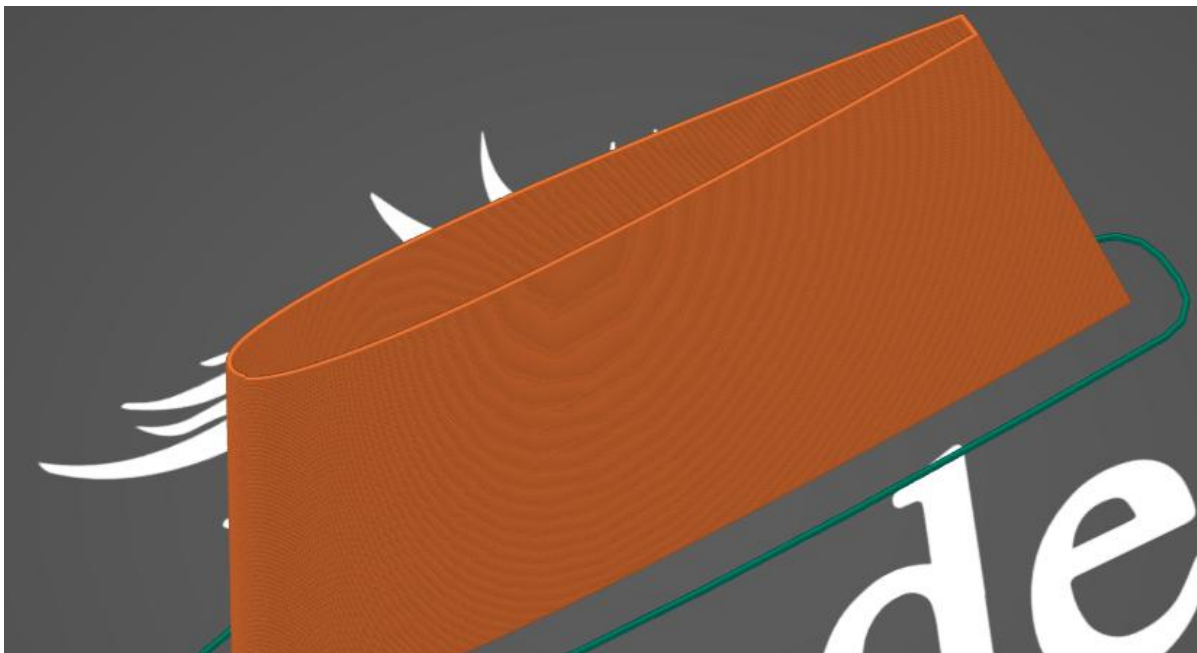


Figure 3.6. Monocoque wing component sliced for printing in spiral vase mode

3.5.3. Design Objectives for Printed UAV Structures

Printing in vase mode also provides several advantages. The primary qualities typically considered when 3D printing UAV components are:

1. High strength-to-weight ratio;
2. High surface finish quality;
3. Geometric complexity of the part;
4. Low printing time and minimal material waste;
5. Ease of model preparation for printing.

For most UAV components with complex geometries, it is not possible to achieve all of these objectives simultaneously; however, the use of vase mode allows several of them to be achieved concurrently (as shown in **Figure 3.7**).

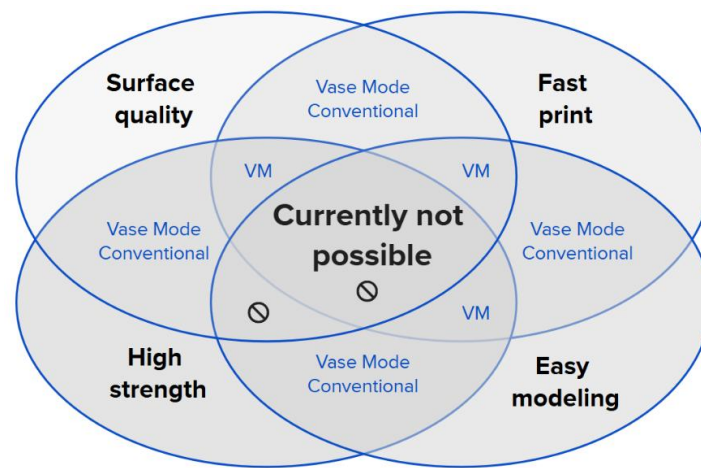


Figure 3.7. Venn diagram for compatibility of printed qualities when using expanding polymers

Conventional printing. The main advantage of conventional printing is the minimal need for model modification prior to printing. However, this approach often results in increased time and material consumption due to support structures, reduced wall strength caused by material oozing, and poor surface quality due to mismatched retraction and re-retraction behaviour. For most UAV components, conventional printing methods allow only two of the stated objectives to be met simultaneously.

Vase-mode and vase-mode-like printing. In contrast, the primary advantages of vase-mode are rapid printing and low material waste, as no travel movements are performed and no support structures are required. Although vase-mode is commonly associated with monocoque structures, the use of microfeatures connected to the external perimeter makes it possible to generate internal structures of varying complexity. The most common structures produced using these microfeatures are described below.

3.5.4. Common Vase-Mode Structural Configurations

Structural wall with a joint in the middle. The simplest microfeature to model is a wall with a central joint. This type of structure is widely used by hobbyists and hobbyist-oriented companies such as Eclipson [27]. An example is shown in **Figure 3.8**. The wall structure depicted in **Figure 3.8** is characterized by indentations on the outer shell surfaces at both ends of the structure, as well as a weak joint in the middle of the wall.

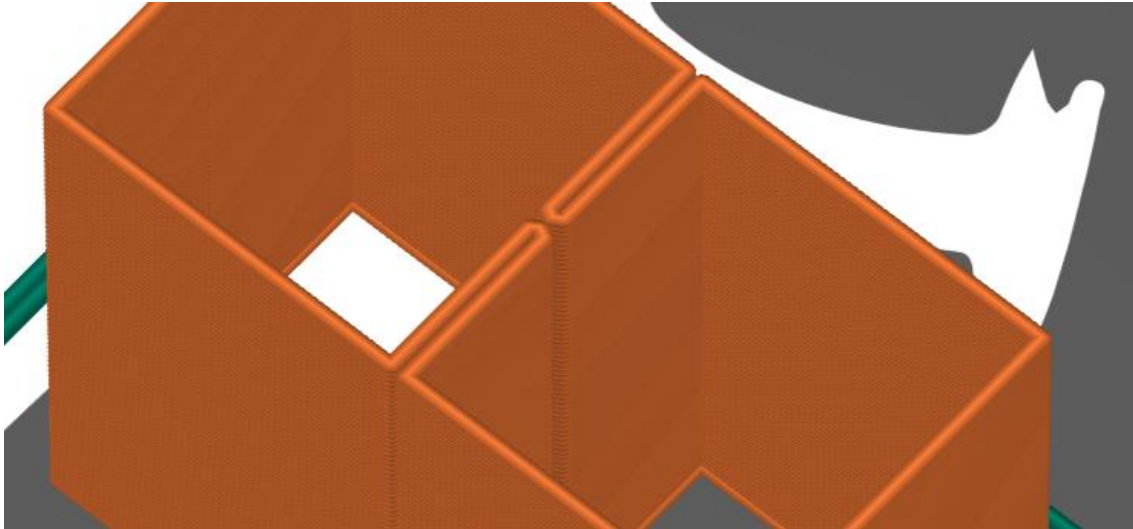


Figure 3.8. Structural wall with a joint in the middle of the part and continuous seams on both sides of the shell

Structural wall with a central gap and lightening holes. The weak joint observed in **Figure 3.8** can be modified into a larger gap to achieve additional mass reduction, as shown in **Figure 3.9**.

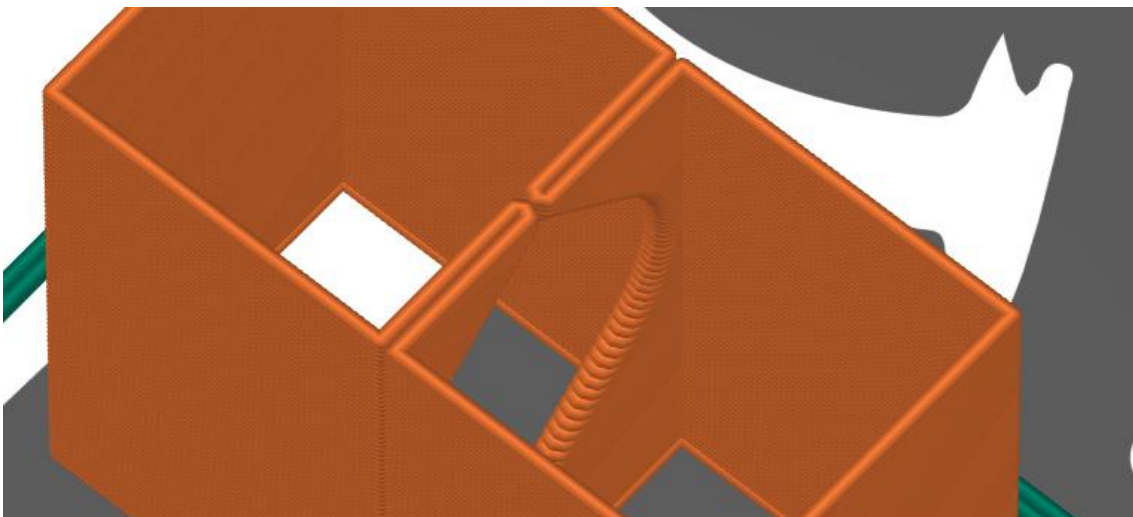


Figure 3.9. Structural wall with lightening holes and a central joint in the part, with continuous seams on both sides of the shell

The wall structure shown in **Figure 3.9** is also characterized by indented outer shell surfaces at both ends of the structure, a weak central joint, and the presence of lightening holes. This type of wall is most commonly used for modelling ribs inclined at 30–45°.

Structural wall with a one-sided joint. In some cases, the geometry of the component allows the use of walls with a one-sided gap, as shown in **Figure 3.10**. The wall structure shown in **Figure 3.10** is characterized by an indented outer shell surface at one end of the structure and a weak joint at the opposite end. Compared to the previous examples, this structure causes less disruption to the outer shell and should therefore be used in place of mid-gap walls whenever feasible.

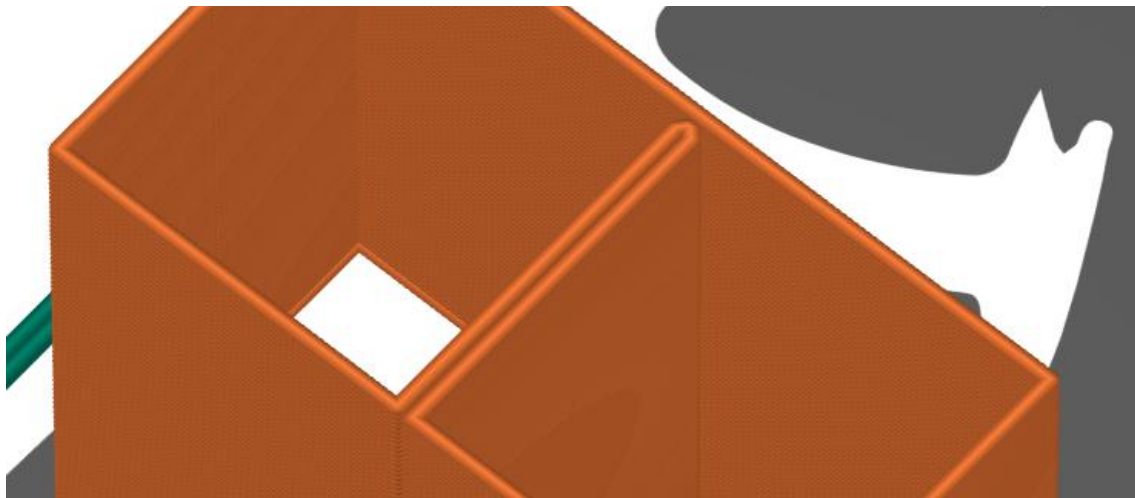


Figure 3.10. Structural wall with a one-sided joint and a continuous seam on one shell's side

Vertical holes. To incorporate vertical holes in vase-mode printing, each hole must be connected to the external contour by a gap, thereby forming a single continuous outer contour in every layer. **Figure 3.11** shows an example of a vertical hole used for a carbon spar.

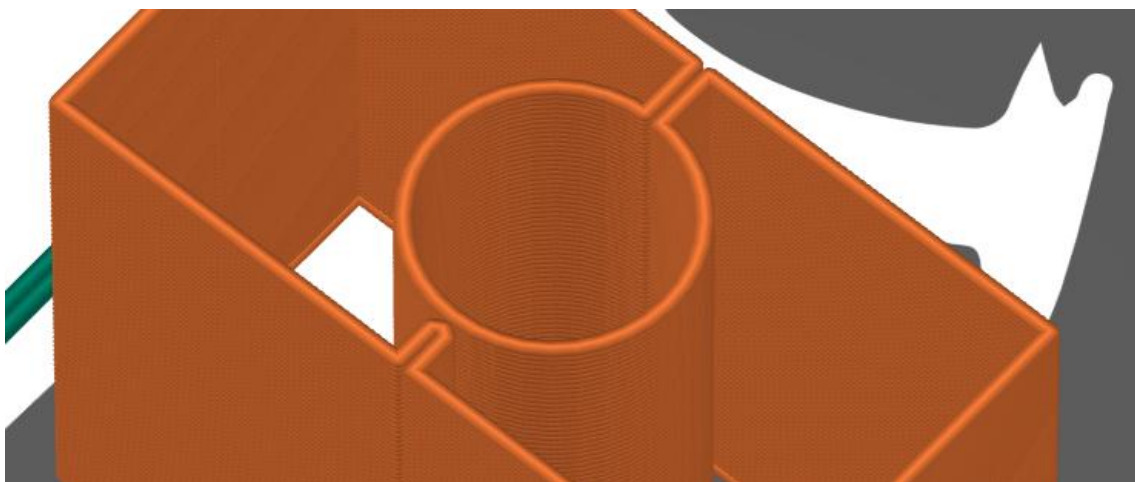


Figure 3.11. Structural wall with a hole for carbon spar placement, with a joint on one side of the hole

Figure 3.11 illustrates that vertical holes can be incorporated using techniques similar to those employed for internal wall structures. However, any internal structure connected to the outer wall results in surface indentations.

3.6. Boundary Layer and Specific Aerodynamics

3.6.1. Influence of Surface Texture and Print Layer Patterns on Aerodynamic Flow: Interaction of Printed Part Geometry with Boundary Layer Behaviour

The surface texture of 3D-printed parts plays a significant role in boundary layer behaviour. Research has shown that surface roughness increases drag on UAV wings at low Reynolds numbers. It can also delay boundary layer separation and improve lift performance, resulting in increased efficiency [28]. Studies on micro-aircraft have shown that adding surface roughness can increase thrust by 2% and reduce energy consumption by 5%, thereby improving aerodynamic efficiency [29].

Another effect of surface roughness is its influence on the acoustic characteristics of airflow. A study on 3D-printed UAV propellers indicated that surface irregularities increase aerodynamic drag and noise output due to vibration [30]. Recent studies have shown that forcing elements used on aircraft surfaces induce laminar-turbulent transition in the boundary layer. This method aims to thin the boundary layer and increase aerodynamic stability [31].

3.6.2. Design Considerations for Aerodynamic Efficiency in 3D Printed UAV Parts

To maximize aerodynamic efficiency, the complex structures enabled by 3D printing must be fully utilized. Drone body designs supported by topology optimization and CFD simulations enable improvements in structural durability and reductions in aerodynamic drag [32]. It is crucial to examine aerodynamic devices under real-world flight conditions. Experimental tests have demonstrated that control surfaces produced using the pressure-based method on UAVs with flying wing designs provide significant benefits in aerodynamic performance and steerability [33]. Biomimetic designs offer significant new opportunities for aerodynamic efficiency. Three-dimensional texture arrangements inspired by owl feather edge structures reduce surface turbulence source forces by more than 50% and also reduce noise by 10% [34].

Aerodynamics is one of the most influential disciplines in aircraft design, as it governs how an aircraft interacts with the surrounding airflow and ultimately determines its performance, efficiency, and controllability. From the earliest conceptual design stages, aerodynamic considerations dictate wing geometry, fuselage shaping, control surface sizing, and operational flight envelopes. The required flight characteristics – such as cruise speed, stall speed, endurance, manoeuvrability, and payload capacity – are therefore closely linked to aerodynamic performance. In particular, the geometry and size of the wing have a decisive impact on lift generation, drag characteristics, longitudinal and lateral stability, and maximum allowable take-off mass. Even relatively small geometric changes, such as variations in airfoil

camber, thickness distribution, or surface finish, can lead to significant changes in aerodynamic behaviour. For this reason, a thorough understanding of the fundamental principles of aerodynamics, as well as the influence of environmental conditions, geometric parameters, and surface properties, is essential for the successful design of any aircraft, especially UAVs operating at low Reynolds numbers.

3.6.3. Boundary Layer

One of the most fundamental concepts in fluid mechanics, applicable to both liquids and gases, is the Reynolds number (Re). The Reynolds number is a dimensionless parameter that expresses the ratio between inertial and viscous forces in a flow. It provides a useful criterion for assessing flow similarity and predicting whether a flow will be laminar or turbulent. The Reynolds number is defined as:

$$Re = \frac{\rho V c}{\mu} = \frac{V c}{\nu}; \quad (3.1)$$

where: Re – Reynolds number; ρ – density, $\frac{kg}{m^3}$; V – free-stream velocity, $\frac{m}{s}$; c – body length (typically the wing chord in aerodynamics), m; μ – dynamic viscosity (sometimes also called absolute viscosity), $\frac{kg}{ms}$; ν – kinematic viscosity (sometimes also called momentum diffusivity), $\frac{m^2}{s}$.

In aviation, designing an UAV that operates at low Reynolds numbers is significantly more challenging. Low Reynolds numbers are associated with low flight speeds and short chord lengths, conditions under which viscous effects dominate. Under such conditions, the aircraft generates very little lift, as seen from the lift equation (3.2), while the drag coefficient D_c increases (see **Figure 3.12**).

$$L = C_L S \frac{\rho V^2}{2}; \quad (3.2)$$

where: C_L – lift coefficient; S – wing surface area, m^2 ; L – lift force, N.

In the context of low-Reynolds-number aircraft considered in this book, it is not appropriate to focus on a single operating point. Instead, the analysis addresses a range of Reynolds numbers representative of small unmanned aerial vehicles and lightweight aircraft. The lower end of this range corresponds to low-speed operating conditions typical of take-off, landing, or loiter flight, where characteristic chord lengths are on the order of 200 mm, and Reynolds numbers fall within the lower part of the low-Reynolds-number regime. It should be noted that this lower-bound characteristic length is not purely an aerodynamic choice, but is constrained by the selected production method. In particular, the use of additive manufacturing imposes limitations on the maximum printable component size, build volume, and achievable structural stiffness without segmentation. These manufacturing constraints

directly influence the maximum feasible wing chord and, consequently, the minimum achievable Reynolds number during operation.

At the upper end of the operating envelope, the aircraft reaches higher Reynolds numbers, which have been previously calculated to be on the order of $Re \approx 5 \times 10^5$ [35]. While the exact combination of chord length and flight speed leading to this value is not specified here, this upper bound remains firmly within the low-to-moderate Reynolds number regime relevant to small UAVs and lightweight aircraft.

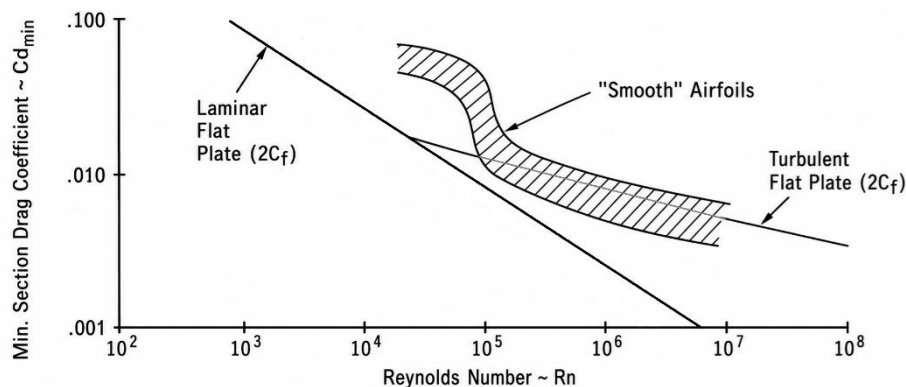


Figure 3.12. Dependence of drag coefficient on Reynolds number

To experimentally determine the drag coefficient D_c of a certain body, such as a sphere, without considering the Reynolds number similarity principle, it would be necessary to account for four independent parameters: V , c , ρ , and μ , which would require performing a very large number of measurements. However, when the Reynolds similarity principle is taken into account, it becomes clear that spheres of different diameters, placed in flows of different velocities and in different media with varying values of μ , ultimately depend on only a single variable – the Reynolds number Re . [36].

Therefore, when conducting experimental research, analysing scientific literature, and designing a new aircraft, the Reynolds number must first be determined. If it differs significantly, the data obtained during experiments will not correspond to real conditions. From this, it can also be concluded that the flow around a body in liquids and gases with identical Reynolds numbers will be the same. For this reason, in the past, aerodynamic studies were often performed in liquids, since they are visible and their parameters are easier to measure. The only difference that must be considered is cavitation – a phenomenon in which a liquid begins to vaporize in regions of low pressure [37].

This behaviour is particularly relevant to aircraft aerodynamics, since the flow accelerates over the upper surface of an airfoil, while changes on the lower surface are less pronounced. According to Bernoulli's principle, an increase in flow velocity results in a decrease in pressure. The lowest pressure occurs near the thickest section of the airfoil.

The boundary layer is a thin region of air that forms adjacent to aircraft surfaces due to fluid viscosity and plays a critical role in aerodynamic performance. Within this region, the flow velocity increases gradually from zero at the surface to the free-stream velocity. Boundary-layer characteristics directly influence drag, lift, and flight stability (see **Figure 3.13**) [38].

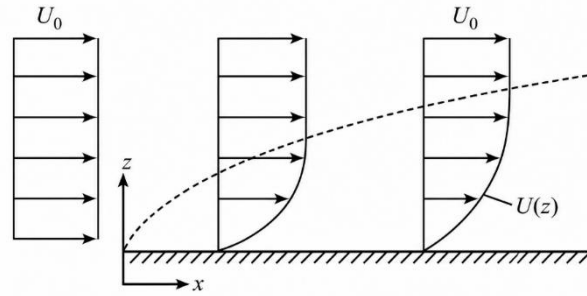


Figure 3.13. Schematic representation of the boundary layer

There is a close relationship between boundary-layer thickness and the Reynolds number. The thickness of the boundary layer can be estimated using equation (3.3):

$$\frac{\delta_{99}(x)}{l} = \frac{5}{\sqrt{Re}} \sqrt{\frac{x}{l}}; \quad (3.3)$$

where: δ_{99} – boundary-layer thickness, mm; l – total plate length, m; x – distance from the leading edge, m. Equation (3.3) shows that an increase in the Reynolds number leads to a thinner boundary layer [39]. Boundary-layer thickness also increases with distance from the leading edge (**Figure 3.13**).

However, it must be clearly emphasized that the concept of boundary-layer thickness is a constructed definition. The transition from the boundary-layer flow to the external flow occurs continuously; therefore, in principle, an exact boundary cannot be defined [36]. Nevertheless, since the concept of boundary-layer thickness is clear and convenient for analysis, it is widely used in practice. The boundary is typically defined as the location at which the flow velocity reaches a specified percentage of the free-stream velocity. For clarity, the index δ_{99} is commonly used.

3.6.4. Stall and Flow Separation

Closely related to boundary-layer behaviour are tangential shear stresses acting on the surface. These stresses are directly associated with the skin-friction coefficient and play an important role in maintaining flow attachment.

$$c_f = \frac{\tau_w(x)}{\frac{\rho}{2} U_\infty^2} = \frac{0.664}{\sqrt{Re}} \sqrt{\frac{l}{x}}; \quad (3.4)$$

where: c_f – skin-friction coefficient; U_∞^2 – free-stream velocity, $\frac{m}{s}$; τ_w – wall shear stress, Pa.

From equation (3.4), it can be observed that the maximum shear stresses occur near the leading edge of the plate, where the boundary layer is thinnest, and that these stresses decrease toward the trailing edge. This is important because when the wall shear stress approaches zero, the flow separates from the surface. As a result, a significant increase in drag occurs, and lift is reduced. In aviation, this phenomenon is referred to as stall (**Figure 3.14**).

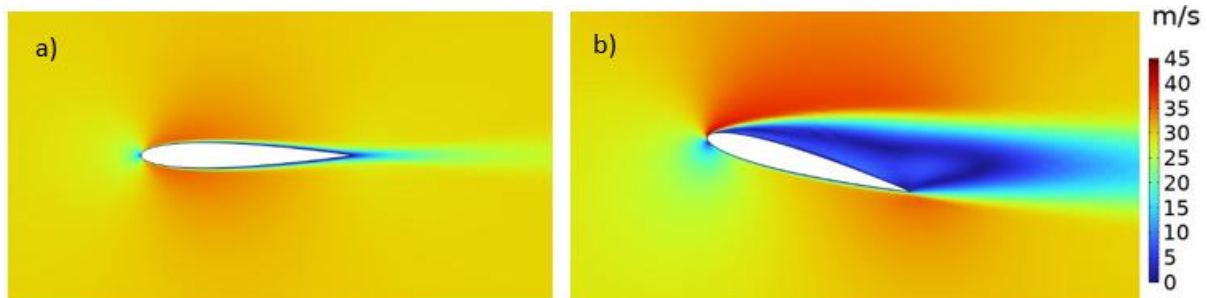


Figure 3.14. Velocity distribution for different angles of attack (AoA), a) at zero lift, b) at stall

When analysing the flow around an airfoil, in addition to shear stresses, pressure distribution is an even more influential factor governing flow separation. The larger the adverse pressure gradient, the higher the probability that the airflow will separate from the surface. This is clearly observed when analysing the flow around a sphere.

In **Figure 3.15**, it can be seen that as air moves from point D to point E, it accelerates, while its static pressure decreases, i.e., kinetic energy increases at the expense of pressure energy [36]. However, after passing the widest section of the sphere, as the flow moves from point E to point F, it encounters a region of increasing pressure. As a result, the surrounding flow imposes an adverse pressure gradient on the boundary-layer, causing flow deceleration, reversal, and eventual separation [40].

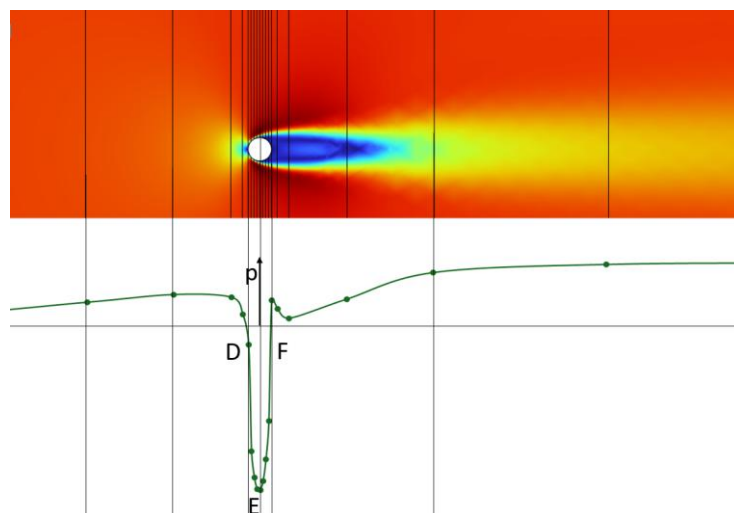


Figure 3.15. Flow around a sphere and pressure variation

This is the primary reason why aerodynamic airfoils have their characteristic shape. They are designed such that the pressure distribution along the airfoil surface is as smooth as possible, thereby minimizing strong adverse pressure gradients (see **Figure 3.16**).

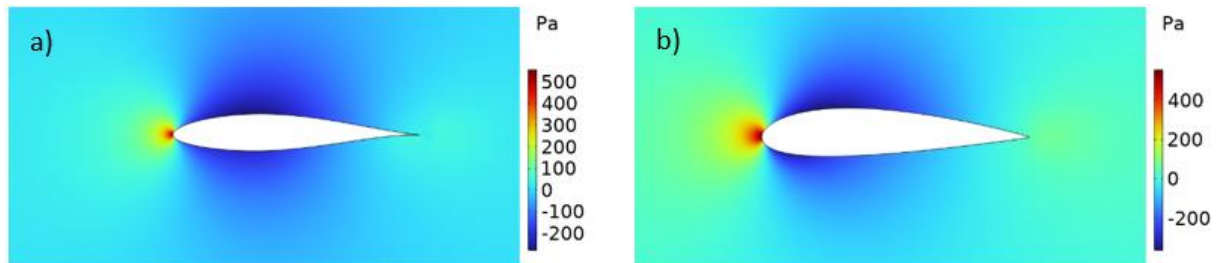


Figure 3.16. Pressure distribution over an air foil, a) laminar airfoil, b) conventional airfoil

It can also be observed that maximum pressure occurs near the thickest section of the airfoil. As the angle of attack increases, the pressure distribution changes, increasing the adverse pressure gradient until a critical angle of attack is reached and flow separation occurs.

3.6.5. Laminar, Turbulent Flow and Transition Point

It should be noted that there are two fundamentally different flow regimes: laminar and turbulent flow. Laminar flow is smooth and orderly, with fluid or gas layers moving parallel to each other and with negligible mixing between them. Fluid particles follow predictable trajectories. In contrast, turbulent flow is characterized by chaotic and stochastic motion, with strong mixing between fluid layers.

Laminar flow most commonly occurs at low velocities and over bodies with smooth surfaces. This type of flow is highly sensitive to external factors such as free-stream velocity fluctuations, pressure variations, and surface roughness. In practice, the surrounding airflow is rarely stable, and airfoil surfaces rarely exhibit extremely negligible roughness. Laminar flow can therefore be easily disturbed by weak gusts of wind, surface contamination (e.g. insects), or surface degradation due to environmental exposure, which may reduce aerodynamic performance by up to 30 % [41].

In most cases, due to the presence of pressure gradient, laminar flow over a wing transitions to turbulent flow after passing the location of maximum airfoil thickness. This region is referred to as the transition zone. To delay transition, laminar airfoils have been developed in which the maximum thickness is shifted towards the trailing edge, thereby reducing the adverse pressure gradient and extending the laminar flow region. Such airfoils are commonly used in gliders, as laminar flow is associated with low skin-friction drag, enabling high aerodynamic efficiency. However, even with optimized airfoil geometry, flow separation at high angles of attack cannot be fully prevented. One method proposed to mitigate this issue is splitting the trailing edge into two separate elements [42].

Experimental investigations have shown that such modifications increase the maximum lift coefficient CL and the angle of attack; however, the corresponding increase in the drag coefficient CD outweighs these benefits, resulting in reduced overall aerodynamic efficiency.

In practical applications, the flow over a wing is predominantly turbulent. Therefore, it is essential to understand its characteristics. Although turbulent flow is associated with higher skin-friction drag, it offers significant benefits. Unlike laminar flow, which is highly sensitive to disturbances and prone to early separation, turbulent flow is more resistant to adverse pressure gradients and remains attached to the surface for longer distances. In many cases, flow separation can be delayed or avoided only when the boundary-layer flow is turbulent.

The turbulent boundary layer consists of multiple regions. The outer region is dominated by inertial effects, while the wall, viscous effects remain significant. This near-wall region is referred to as the viscous sublayer δ_v . Consequently, the turbulent boundary layer can be described as comprising an outer turbulent region and an inner viscous sublayer. The relative thickness of these regions depends strongly on the Reynolds number. As the Reynolds number increases, the overall boundary-layer thickness increases, while the viscous sublayer becomes relatively thinner, reflecting the reduced influence of viscosity in high-Reynolds-number flows.

Representative values for turbulent flow over a flat plate demonstrate this behaviour. For airflows with Reynolds numbers on the order of 10^6 – 10^8 , the boundary-layer thickness typically ranges from approximately 8 mm to 70 mm, while the viscous sublayer thickness remains on the order of 0.1–0.4 mm. In water flows, where Reynolds numbers can reach 10^9 , the boundary-layer thickness may exceed 1 m, whereas the viscous sublayer remains limited to approximately 0.1–1 mm. These results indicate that although the absolute boundary-layer thickness increases significantly, the viscous sublayer occupies an increasingly smaller fraction of it [43].

This structure highlights the fundamental nature of turbulent boundary layers: viscous effects are confined to a very thin near-wall region, while the bulk flow is governed by inertial forces. This distribution contributes to the increased drag associated with turbulent flow compared to laminar flow.

As previously noted, the boundary layer over a flat plate is laminar near the leading edge and becomes turbulent further downstream. The onset of transition, denoted as x_{crit} , can be estimated using the critical Reynolds number Re_{crit} . Although transition occurs over a finite region, it is often approximated as a discrete transition point for analytical simplicity. The numerical value of Re_{crit} depends strongly on the level of external disturbances. For highly distributed flow, a typical value $Re_{crit} = 1 \cdot 10^5$, whereas under controlled laboratory conditions, values up to $Re_{crit} = 3 \cdot 10^6$ may be observed. Transition is typically accommodated by a rapid increase in boundary-layer thickness. It has also been shown that increasing angle of attack and flow unsteadiness shifts the transition point x_{crit} towards the leading edge [43].

In general, at low angles of attack, the boundary layer remains laminar over a larger portion of the surface, and the transition point is located further downstream. As the angle of attack increases, pressure gradients intensify, promoting the growth of disturbances within the laminar boundary layer. Consequently, transition occurs earlier, and the transition point gradually shifts toward the leading edge. This behaviour reflects the increasing instability of laminar flow under aerodynamic loading. This effect is most pronounced at low Reynolds numbers and becomes less significant for $Re \geq 10^6$ [44].

It has also been observed that separated flow, or flow that has transitioned from laminar to turbulent, can gain energy from the external flow and reattach to the surface [45]. In such cases, a laminar separation bubble (LSB) is formed (see **Figure 3.17**).

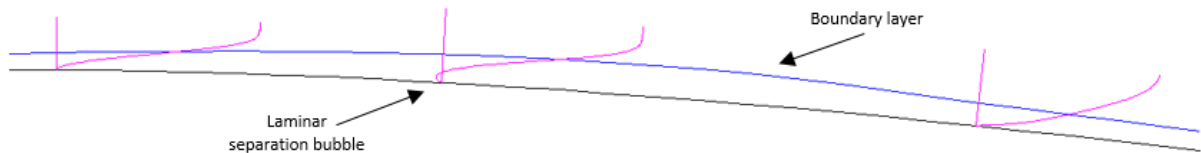


Figure 3.17. Laminar separation bubble showed by the velocity profiles showed in purple (left to right – laminar, separated, turbulent flow)

This bubble has a significant influence on aerodynamic performance. If the flow does not reattach, performance deteriorates; however, when a laminar separation bubble forms and reattachment occurs, aerodynamic characteristics may improve. As a result, at low Reynolds numbers, a flat plate can exhibit better aerodynamic performance than a cambered airfoil.

For a flat plate, the sharp leading edge generates a strong pressure gradient, promoting early transition. At the same time, the flow conditions allow the formation of a laminar separation bubble, which contributes to maintaining favourable aerodynamic characteristics. In contrast, for a cambered airfoil, flow separation tends to occur further downstream, which may prevent timely bubble formation (see **Figure 3.18**).

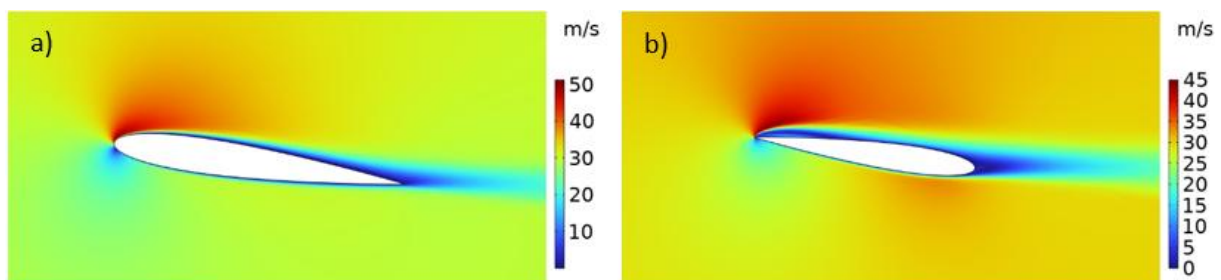


Figure 3.18. Velocity distribution over a conventional and inverted NACA 0012 airfoil, a) conventional, b) inverted

This behaviour is reflected in the variation of the lift coefficient with angle of attack. In the inverted configuration, the lift coefficient increases more rapidly at low angles of attack and

reaches higher values at moderate angles, indicating delayed flow separation. Additionally, the critical angle of attack is higher, meaning that stall occurs later compared to the conventional configuration. At higher angles of attack, the differences diminish as flow separation dominates [44].

The differences in aerodynamic performance are closely related to the near-wall flow structure, where the presence or absence of a laminar separation bubble governs boundary-layer stability and stall onset. Depending on the required performance, either flow regime may be preferable. Therefore, accurate prediction and control of the transition point are essential. This will be discussed in the following subsection.

3.6.6. Boundary-Layer Control Methods

It has long been observed that the boundary layer responds differently to flow disturbances at different Reynolds numbers. Certain disturbances, such as increased surface roughness or the introduction of vortex generators, may improve aerodynamic performance at low Reynolds numbers, while the same features can degrade performance under other conditions. As a result, numerous boundary-layer control methods have been developed. These methods are generally classified into two main categories: active and passive.

Active methods include wing mechanization (flaps, leading-edge devices, spoilers) as well as techniques that directly supply energy to the boundary layer. These systems are typically more complex but enable more precise control of flow behaviour and are generally more effective at higher flight speeds. Examples include:

- Boundary-layer suction: removal of low-momentum fluid/air from the boundary layer through slots or porous surfaces, thereby maintaining laminar flow or delaying separation;
- Blowing: injection of high-momentum fluid into the boundary layer to delay separation and improve flow attachment;
- Plasma actuators: ionization of air using electric fields to introduce momentum into the flow;
- Oscillating surfaces: introduction of controlled surface oscillations to influence separation and reduce drag [46].

Although these methods are highly effective, they are not the focus of the present study. Instead, this work concentrates on passive control methods, which rely on fixed geometric features or surface modifications and do not require external energy input. Examples include:

- Surface geometry modification: addition of devices, such as vortex generators;
- Surface texturing: application of grooves or controlled roughness;

- Pressure-gradient control: aerodynamic shaping, for example, through laminar airfoil design.

Laminar airfoils have been discussed in the previous subsection. Greater attention is therefore given to the remaining passive methods.

Vortex generators (VGs) are among the most commonly used passive control devices. These consist of small plates mounted on the airfoil surface at an angle to the flow, generating streamwise vortices that transport high-momentum fluid from the outer flow toward the surface. At low velocities, properly designed VGs can significantly increase the maximum lift coefficient and allowable angle of attack, albeit at the cost of increased drag. However, studies have shown that poorly designed VGs may degrade aerodynamic performance, and configurations optimized for one airfoil are not necessarily transferable to others [47,48].

The placement of vortex generators has a significant influence on aerodynamic performance. Experimental results indicate that relocating VGs closer to the leading edge (e.g., from $x = 0.5c$ to $x = 0.3c$) increases the lift coefficient by up to approximately 16.3%, primarily due to enhanced boundary-layer energization and delayed flow separation. However, this improvement is accompanied by an increased drag, reducing overall aerodynamic efficiency [49].

A more detailed analysis of the lift characteristics shows that upstream VG placement improves lift over a wide range of angles of attack, particularly near stall, where separation is delayed and the stall angle increases. Conversely, downstream placement results in smaller lift gains but more favourable drag characteristics. Thus, optimal VG placement represents a compromise between lift enhancement and drag penalty, depending on the flow conditions and airfoil geometry [49]. Similar sensitivities have been observed for other passive protrusions, confirming that effectiveness depends strongly on streamwise position relative to boundary-layer development and separation [49].

A related method for improving aerodynamic performance is controlled surface roughness. Roughness may be applied globally or locally. It can be observed that the double roughness zone configuration achieves the highest maximum lift coefficient. In the angle-of-attack range of $10\text{--}25^\circ$, the single roughness zone configuration exhibits more favourable drag characteristics. The highest average aerodynamic efficiency (CL/CD) is achieved by the later airfoil. As with vortex generators, optimal performance is typically obtained when roughness is applied near one-third of the chord length [50]. When investigating the influence of surface roughness distributed over the entire airfoil on flight characteristics, it was found that at low Reynolds numbers, the effect of surface-roughness height on aerodynamic parameters is either negligible or beneficial.

Studies of distributed roughness indicate that its effect depends strongly on Reynolds number. At very low Reynolds numbers ($Re < 10^4$), surface roughness has little influence on

aerodynamic performance. In the range $5 \cdot 10^4 \leq Re \leq 10^5$, roughness can improve efficiency by delaying flow separation. At $Re = 1.5 \cdot 10^5$, this beneficial effect persists provided that the roughness height does not exceed $h = 0.2$ mm. For larger roughness height ($h > 0.2$ mm), the lift-to-drag ratio (CL/CD) decreases, although it may still remain above that of a smooth surface. At higher Reynolds numbers (e.g., $Re = 2.5 \cdot 10^5$), surface roughness has a positive effect on performance as long as the roughness height is approximately $h \approx 0.1$ mm. At even higher Reynolds numbers (e.g., $Re = 3.5 \cdot 10^5$) the flow becomes fully turbulent, and skin-friction drag becomes significantly higher than in the laminar-flow case. At the same time, surface roughness further intensifies the interaction between the flow and the surface, leading to a substantial increase in the drag coefficient and a reduction in the lift-to-drag ratio [51].

Another method that contributes to increased wing efficiency is the suppression of spanwise flow and lateral motion of the airflow. Two approaches have been developed for this purpose: partitions arranged along the wing profile [52] and surface grooves [53]. The variation of the skin-friction coefficient along a flat plate is influenced by the presence of longitudinal V-grooved riblets of different sizes. In comparison to a smooth surface, riblet-configured surfaces generally exhibit lower skin-friction values over a wide range of Reynolds numbers. This reduction is particularly noticeable near the leading-edge region, where the boundary layer is still developing, and the local Reynolds number is low [53]. As the flow progresses downstream and the Reynolds number increases, the skin-friction coefficient decreases for all cases, and the differences between the smooth and riblet surfaces become smaller. Although all riblet configurations tend to reduce friction relative to the smooth surface, the magnitude of this reduction depends on the groove size, indicating the existence of an optimal riblet geometry. Larger riblets do not necessarily provide additional benefits and may approach the behaviour of surface roughness elements at higher Reynolds numbers. The presented trends are consistent across different free-stream velocities, demonstrating that riblets can effectively reduce skin-friction drag, particularly in the early stages of boundary-layer development, while their relative influence diminishes as the flow becomes more fully developed [53].

It can be observed that longitudinal grooves reduce the skin-friction coefficient. A particularly pronounced effect is observed at low Reynolds numbers ($Re < 10^5$). Under these conditions, larger grooves have a stronger influence. However, as the Reynolds number increases, this effect diminishes, and large grooves begin to degrade aerodynamic performance. If the grooves are treated as a form of surface roughness, a clear correlation can be established with the previously discussed studies on roughness effect. An additional effect has been observed when grooves are arranged transverse to the direction of the external airflow [54]. When the grooves are sufficiently large, vortices can form within them, reducing wall shear stress, i.e., skin-friction drag (see **Figure 3.19**).

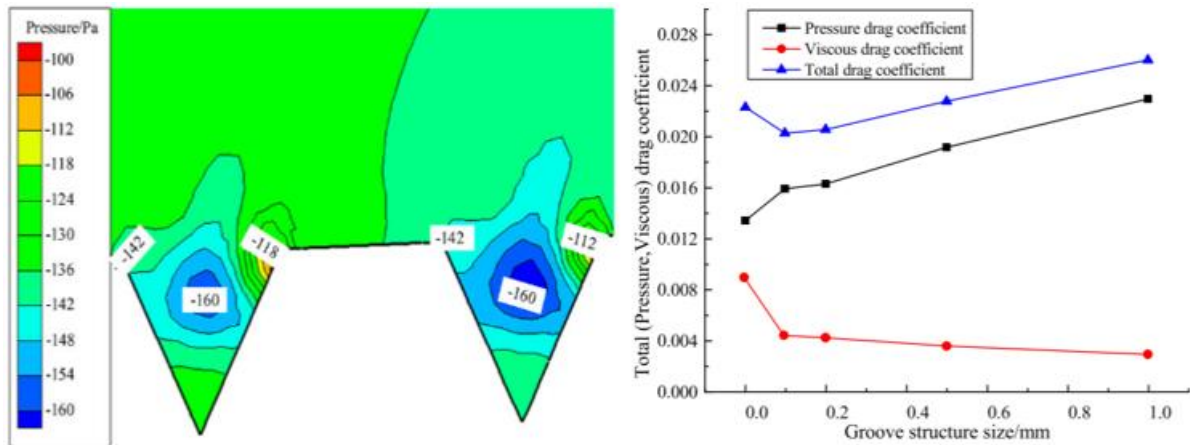


Figure 3.19. Vortices formed inside transverse grooves and their influence on drag coefficients [55]

As can be seen, skin-friction drag decreases with increasing groove size, while pressure drag increases; consequently, beyond a certain groove size, the total drag begins to increase. It should be noted, however, that the cited study was conducted at a flow velocity of 20 m/s and therefore does not represent conditions at lower Reynolds numbers. Nevertheless, it provides insight into the underlying physical mechanism. At present, no studies have been identified that investigate this effect at low velocities.

Furthermore, it remains unclear how grooves affect the flow when applied to the lower surface of a wing. In the study addressing this configuration, the lowest investigated speed was Mach 0.3, which is significantly higher than the Reynolds-number range considered in the present work [56]. Therefore, the aim of this study is to examine the effect of such a modification under low-Reynolds-number conditions. Data from the aforementioned study indicate that, at high speeds, defects on the lower surface have a negative effect on aircraft aerodynamic characteristics. In further investigations, it was found that when a portion of the airfoil surface is removed, a vortex forms within the cut-out region, redirecting the flow such that the airfoil behaves as if the cut-out were absent (see **Figure 3.20**). Airfoils of this type are referred to as step profiles.

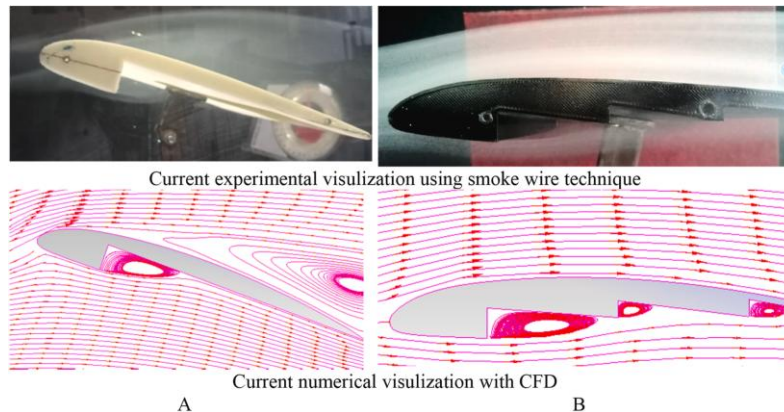


Figure 3.20. Streamlines around NACA 23012C with $Re = 88.3 \times 10^3$: A) single-step configuration at AoA 16° B) three-step configuration at zero AoA [57]

Similarly, to surface grooves, a cut-out region reduces skin-friction drag by creating a region in which the flow follows its natural trajectory without direct contact with the surface.

The results of the conducted study clearly indicate that step features can significantly increase aerodynamic efficiency at very low Reynolds numbers (see **Figure 3.21**). Nearly all airfoils exhibited a substantial reduction in drag, with the exception of the three-step airfoil, which achieved the highest C_L value. In contrast to the three-step configuration, the lift coefficients of the other modified airfoils were lower than those of the baseline airfoil.

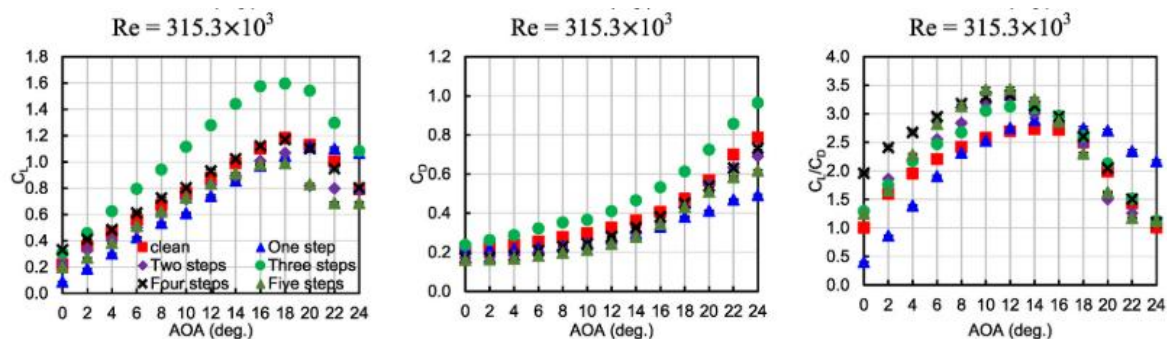


Figure 3.21. Influence of the number of steps in a stepped airfoil on aerodynamic characteristics [57]

The reviewed literature indicates that, at low Reynolds numbers, a properly designed airfoil can significantly improve aircraft performance, and that surface modifications and defects – such as roughness, grooves, and protrusions – may have a beneficial effect, in contrast to their influence at high flight speeds. It is evident that boundary-layer behaviour plays a decisive role in determining aerodynamic performance, particularly for aircraft operating at low Reynolds numbers. The analysis shows that laminar, turbulent, and transitional flows exhibit fundamentally different characteristics, with flow separation, transition location, and laminar separation bubbles strongly influencing lift, drag, and overall aerodynamic efficiency. It is shown that, contrary to high-Reynolds-number aerodynamics, surface imperfections and

passive flow-control devices – such as vortex generators, localized roughness, grooves, and stepped geometries – can have a beneficial effect at low Reynolds numbers by promoting flow reattachment, delaying separation, or stabilizing the boundary layer. The reviewed studies indicate that the effectiveness of these methods is highly sensitive to Reynolds number, surface geometry, and placement, and that improper design can negate potential benefits. Overall, the findings underline that low-Reynolds-number aerodynamics requires design strategies fundamentally different from those used at higher speeds, and that careful boundary-layer control represents a key opportunity for improving the performance of small UAVs and lightweight aircraft.

3.7. Mechanical Characterization of Common LW-PLA Vase-Mode Structures

Common vase-mode UAV airframe structures include:

- single-wall elements (outer shells, wiring conduits, spar tubes),
- double-wall elements (load-bearing ribs and frames).

Due to the continuous toolpath, these elements are joined through various seam configurations. **Figure 3.22** shows a wing section sliced for vase-mode printing.

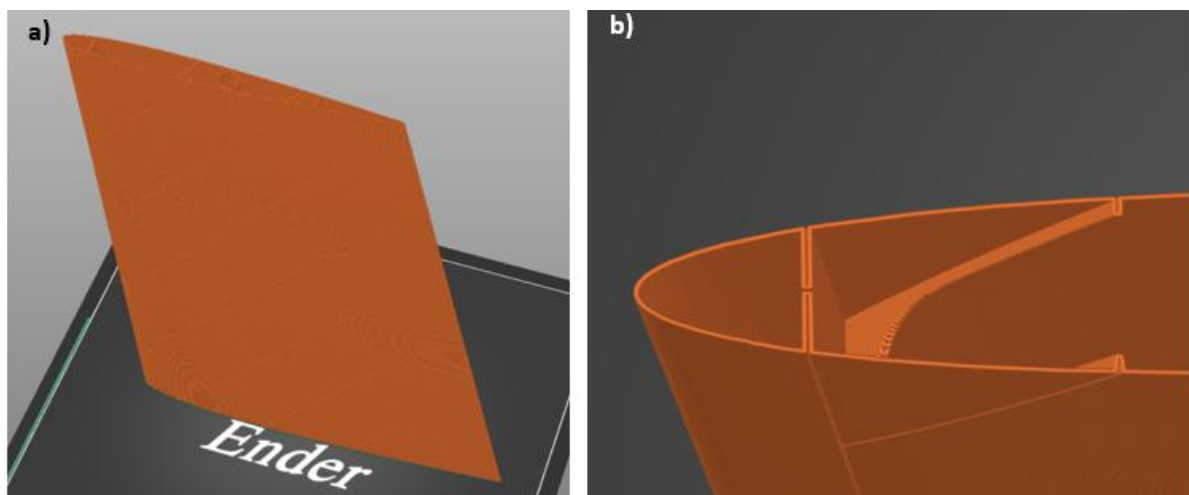


Figure 3.22. Wing section sliced for vase-mode printing, a) full view, b) close-up of structural elements.

Despite widespread use of LW-PLA in experimental UAVs, mechanical data specific to thin-wall, UAV-relevant geometries remain limited. Designers frequently rely on trial-and-error methods when selecting wall thicknesses and internal structures, often resulting in suboptimal designs. Material properties of PLA can vary significantly due to manufacturing and environmental conditions [58], and infill and wall topology have a strong influence on mechanical performance [59]. This study focuses on comparing the tensile and shear performance of common single- and double-wall vase-mode structures. Test samples were sliced using PrusaSlicer and fabricated from commercially available ColorFabb LW-PLA

filament [60] on a Creality Ender-3 Pro printer [61]. Printing parameters were held constant across all samples to minimize variability. These parameters are summarized in **Table 3.2**.

Table 3.2. Printer and slicer parameters.

Parameter	Value	Parameter	Value
printer type	bowden	line width, mm	0.4
printer nozzle diameter, mm	0.4	flow rate, %	53
bed temperature, °C	60	print speed, mm/s	25
nozzle temperature, °C	246	layer height, mm	0.2

Two panel types (150 × 150 mm) were printed vertically on the build plate to replicate typical UAV wall structures:

- Single-wall: printed as an outer contour of the part, depicted in **Figure 3.23**.
- Double-wall: produced by introducing 0.02 mm separation gaps in the model, depicted in **Figure 3.24**.

The wall thickness after printing was measured to be 0.5 mm and 1 mm, respectively.

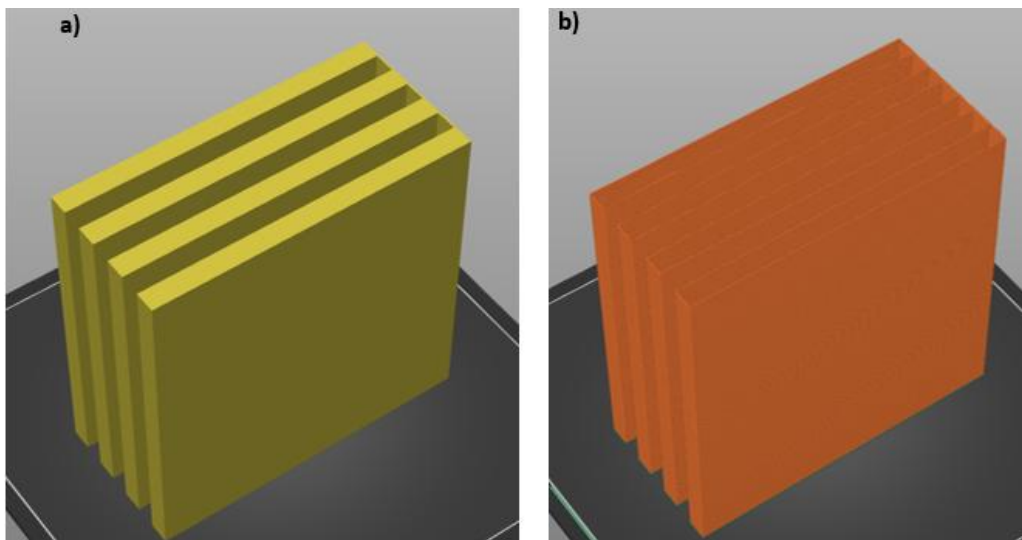


Figure 3.23. Preparation of single-layer panels, a) part geometry, b) sliced part.

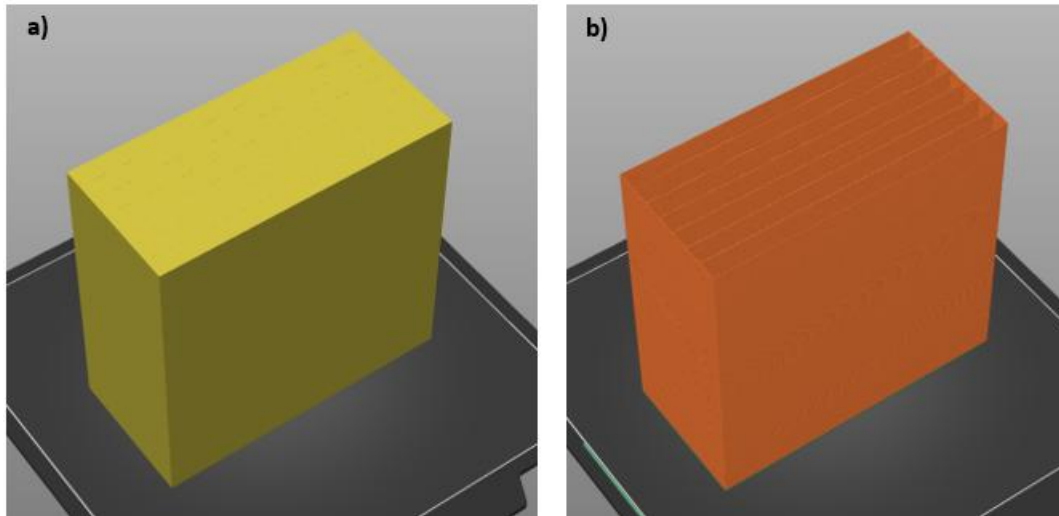


Figure 3.24. Preparation of double-layer panels, a) part geometry, b) sliced part.

Panels were cut into 70 mm × 12 mm rectangular strips (both layer-parallel and layer-perpendicular, **Figure 3.25a**) using a mechanical cutting method rather than laser cutting. This approach avoided the potential thermal degradation and material hardening often associated with laser cutting. No additional shaping (e.g., dog-bone specimens or tabs) was used in order to preserve the integrity and natural behaviour of the printed material. The chosen specimen geometry is prone to stress concentrations during tensile testing, resulting in lower measured ultimate strength values for samples with loading parallel to the print direction [62]; however, for samples perpendicular to the layer direction, stress concentrations are unavoidable.

Two types of mechanical tests were conducted:

- Tensile Test: specimens were clamped at both ends and loaded in tension along their length (**Figure 3.25b**) until failure, recording the maximum tensile force.
- Shear Test: specimens were mounted in a fixture applying lateral force (**Figure 3.25c**) until shear failure occurred, again recording the maximum force.

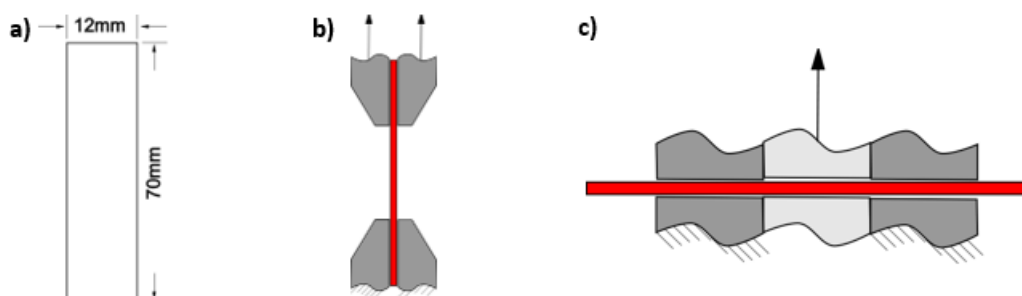


Figure 3.25. Specimen geometry (a) and loading conditions for tensile testing (b) and shear testing (c).

For each test, only the maximum force prior to failure was recorded.

Ultimate tensile and shear stresses were calculated as:

$$\sigma_U = \frac{F_{UT}}{S} \quad (3.5)$$

$$\tau_U = \frac{F_{US}}{2S} \quad (3.6)$$

where σ_U - ultimate tensile stress, τ_U - ultimate shear stress, F_{UT} - ultimate tensile force, F_{US} - ultimate shear force; and S – cross-sectional area of the test specimen (6 mm² for single-wall and 12 mm² for double-wall specimens).

Resulting ultimate tensile and shear stress values are shown in **Figure 3.26** and **Figure 3.27**. From **Figure 3.26**, the ultimate tensile stress along the print direction is 10.45 MPa and 10.87 MPa, while perpendicular to the print direction, it is 3.25 MPa and 3.39 MPa for single- and double-layered specimens, respectively. However, due to the absence of a dog-bone specimen geometry, the actual ultimate stress values should be estimated to be approximately 25% higher (13.06, 13.59; 4.06, 4.24 MPa).

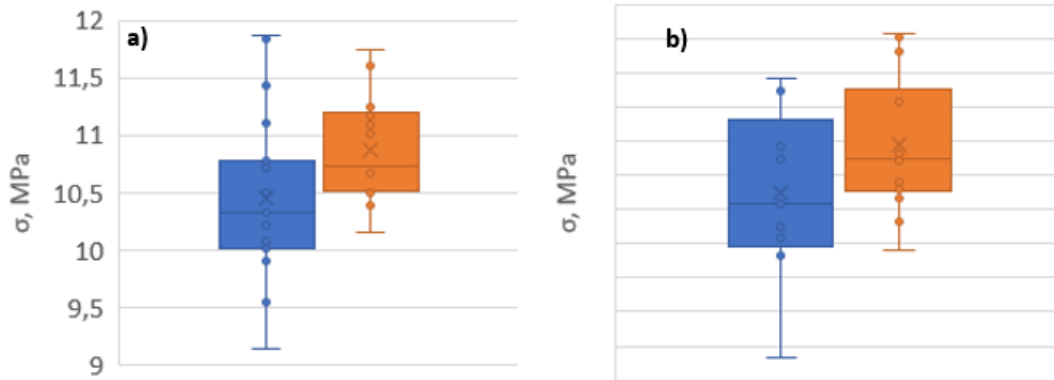


Figure 3.26. Tensile test results: a) parallel to the print direction, b) perpendicular to the print direction; blue represents single-layer results, orange – double-layer results

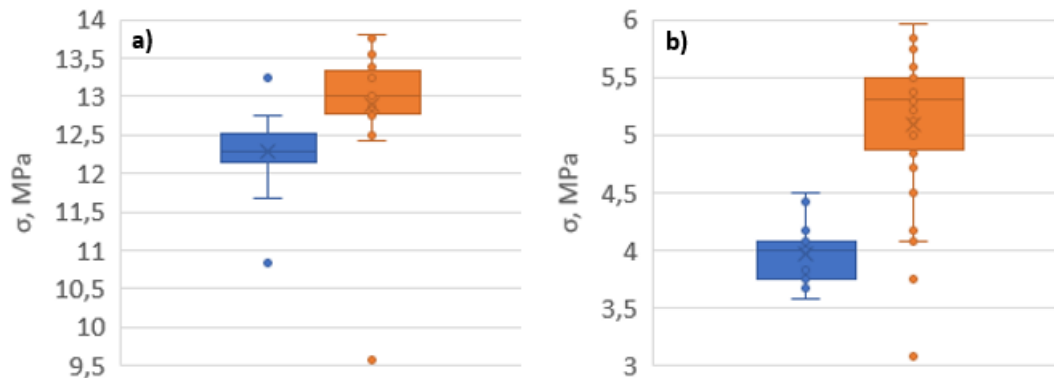


Figure 3.27. Shear test results: a) parallel to the print direction, b) perpendicular to the print direction; blue represents single-layer results, orange – double-layer results

From **Figure 3.27**, ultimate shear stress parallel to the print direction is 12.28 MPa and 12.89 MPa, while perpendicular to the print direction is 3.97 MPa and 5.09 MPa for single- and double-layered specimens, respectively. Both tensile and shear test results show that material strength parallel to the print direction is approximately three times higher than perpendicular direction. It can also be observed that double-layer specimens exhibit higher strength; this is attributed to improved interlayer bonding, which reduces the ratio between outer perimeter defects and cross-sectional area.

3.7.1. Advanced Vase-Mode Structural Features: Alternating One-Sided Joint and Split-Gap Structures

Concealing surface indentations and strengthening seam regions requires substantial effort during model preparation. More advanced structural configurations that allow partial concealment of outer shell defects while also improving joint strength are described below. The joint position of the wall structure can be shifted between layers, as shown in **Figure 3.28**.

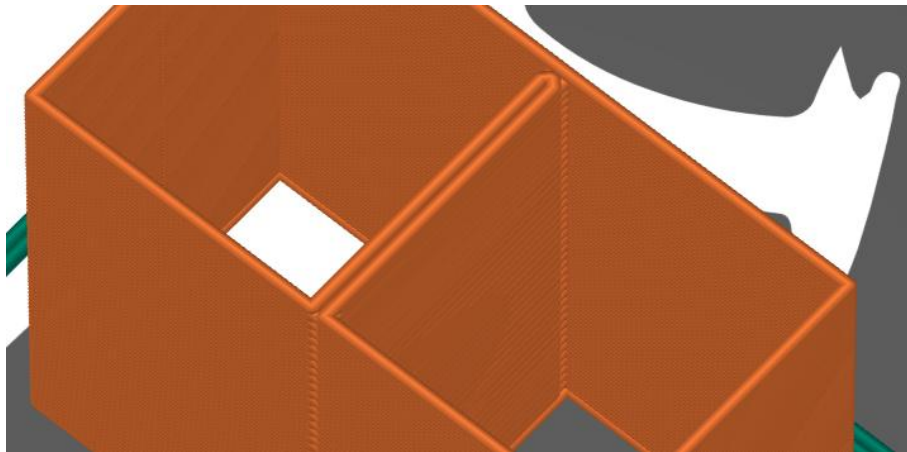


Figure 3.28. Structural wall with joint and seam position alternating between layers

The wall structure shown in **Figure 3.28** is characterized by largely concealed surface indentations and strong joints at both ends of the structure. This method is effective for walls without gaps or lightening holes, but it cannot be applied when lightening holes are required, as such features must be connected to the outer shell in every layer.

When a structure must be connected to the outer shell in every layer, the footprint on the shell can be reduced by splitting the ends of the structure into two lines and alternating between them, as shown in **Figure 3.29**.

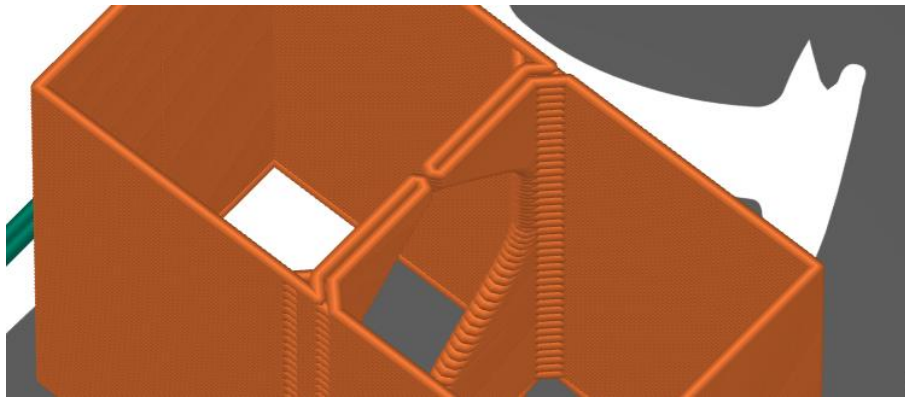


Figure 3.29. Structural wall with lightening holes, a central joint, and split seams on both sides of the shell

The structure shown in **Figure 3.29** is characterized by a reduced footprint on the outer shell, a strong shell–structure connection, and the ability to incorporate lightening holes. However, as in previously discussed configurations, the central joint remains weak. To strengthen this joint, alternating the position of the central gap between layers is recommended, as shown in **Figure 3.30**.

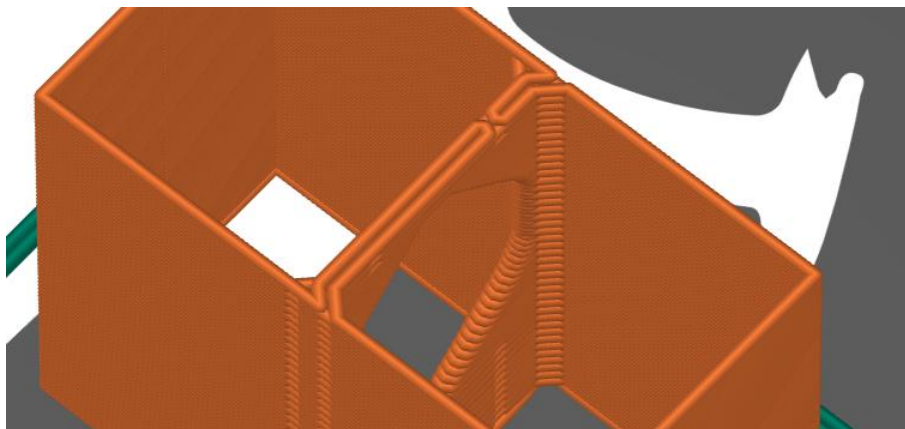


Figure 3.30. Structural wall with lightening holes, alternating joint position, and split seams on both sides of the shell

The structure illustrated in **Figure 3.30** is characterized by a reduced outer shell footprint, strong connections, and compatibility with lightening holes. However, this configuration is among the most challenging to model.

3.7.2. Distributed Joint Structures

When a single internal structure contacts the outer wall at multiple locations, the joint position may alternate between these points, further concealing surface indentations. However, this typically results in weaker structure-to-shell joints, as shown in **Figure 3.31**.

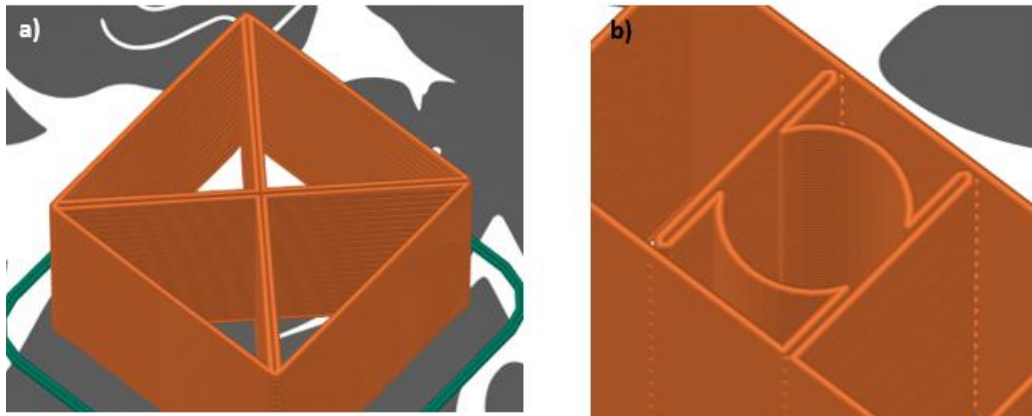


Figure 3.31. Structural walls with seams alternating between four positions on the shell

The structures in **Figure 3.31** are characterized by an almost imperceptible outer shell footprint; however, the joints between the structure and the shell are weaker because bonding occurs only every fourth layer. Increasing the connection area allows continuous positioning of the joint between the shell and the structure, resulting in an effective I-beam structure with improved structural characteristics (see **Figure 3.32**).

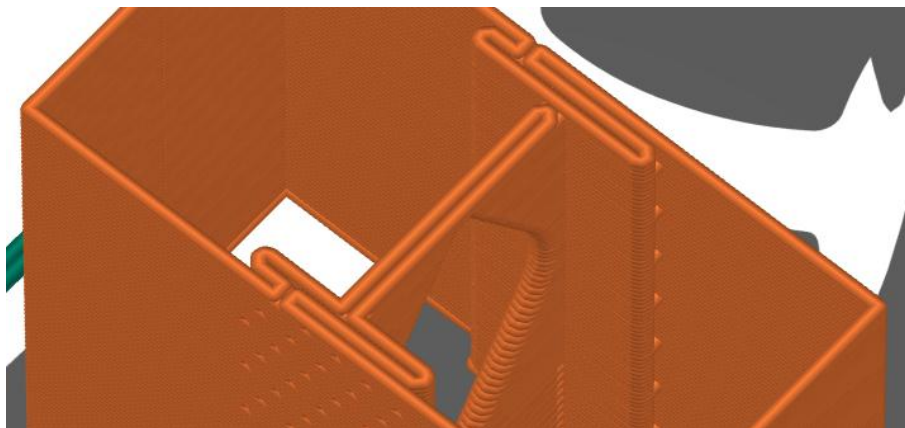


Figure 3.32. Structural I-beam with lightening holes and seams alternating between multiple positions on the shell

The I-beam structure shown in **Figure 3.32** is characterized by a barely perceptible footprint on the outer shell, strong structure-to-shell connection, and the ability to incorporate lightening holes.

3.7.3. Seam Strength in Vase-Mode Structures

Vase-mode designs rely heavily on seams to connect outer shells and internal structures. To compare seam performance, tensile tests were conducted on 4 mm thick dog-bone specimens incorporating different seam configurations. Each specimen contained 29 parallel inner walls,

meaning failure occurred at the weakest seam. The dog-bone specimen is shown in **Figure 3.33**.



Figure 3.33. Vase-mode printed dog-bone specimen

In **Figure 3.33** dog-bone specimen *ears* are modelled as 100% infill using walls with the alternating seam method described earlier. The seam structure samples tested were central-gap seam, one-sided seam, alternating seam and split seam, shown in **Figure 3.34**.

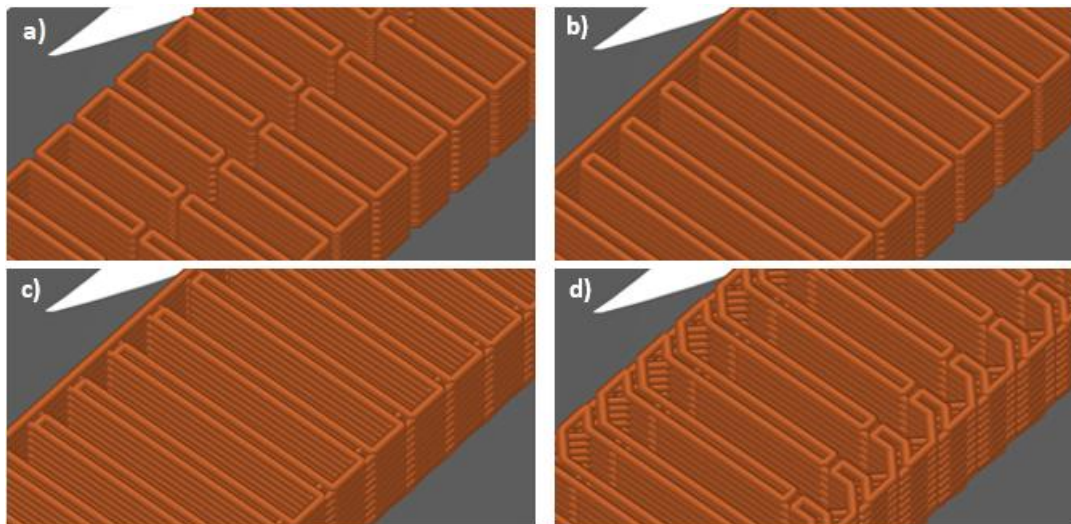


Figure 3.34. Different types of seam structures: a) central-gap seam, b) one-sided seam, c) alternating seam, and d) split seam

Resulting comparative tensile stress values were calculated for uninterrupted wall cross-section area (4 mm²), while strain values were calculated for the 60 mm seamed section. Comparative stress-strain curves are shown in **Figure 3.35**.

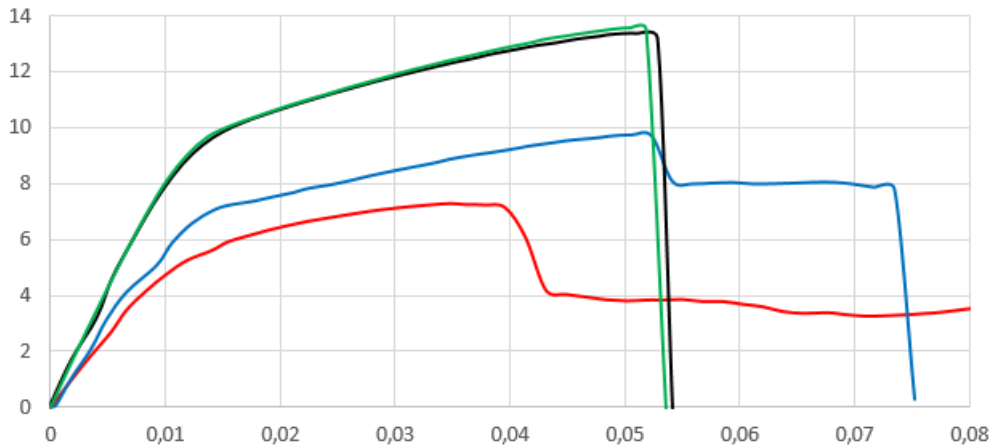


Figure 3.35. Comparative stress-strain curves for seam types (red – central-gap seam; blue – one-sided seam; black - alternating seam; green - split seam)

From **Figure 3.35**, the alternating (black) and split (green) seam specimens show nearly identical responses: a linear elastic increase to a high ultimate stress (~ 13 – 13.5 MPa) at a strain of approximately ≈ 0.05 – 0.052 . These peak values are comparable to the uninterrupted single-layer wall results, indicating that the seams in these configurations do not significantly reduce ultimate strength. Both specimens exhibit sudden, near-brittle failure immediately after the peak (sharp stress drop), consistent with fracture occurring in the continuous wall segments between seams. The abrupt post-peak collapse indicates minimal residual load-carrying capacity after fracture.

Central-gap and one-sided seams exhibit lower peak strength. The central-gap (red) specimen reaches approximately 6.5 – 7 MPa at a strain of about ≈ 0.035 – 0.04 , while the one-sided seam (blue) reaches approximately 9 – 9.5 MPa at a strain of about ≈ 0.05 . Unlike the alternating and split specimens, the central-gap and one-sided seams do not show an immediate, complete loss of load after peak. Instead, they exhibit greater strain capacity before final separation (particularly the one-sided seam, which maintains appreciable stress beyond strains of 0.07). This behaviour indicates that failure initiates at seam locations, but the geometry or interlayer interaction preserves partial load transfer, allowing larger deformations without total separation.

3.8. Other Features of Vase-Mode Printing

3.8.1. Horizontal Features

Using FDM, strong overhangs cannot be printed reliably [63]. When printing in vase mode, both inner and outer shell overhangs must be considered. Horizontal and rounded upper surfaces should be replaced with 60° overhanging roof structures (see **Figure 3.36**).

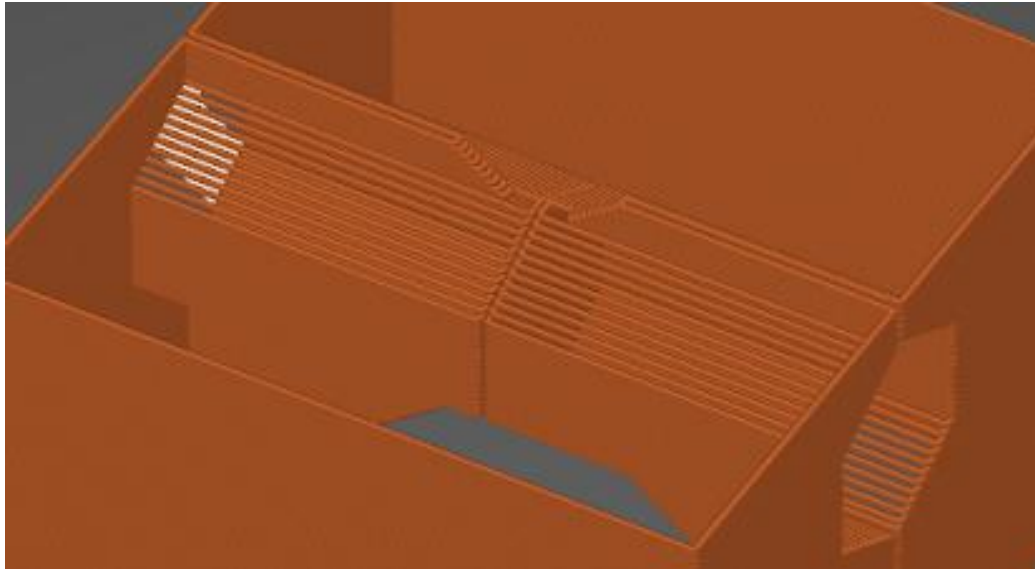


Figure 3.36. Structural horizontal hole with 60° overhangs

Figure 3.36 shows the roof structure used for the upper surfaces of horizontal features. For the lower surfaces of both rounded and flat features, it is recommended to use 45° support tree structures grown from the outer shell. An example is depicted in **Figure 3.37**.

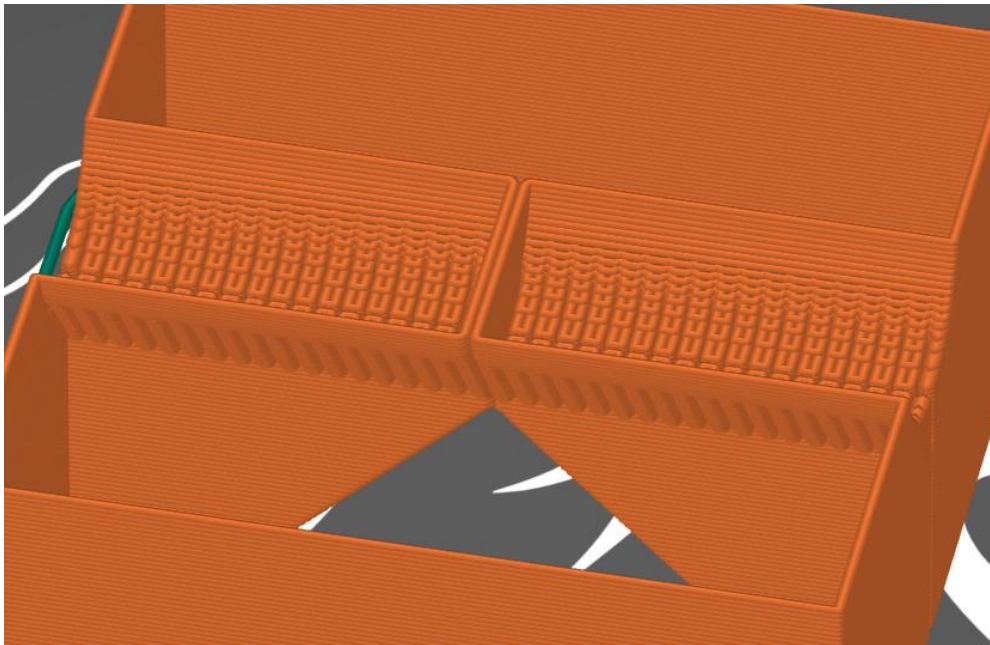


Figure 3.37. Support tree for the bottom of a circular horizontal structural hole

Figure 3.37 shows 45° support structures for the lower part of the circular horizontal hole. It is worth noticing that, in order to preserve the single-contour quality of each layer, the modelled hole indicates a thin wall that is removed during post-processing. Structures

designed to be removed during post-processing are commonly used in both conventional and vase-mode printing and are referred to as sacrificial structures. These include sacrificial walls (**Figure 3.37**), layers (**Figure 3.38**), bed adhesion tabs for corners (**Figure 3.39**), as well as anti-wobble supports (**Figure 3.40**).

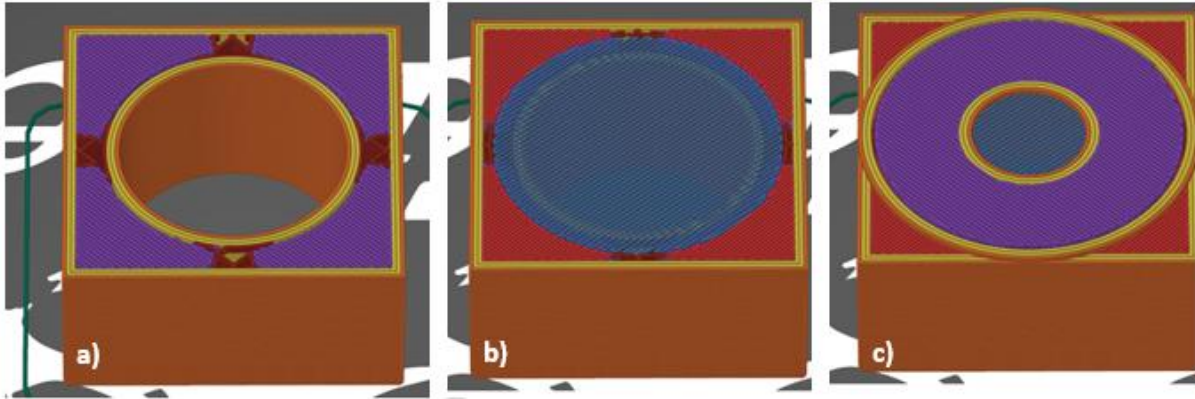


Figure 3.38. Sacrificial bridge layer (b) used for 90° overhangs of rapidly decreasing (from a to c) hole diameter

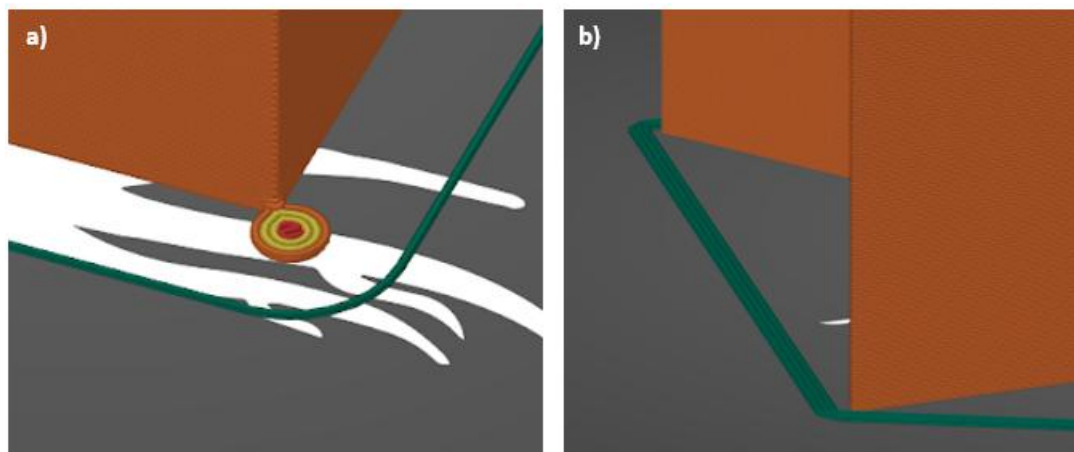


Figure 3.39. Corner bed adhesion tab (a), skirt for corner adhesion (b)

All the microfeatures are typically modelled as arbitrarily thin cuts (0.01-0.02mm), leaving joints no thinner than twice the nozzle diameter (in the shown examples, the nozzle diameter is 0.4 mm), while sacrificial structures are modelled as two-layer walls (0.8 mm for a 0.4 mm nozzle).

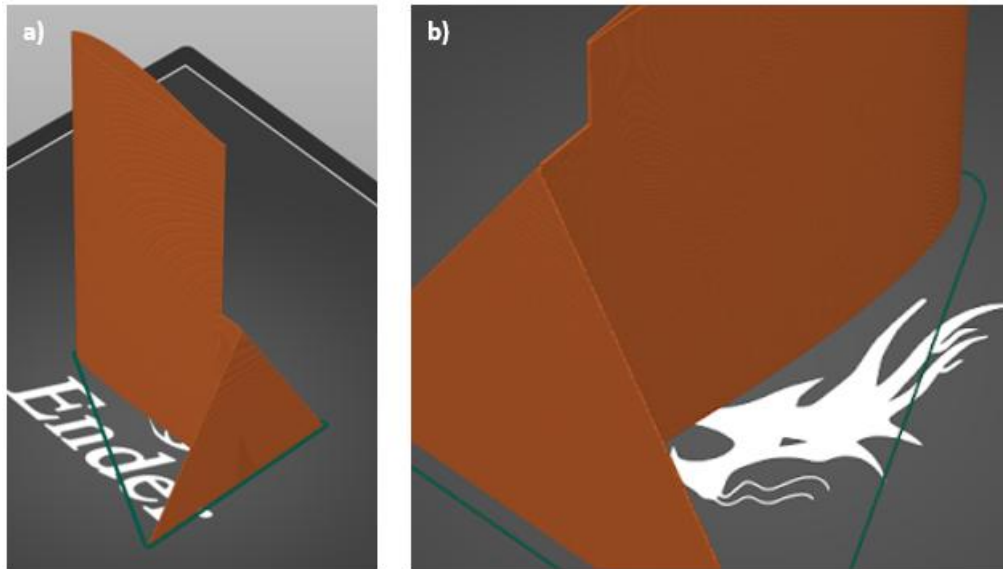


Figure 3.40. Anti-wobble support for vase-mode printed tall, thin parts

3.8.2. Positive and Negative Volumes

Modelling parts with many microfeatures, especially advanced ones, may be computationally demanding. Therefore, microfeatures may be modelled separately and applied as negative volume bodies directly in PrusaSlicer (**Figure 3.41**). In this case, microfeatures are modelled as arbitrarily thin surfaces with gaps equal to twice the nozzle diameter. Some microfeatures modelled in this way are universal and may be reused across different prints; therefore, creating a library of negative feature volumes, such as simple walls, horizontal holes, or servo motor mounts, is recommended (**Figure 3.42**). Similarly, commonly used sacrificial features may be implemented as positive volume bodies.

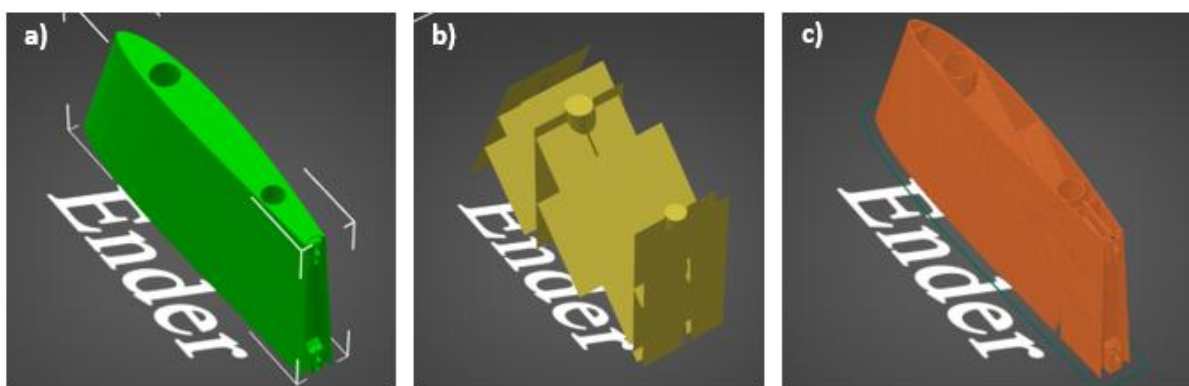


Figure 3.41. Microfeatures using negative volumes: a) initial part, b) negative body, c) result

Figure 3.41 shows G-code preparation steps using a negative volume body for a central joint structure. In this example, some microfeatures, such as vertical holes and holes for control

surface hinges, are already modelled in the initial part, while additional features, such as longer joints and rib structures, are added as negative volumes.

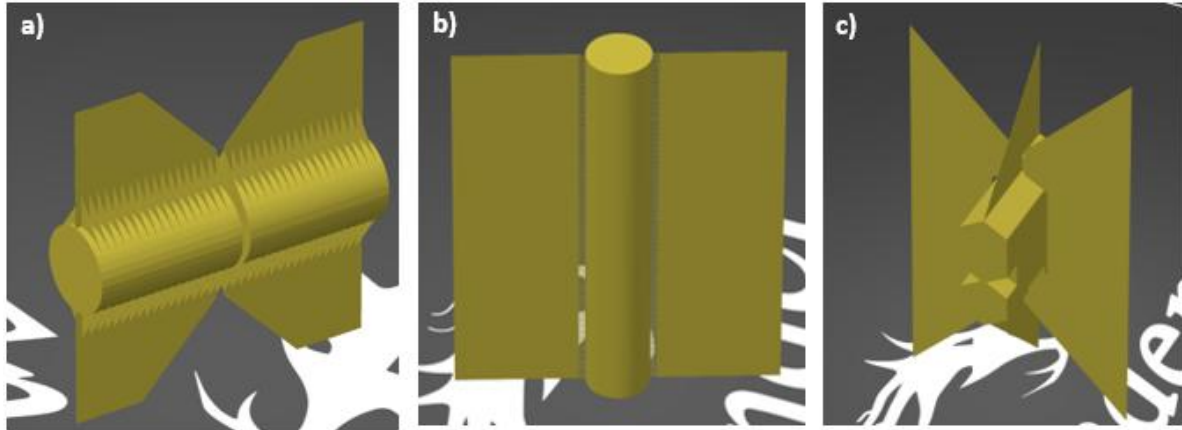


Figure 3.42. Universal negative bodies: a) horizontal hole, b) vertical hole, c) servo mounting hole

Examples shown in **Figure 3.42** include a horizontal hole supported by 45° branched wall structures, a vertical hole with alternating seam positions on the hole surface, and a 2 g servo mounting hole supported by additional side walls.

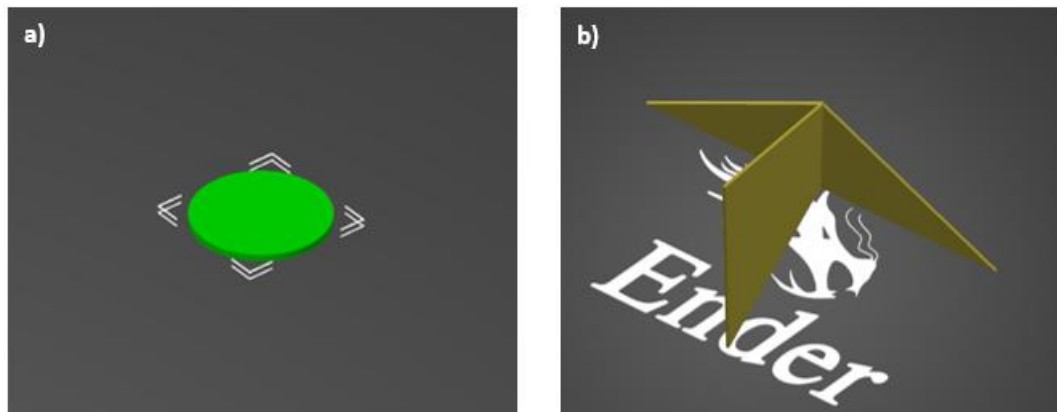


Figure 3.43. Universal positive bodies: a) corner adhesion tab, b) anti-wobble support

For the corner adhesion tab shown in **Figure 3.43**, the default shape provided by the slicer, such as a cylinder, can be used. Anti-wobble supports shown in the same figure are used when printing tall, thin structures, especially control surfaces.

3.9. Conclusions

Vase-mode printing is employed to produce single-contour UAV components that minimize travel movements and material waste. Microfeatures are commonly represented as thin cuts or as negative volume bodies inserted in the slicer. Reusable libraries of such feature bodies expedite model preparation, while alternating and split-seam strategies are used to conceal

outer shell indentations and enhance joint strength. Sacrificial elements (walls, bridge layers, bed adhesion tabs, anti-wobble supports) enable the fabrication of complex horizontal and thin structures, while 60° roof geometries and 45° support-tree arrangements are used to manage overhangs in vase-mode builds with expanding filaments.

Printed aerodynamics for low-Reynolds-number UAVs integrates surface texture and purposeful surface modifications as flow-control tools. Localized roughness, vortex generators, grooves, and stepped geometries alter transition and separation behaviour, often promoting reattachment and improving lift-to-drag performance at small scales. The design and placement of these passive devices require coupled CFD analysis and experimental validation, as their effectiveness is highly sensitive to Reynolds number, geometry, and location. Excessive roughness or improperly sized grooves increase drag and reduce aerodynamic efficiency at higher Reynolds numbers.

Operational practice for 3D-printed UAVs emphasizes modularity, in-process monitoring, and non-destructive inspection to maintain airworthiness. Modular printed components simplify field replacement and spare parts logistics; real-time parameter monitoring and sensor feedback reduce process variability; and NDT techniques (e.g., ultrasonic inspection, thermography, etc.) are used to assess internal defects and porosity. Material handling, periodic recalibration of printing parameters, and empirical parameter qualification remain essential to ensure repeatable mechanical performance and reliable lifecycle operation.

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CHAPTER 4

Case Studies from Aerospace Applications

Umut Çoban¹, Oğuz Acar¹, Emre Özeren¹, Bengü Zuhul Kutlu¹, Mehmet Alper Sofuoğlu², Turgay Urla³, and Selim Gürgen^{3,*}

¹TUSAŞ Engine Industries (TEI) Inc., Eskişehir, Türkiye

²Department of Mechanical Engineering, Eskişehir Osmangazi University, Eskişehir, Türkiye

³Department of Aeronautical Engineering, Eskişehir Osmangazi University, Eskişehir, Türkiye

*Corresponding author: sgurgen@ogu.edu.tr

4.1. Introduction

Over the past few decades, additive manufacturing—more commonly known as 3D printing—has evolved from a niche prototyping tool into a transformative force across industries. This shift has been driven not only by advances in materials and hardware, but also by the rapid development of digital technologies that underpin every stage of the 3D printing process. From design conception to final production, digital tools have become the backbone of modern additive manufacturing systems. At its core, 3D printing is a digitally driven process. Objects are created layer by layer based on digital models, typically generated using Computer-Aided Design (CAD) software or captured through 3D scanning technologies. These models are then processed through slicing software, which translates complex geometries into machine-readable instructions. This seamless integration of digital workflows enables unprecedented levels of precision, customization, and efficiency, distinguishing 3D printing from traditional subtractive manufacturing methods.

The role of digital technologies extends far beyond design and fabrication. Emerging innovations such as cloud computing, Artificial Intelligence (AI), the Internet of Things (IoT), and digital twins are reshaping how 3D printing systems are managed, optimized, and scaled. Cloud-based platforms allow for distributed manufacturing and real-time collaboration, while AI-driven algorithms enhance design optimization, defect detection, and process control. IoT-enabled printers can monitor performance and material usage, generating valuable data that feeds back into continuous improvement cycles. Moreover, digital technologies are enabling new paradigms such as mass customization and decentralized production. Manufacturers can now produce highly individualized products without the cost penalties traditionally associated with customization. At the same time, digital file sharing allows designs to be transmitted globally and produced locally, reducing supply chain complexity and environmental impact. Despite these advancements, challenges remain. Issues related to data security, intellectual property protection, interoperability, and standardization continue to shape the development

and adoption of digital 3D printing ecosystems. Addressing these challenges is critical to unlocking the full potential of additive manufacturing in sectors ranging from healthcare and aerospace to construction and consumer goods.

This chapter aims to provide a comprehensive and detailed overview of the 3D printing workflow in the aerospace sector, spanning the full spectrum from digital process design to the production of physical components. To establish a solid foundation, the fundamental principles of process design within a digital environment are first introduced. Building on this foundation, the chapter presents two representative case studies drawn from real-world aerospace applications. As 3D printing technologies have been successfully adapted to a wide range of materials—from polymer-based systems to high-performance metallic alloys—their applications now extend across multiple scales and functions within modern air vehicles. To illustrate this diversity, the first case study focuses on the additive manufacturing of a polymer material commonly used in the structural components of Unmanned Aerial Vehicles (UAVs). The second case study explores the 3D printing of a metallic alloy widely employed in aero-engine components for large commercial aircraft, such as the Boeing 737 and Airbus A320. Together, these case studies demonstrate how digital design and manufacturing processes are translated into functional aerospace components, offering insights into both the opportunities and challenges associated with implementing 3D printing technologies in this highly demanding industry.

4.2. Digital Product Design

Product development is inherently iterative, involving cycles of design creation, digital modeling, performance assessment, and subsequent refinement. In today's intensely competitive market environment, minimizing the time required to develop new products is critical to achieving commercial success. In response, AI has increasingly been integrated into design workflows, particularly in enabling intelligent decision-making systems that assist in generating and evaluating design alternatives. Modern CAD methodologies have significantly enhanced the efficiency and reusability of digital product development. These tools allow designers to rapidly generate adaptable design solutions while maintaining consistency across complex systems. Complementing this, performance simulations via numerical analysis provide robust capabilities for evaluating product efficiency, verifying design integrity, and guiding optimization efforts [1].

The product design process itself unfolds through several structured stages. It begins with the interpretation of service needs or required design objectives, which are systematically translated into technical parameters, geometric constraints, assembly configurations, and governing design rules. At this conceptual stage, the focus is on understanding user requirements and formulating viable product concepts. Following this, design tools—mostly AI-supported tools in modern approaches—are employed to generate preliminary design solutions for individual functional modules. These solutions define both the components and their interrelationships within the overall system architecture. Through iterative interaction

between designers and intelligent design systems, these preliminary concepts are further developed into detailed digital models using CAD tools. This stage results in comprehensive representations of parts and assemblies, enabling a transition from abstract concepts to tangible designs. Once an initial digital model is established, its functional behavior and performance characteristics are rigorously evaluated using engineering analysis tools. Based on the outcomes of these analyses, the design undergoes optimization or refinement, with alternative configurations assessed until all performance and functional requirements are met. This iterative refinement ultimately leads to the final digital representation of the product. Overall, the integration of generative design techniques with engineering analysis defines a cohesive digital design ecosystem, in which design generation and performance evaluation occur in parallel, fostering a highly collaborative and efficient development process [1,2]. **Figure 4.1** shows the successive steps used in digital product design.

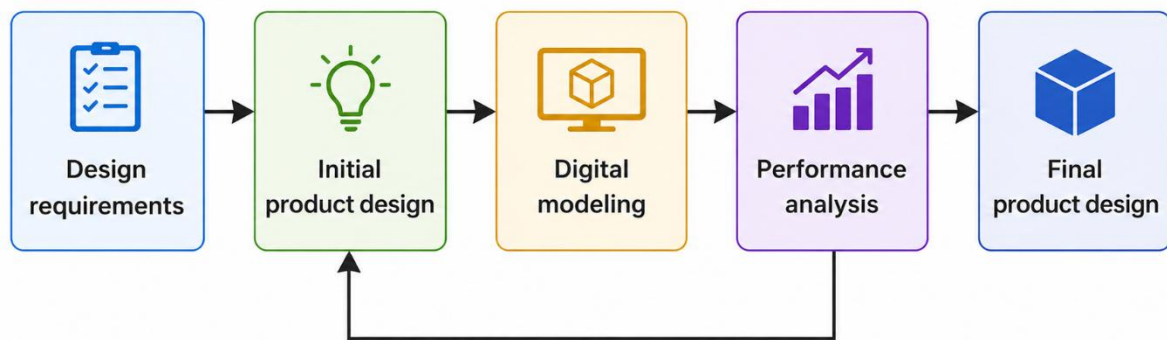


Figure 4.1. Successive steps in digital product design.

The approach, Design for Manufacture and Assembly (DFMA) has focused on adapting product designs to simplify production and reduce the costs associated with fabrication, assembly, and supply-chain operations. The emergence of additive manufacturing technologies, however, calls for a broader interpretation of this concept. Because these technologies offer capabilities that differ fundamentally from those of conventional manufacturing, design methodologies must be redefined to exploit their unique advantages, including greater geometric freedom, part consolidation, and reduced assembly requirements. For aerospace applications, additive manufacturing is particularly well suited to the production of aircraft components, where production volumes are often relatively low and engineering modifications must be incorporated efficiently. The technology supports rapid implementation of design changes, enables the creation of highly optimized geometries, and significantly reduces the number of individual parts, thereby simplifying assembly and lowering system complexity. Beyond these advantages, additive manufacturing introduces unprecedented opportunities for product customization, multifunctional integration, enhanced performance, and reduced total manufacturing cost. These benefits stem from several distinctive capabilities inherent to additive manufacturing. Geometric complexity allows the fabrication of nearly any shape,

including forms that are impractical or impossible to produce using conventional methods. Hierarchical complexity makes it possible to design and manufacture structures across multiple length scales, ranging from tailored microstructures to millimeter-scale mesostructures and full-scale components. Material complexity enables precise control over material deposition at the point-by-point or layer-by-layer level, allowing local variation of composition and properties. Finally, functional complexity permits complete assemblies and moving mechanisms to be produced directly, often eliminating the need for separate manufacturing and assembly steps. Together, these capabilities position additive manufacturing as a transformative technology for the aerospace sector, where lightweight structures, integrated functionality, and efficient production are essential design objectives [3,4].

DFMA initiatives are generally grouped into three broad categories.

- Industrial implementation practices, which involve restructuring product development processes through approaches such as integrated product teams, concurrent engineering, and other collaborative frameworks.
- Compilations of DFMA guidelines and best practices, which provide designers with practical rules to improve manufacturability and reduce production costs.
- Academic research, which focuses on developing advanced DFMA methodologies, decision-support tools, and digital design environments.

A central objective of these efforts is to strengthen communication among all stakeholders involved in product development. By fostering close collaboration between design engineers, manufacturing specialists, and customer representatives, design decisions can be made with a comprehensive understanding of production capabilities, process limitations, and end-user requirements. At the same time, manufacturing engineers gain early insight into the reasoning behind design choices, allowing them to begin process planning, tooling design, and production preparation while the design is still evolving. This integrated approach helps identify and resolve conflicts at the earliest possible stages of development, thereby minimizing costly redesigns and avoiding major modifications to tooling and manufacturing systems after production has already commenced [4].

While DFMA primarily focuses on simplifying production and reducing fabrication and assembly costs, Design for Additive Manufacturing (DFAM) expands this perspective by incorporating the distinctive capabilities and constraints of additive manufacturing technologies. DFAM encourages designers to move beyond traditional design conventions and to develop innovative concepts that fully exploit the opportunities offered by additive manufacturing. At the same time, these designs must remain compatible with the technical limitations and process requirements of the selected additive manufacturing technology. As a result, DFAM spans a broad spectrum of design activities, ranging from the creation of entirely new concepts to the detailed definition of geometries that can be fabricated reliably [4].

4.3. Capabilities of 3D Printing in Digital Design and Manufacturing

The layer-by-layer fabrication principle of additive manufacturing provides a set of design capabilities that distinguish it fundamentally from conventional manufacturing methods. Rather than removing material from a solid block or shaping components through molds and tooling, additive manufacturing builds parts directly from digital models, enabling levels of complexity and integration that are difficult or impossible to achieve using traditional processes. One of the most significant advantages of additive manufacturing is geometric complexity, which allows the production of virtually any three-dimensional shape without the constraints typically associated with machining, casting, or molding. Intricate internal passages, lattice structures, and organically optimized forms can be manufactured with minimal additional cost or process complexity. A second distinguishing feature is hierarchical complexity, which enables the design and fabrication of structures across multiple length scales. Engineers can tailor material architecture from the microstructural level to meso-scale features, such as cellular lattices, and ultimately to the overall component geometry. This multi-scale control allows for improved mechanical performance, reduced weight, and enhanced functional behavior. Additive manufacturing also offers functional complexity, whereby complete assemblies, mechanisms, and multifunctional devices can be produced in a single build. Components that would traditionally require numerous individually manufactured parts and assembly operations can instead be consolidated into one integrated structure, reducing part count, simplifying assembly, and improving reliability. Finally, material complexity provides the ability to deposit material selectively at each point or layer. This capability supports the use of single materials, graded compositions, and in some cases multiple materials within the same component, enabling local control of properties such as strength, stiffness, thermal conductivity, and wear resistance. Together, these capabilities make additive manufacturing a powerful design and production technology, opening new opportunities for lightweight structures, integrated functionality, and highly optimized products across demanding industries such as aerospace, healthcare, and energy [4]. **Figure 4.2** shows the main capabilities of 3D printing in digital design and manufacturing.

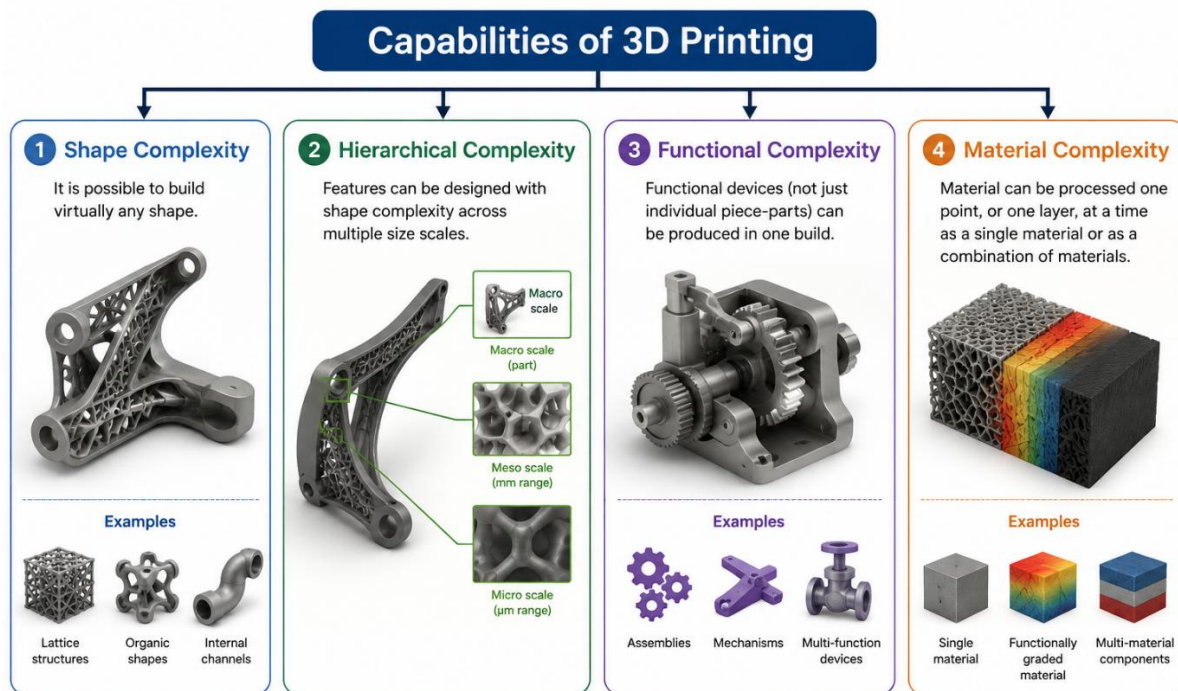


Figure 4.2. Main capabilities of 3D printing in digital design and manufacturing.

Shape complexity refers to the ability of additive manufacturing to fabricate highly intricate and unconventional geometries with little or no increase in manufacturing difficulty or cost. Unlike conventional manufacturing methods—such as machining, casting, or injection molding—which are constrained by tool access, mold design, and assembly requirements, additive manufacturing constructs components layer by layer directly from digital models. This approach makes it possible to produce virtually any three-dimensional shape that can be represented in a CAD environment. In traditional manufacturing, complex geometries often require multiple processing steps, specialized tooling, or assembly of numerous individual parts. Features such as internal channels, undercuts, lattice structures, and curved organic forms may be difficult, expensive, or even impossible to manufacture. Additive manufacturing largely removes these constraints because each layer is formed independently, allowing material to be placed only where it is needed. As a result, engineers can design components with internal cooling passages, conformal channels, topology-optimized shapes, and lightweight lattice cores without significantly increasing production complexity. In many cases, highly complex parts can be produced in a single build, eliminating the need for separate components and assembly operations. A key principle often associated with shape complexity in additive manufacturing is that complexity is essentially free. This means that increasing geometric sophistication does not necessarily lead to proportional increases in manufacturing cost, unlike conventional processes where more complex designs usually demand additional tooling, machining time, and labor. In aerospace applications, shape complexity enables the development of lightweight brackets, fuel nozzles, and turbine components with optimized

load paths and integrated functions. These designs can reduce weight, improve performance, and simplify maintenance while achieving geometries that are unattainable through traditional methods [1,4].

Hierarchical complexity refers to the ability of additive manufacturing to design and fabricate structures with controlled geometric features across multiple length scales within a single component. These scales typically range from the material microstructure (micrometer scale), through mesostructures such as lattice or cellular architectures (millimeter scale), to the overall part geometry at the macroscopic scale. This multi-scale design capability is one of the most distinctive advantages of additive manufacturing and enables engineers to tailor component performance far beyond what is possible with conventional manufacturing methods. In traditional manufacturing, each structural scale is often addressed separately. Material properties are determined during alloy production or processing, meso-scale features are limited by tooling constraints, and part geometry is designed independently. Additive manufacturing, by contrast, integrates these scales into a unified digital workflow, allowing designers to simultaneously control internal architecture, local density, and overall shape [1]. At the micro-scale, process parameters such as laser power, scan speed, and cooling rate influence grain structure, porosity, and phase composition, thereby determining mechanical and thermal properties. At the meso-scale, engineers can incorporate lattice structures, cellular cores, and graded porosity to reduce weight, absorb energy, or enhance heat transfer. At the macro-scale, the external geometry is optimized to meet structural, aerodynamic, or functional requirements. The interaction among these scales enables highly customized performance. For example, an aerospace bracket may combine a topology-optimized outer shape, an internal lattice for weight reduction, and locally controlled microstructures to improve fatigue resistance. Each level contributes to the overall behavior of the component. Hierarchical complexity is particularly valuable in aerospace, biomedical, and energy applications, where components must meet demanding and often conflicting requirements such as low mass, high strength, thermal efficiency, and durability. In essence, hierarchical complexity allows additive manufacturing to move beyond simply creating complex shapes. It enables the engineering of material and structural architecture across multiple scales, resulting in components with optimized and highly integrated performance characteristics [1,4].

Functional complexity describes the ability of additive manufacturing to create parts that combine several functions, moving features, or even fully assembled mechanisms within a single production step. Instead of manufacturing numerous individual components and joining them afterward, additive manufacturing makes it possible to fabricate integrated systems directly from a digital model, requiring little more than limited post-processing before use. In traditional manufacturing, different functions are typically assigned to separate parts. These components are produced independently and then connected through methods such as bolting, welding, or adhesive bonding. This conventional approach increases the total number of parts, extends assembly time, raises inventory and logistics demands, and introduces potential failure points at interfaces and joints. By contrast, additive manufacturing builds

intricate geometries and interconnected features layer by layer in one uninterrupted process, eliminating many of these drawbacks. This capability allows designers to merge what were previously multiple components into a single consolidated structure without sacrificing functionality. Components such as print-in-place hinges, enclosed gear systems, manifold networks, heat exchangers, and structural elements with embedded cooling or sensing functions are representative examples. Integrating these functions into one part reduces assembly operations and enhances overall system robustness. The benefits of functional complexity are particularly significant in aerospace engineering, where reducing weight and minimizing part count are essential objectives. A well-known example is the redesign of fuel nozzles, which can be transformed from assemblies containing dozens of individual pieces into single additively manufactured components that incorporate internal flow channels, attachment features, and structural elements. This consolidation simplifies assembly, decreases maintenance needs, and often leads to improved operational performance. Functional complexity also enables true multifunctional design. A single component can simultaneously fulfill structural, thermal, fluidic, and vibration-control roles, creating highly integrated systems that are difficult to realize with conventional manufacturing methods [1,4].

Material complexity is one of the most distinctive features of additive manufacturing, describing the ability to vary material composition and material properties throughout a component during fabrication. Since additive manufacturing builds parts incrementally, depositing material selectively at each point and in each layer, it enables precise control over local characteristics instead of restricting the entire component to a single uniform material. As a result, parts can be produced with location-dependent properties, gradual transitions in composition, or combinations of multiple materials within a single structure. In traditional manufacturing, components are generally fabricated from one homogeneous material chosen at the outset. When different regions require different behaviors, manufacturers must rely on secondary operations such as surface coatings, heat treatments, welding, or joining dissimilar materials. These added steps increase production complexity, cost, and the risk of defects at interfaces. Additive manufacturing eliminates many of these challenges by allowing both material placement and process conditions to be modified dynamically as the part is built. Material complexity can be implemented at several levels. In the simplest approach, a single material is used, but local properties are adjusted by altering processing parameters such as energy input, scan strategy, and cooling rate. More sophisticated techniques employ functionally graded materials, in which composition changes progressively to produce smooth variations in properties such as hardness, stiffness, thermal conductivity, or corrosion resistance. In multi-material additive manufacturing, entirely different materials can be deposited in designated regions to combine structural, thermal, electrical, or biological functions within one component. This capability is particularly advantageous in demanding engineering fields. In aerospace, components can be engineered to exhibit superior heat resistance in critical zones and enhanced toughness elsewhere. In biomedical applications, implants may feature dense wear-resistant surfaces combined with porous interiors that encourage tissue integration. In energy systems, thermal devices such as heat exchangers can incorporate localized material enhancements to maximize heat transfer efficiency. Material

complexity also enables the integration of advanced functionalities directly into structural parts. Conductive pathways, embedded sensors, heating elements, and compliant regions can all be incorporated during fabrication by selectively depositing materials with different mechanical or electrical characteristics [1,4].

4.4. Fundamental Steps in DFAM

Although the stages in DFAM vary depending on the additive manufacturing process, the fundamental steps are generally categorized into five phases: design requirements, conceptual design, embodiment design, detail design, and manufacturing. **Figure 4.3** shows the general framework in DFAM.

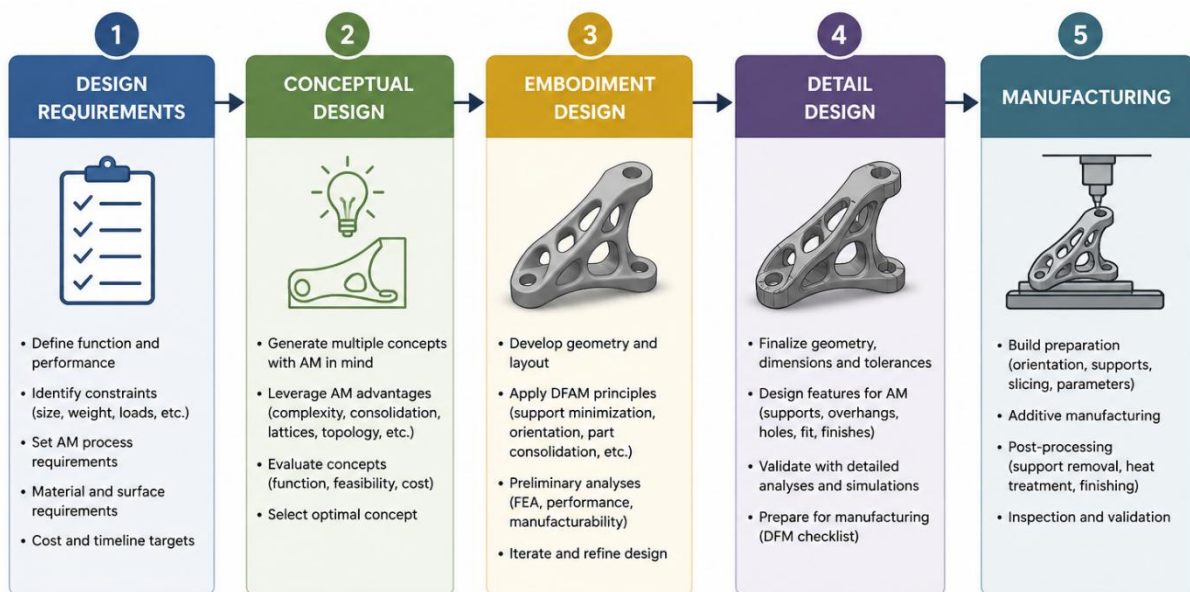


Figure 4.3. Fundamental steps in DFAM.

The design requirements stage defines the fundamental foundation of the entire design process by clearly specifying what the part must achieve and under which conditions it must operate. This phase includes the identification of functional requirements such as load-bearing capacity, stiffness, thermal performance, and other application-specific behaviors, as well as the definition of the service environment, including temperature, pressure, wear, corrosion, and loading conditions. It also involves material-related considerations, ensuring that the selected material is compatible with both the required performance and the chosen additive manufacturing process. In addition, additive manufacturing-specific constraints are established at this stage, such as minimum feature size, wall thickness limits, allowable overhang angles, build orientation effects, and the potential need for support structures and

post-processing. Economic and production factors, including cost limitations, build time, weight reduction objectives, and production volume, are also incorporated into the requirements [5]. Finally, applicable regulatory and safety standards are considered to ensure compliance with industry-specific guidelines. Overall, the design requirements stage in DFAM serves to define a comprehensive set of functional, technical, and manufacturing constraints that guide all subsequent stages of design, ensuring both performance and manufacturability from the outset [1,4].

The conceptual design stage involves transforming the defined design requirements into preliminary design solutions that outline possible ways of fulfilling the intended function of the component. Rather than focusing on detailed geometry, this phase emphasizes the exploration of alternative concepts that can meet performance goals while effectively leveraging the capabilities of additive manufacturing. Multiple design options are typically generated, with attention given to aspects such as load transfer mechanisms, material distribution, and opportunities for functional integration or part consolidation, which are key advantages of additive manufacturing. Methods such as topology optimization and bio-inspired design are often employed to develop efficient structural configurations that achieve weight reduction without compromising mechanical performance. At the same time, basic manufacturability considerations—such as build orientation, support structure requirements, and geometric complexity—are taken into account at a preliminary level. Overall, the conceptual design stage acts as an intermediate step between requirements definition and detailed design, enabling the selection of the most suitable concept based on performance, feasibility, and manufacturing efficiency [3,4].

Embodiment design is the stage where the selected conceptual solution is developed into a more defined and physically consistent product layout. At this phase, the overall structure, configuration, and main geometric features of the component are established in greater detail, while still not reaching full final dimensions or manufacturing-ready specifications. The focus is on translating functional concepts into a coherent structural form by defining key elements such as load-bearing regions, connections between features, material distribution, and overall shape refinement. During embodiment design, engineers also begin to address manufacturability in a more concrete way, considering additive manufacturing constraints such as overhang angles, minimum feature sizes, wall thickness uniformity, and the need for support structures. The integration of multiple functions into a single component is further refined, and unnecessary parts or joints are reduced to take advantage of part consolidation enabled by additive manufacturing. Material selection may also be finalized at this stage if not already fixed earlier. In addition, preliminary validation of the design is often performed using simulation tools such as finite element analysis (FEA) to assess mechanical performance, stress distribution, and potential failure regions. Iterative modifications are common to improve both performance and manufacturability. Overall, the embodiment design stage serves as a critical transition between conceptual thinking and detailed engineering, ensuring that the design is structurally sound, functionally complete, and feasible for additive manufacturing [1,4].

The detail design stage involves fully defining the product in a form that is ready for manufacturing. At this point, the design is translated into a complete and precise representation, where all geometric details, dimensions, tolerances, and surface finish requirements are clearly specified. The main objective of this stage is to finalize the component so that it can be directly produced using the selected additive manufacturing process. During detail design, key manufacturing aspects are finalized, including build orientation, support structure requirements, and any necessary adjustments to accommodate process limitations such as minimum feature size, layer resolution, overhang constraints, and potential distortion effects. Material selection is confirmed, and design modifications are made to account for process-induced characteristics such as anisotropy or the need for post-processing operations. At this stage, detailed verification is often carried out using simulation tools to assess structural performance, thermal response, and possible failure mechanisms under service conditions [6]. Comprehensive documentation is also prepared, including final CAD models, engineering drawings, and production instructions. Tolerances and surface quality specifications are defined in consideration of as-built additive manufacturing capabilities and any required finishing processes such as machining or polishing. Overall, the detail design stage ensures that the DFAM component is fully optimized, accurately defined, and ready for consistent and reliable additive manufacturing [1,4].

The manufacturing stage represents the final phase where the validated and fully detailed design is physically produced using an additive manufacturing process. At this stage, the digital model is translated into a build-ready format, typically involving file preparation such as STL or AMF conversion, slicing into layers, and generation of machine-specific toolpaths or scan strategies. Critical process parameters—such as layer thickness, laser or extrusion power, scan speed, build orientation, and support structure configuration—are finalized to ensure accurate and stable fabrication. During manufacturing, the part is produced layer by layer under controlled process conditions specific to the selected additive manufacturing technology (e.g., powder bed fusion, material extrusion, or binder jetting). Real-time monitoring may be employed in advanced systems to detect defects, ensure process stability, and maintain quality consistency. Thermal effects, residual stresses, and potential distortions are managed through controlled build strategies and, where necessary, in-situ or post-process adjustments. After fabrication, the component often undergoes post-processing operations such as support removal, heat treatment, surface finishing, or machining to achieve the required dimensional accuracy and surface quality. Quality assurance and inspection techniques, including dimensional measurement and non-destructive evaluation, are applied to verify that the manufactured part meets the design specifications. The manufacturing stage in DFAM encompasses the complete transformation of a digital design into a physical component, while ensuring process control, quality assurance, and compliance with functional requirements [1,7,8].

4.5. Case Studies for Aerospace Components

4.5.1. 3D Printing of a Polymeric Material

In this case study, lightweight polylactic acid (LW-PLA), which is widely used in aerospace applications – mostly for drones, was selected to print out a sample part. LW-PLA is a modified form of standard PLA filament designed for 3D printing applications where reduced weight and tailored mechanical properties are required [9]. It contains a chemical or physical foaming agent that activates during extrusion, causing the material to expand and form a low-density cellular structure. By adjusting printing temperature, flow rate, and extrusion parameters, the density of LW-PLA can be significantly reduced—often by up to 50% or more compared to conventional PLA—while still maintaining acceptable dimensional stability and surface quality. These characteristics make LW-PLA particularly attractive for aerospace-related 3D printing applications, where weight reduction is a critical design constraint. It is commonly used for manufacturing non-structural or semi-structural components such as UAV airframes, aerodynamic fairings, interior cabin parts, cable guides, ducts, and lightweight prototypes for wind tunnel testing [10]. In addition to its low density, LW-PLA offers advantages such as ease of processing, low warping tendency, and compatibility with standard fused deposition modeling (FDM) printers, making it a cost-effective material for rapid prototyping and iterative design in aerospace engineering. **Table 4.1** compares the mechanical properties of LW-PLA and PLA.

Table 4.1 Mechanical properties of LW-PLA and PLA.

Properties	LW-PLA at unfoamed state (200°C)	LW-PLA at foamed state (250°C)	PLA
Density (g/cm ³)	1.20-1.24	0.40-0.65	1.24
Tensile strength (MPa)	40-43	10-24	45-60
Modulus (GPa)	3.00-3.30	0.85-1.70	3.50-4.20
Elongation at break (%)	8-9	12-15	4-6

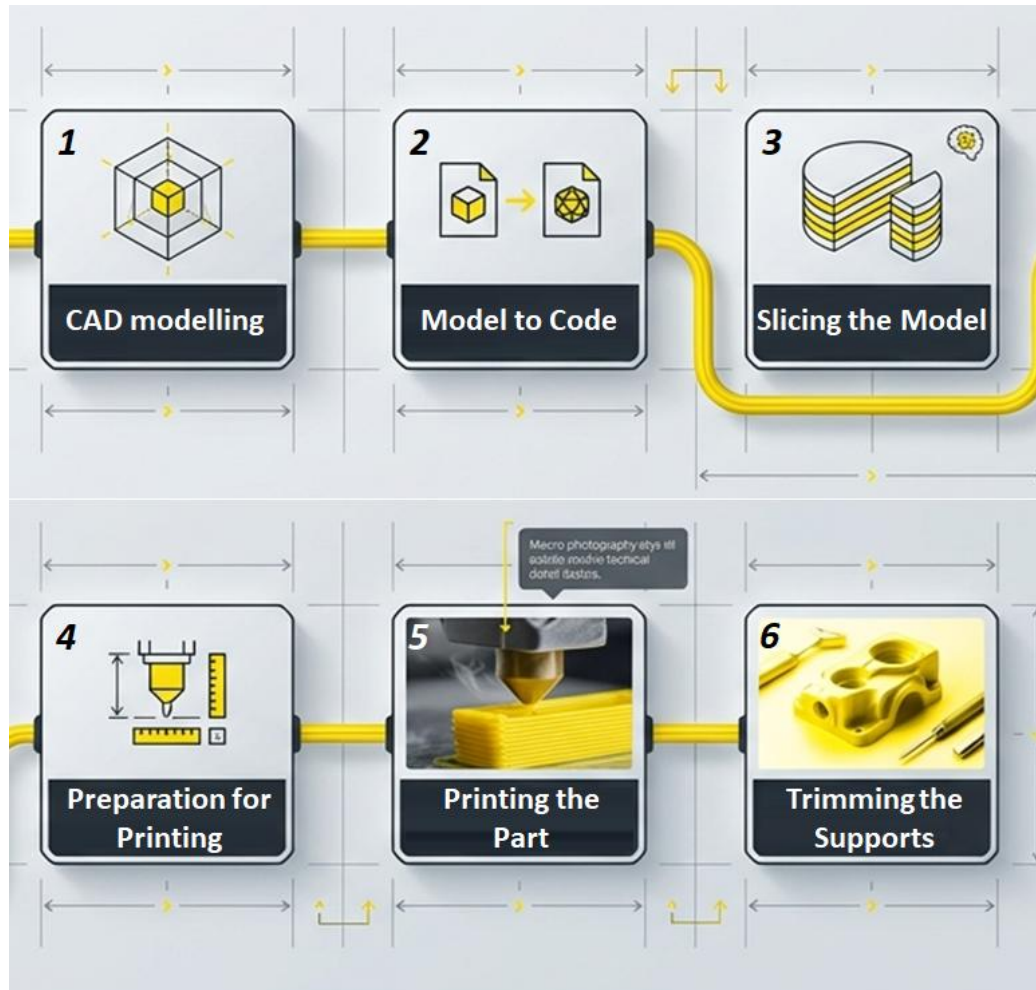


Figure 4.4. Six main stages in the 3D printing of LW-PLA.

The process was completed in six main steps, as shown in **Figure 4.4**. During the CAD modeling stage, Solid Edge 2026 software was employed to develop the 3D part geometry. The physical object was first defined as a parametric solid model, where the initial geometry established the mathematical boundaries of the component. Critical angles were explicitly incorporated into the design to minimize the requirement for external support structures. Where necessary, support features were intentionally assigned as structural anchor points within the model to ensure manufacturability during additive fabrication. Following the completion of the 3D model, the geometry was exported through a file format conversion step. In conventional workflows, the Standard Triangle Language (STL) format is commonly used for this purpose. However, this legacy format presents several limitations, as it contains only raw geometric mesh data and does not retain information related to scale, color, or material properties. In contrast, the 3D Manufacturing Format (3MF) was adopted in this study due to its compatibility with the Bambu Lab X1 Combo 3D printing system. Unlike STL, the 3MF format preserves enriched metadata, including embedded color information, material definitions,

and precise unit specifications, in addition to the geometric model. **Figure 4.5** shows the CAD modeling workflow and file format conversion stages.

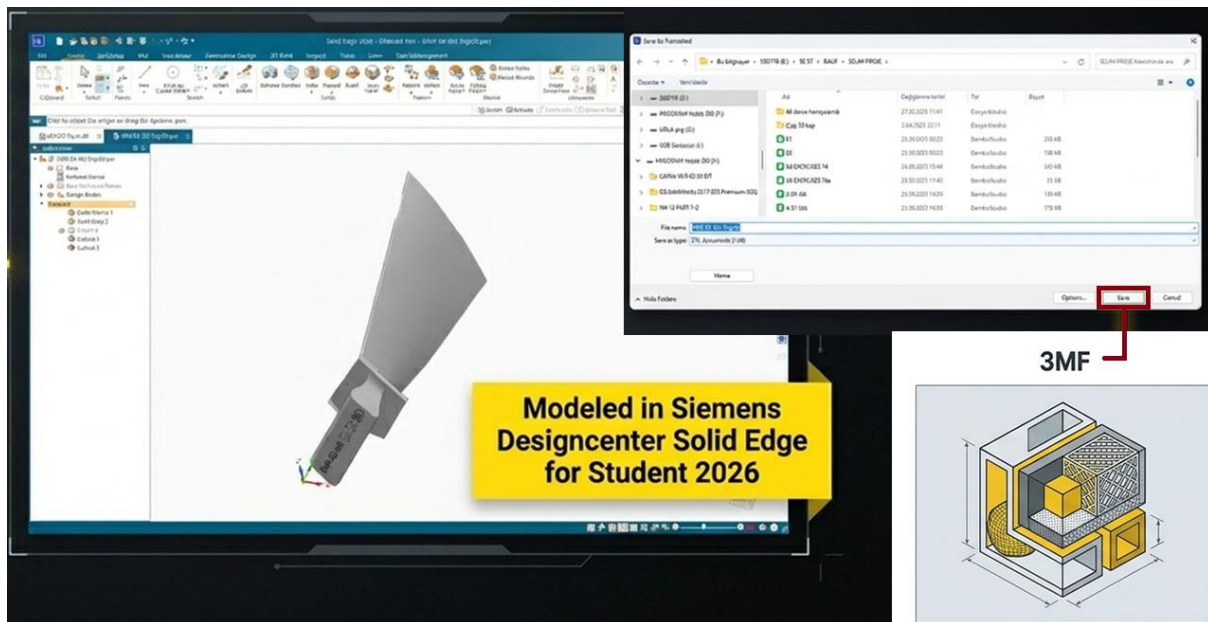


Figure 4.5. CAD modelling and file format stages.

In the slicing stage, the software decomposed the solid model into thousands of thin, horizontal layers, enabling layer-by-layer fabrication. Subsequently, G-code generation was performed to extract the toolpath coordinates and extrusion commands required to control the printer nozzle. The selected layer height defined the resolution of the build in the Z-axis direction, directly influencing surface quality and geometric fidelity. To ensure adequate mechanical performance and efficient load distribution, an increased perimeter (wall) thickness was applied along the outer contours of the part. In addition, a lattice-based internal infill structure with a wave-like pattern was implemented to enhance structural integrity while minimizing material usage. This approach improved the strength-to-weight ratio by eliminating the need for a fully solid core while maintaining mechanical stability. In the subsequent stage, the 3D printer was prepared for fabrication. The generated G-code was transferred to the printer via a network connection, ensuring a seamless transition from digital design to physical manufacturing. At this stage, the build platform was carefully inspected and cleaned to ensure proper adhesion and process reliability. The build plate, featuring a textured surface, provided enhanced bonding for the first deposited layer. Finally, all process parameters were set to appropriate values to ensure stable and high-quality printing conditions. **Figure 4.6** shows the key steps involved in the slicing and process preparation stages.



Figure 4.6 Main steps in the model slicing and process preparation stages.

After completing all preparatory procedures, including thermal stabilization, automatic bed leveling, mechanical purging, and micro-LiDAR calibration, the fabrication of the initial layer was initiated on the build platform. The nozzle temperature was raised to the required level to ensure proper melting and extrusion of the LW-PLA filament, enabling controlled deposition onto the build surface. Upon completion of each layer, the nozzle was incrementally raised to allow for precise construction of subsequent layers in a layer-by-layer fashion. Effective thermal management was critical throughout the process to prevent defects such as delamination, warping, and thermal cracking. For this reason, controlled cooling was applied between layers to ensure gradual heat dissipation and to maintain dimensional stability of the printed part. This approach helped mitigate residual thermal stresses and improved overall structural integrity. Following completion of the printing process, the part was carefully removed from the build platform, and support structures were mechanically trimmed using a precision cutter. **Figure 4.7** presents representative stages of the printing and post-processing (trimming) operations.

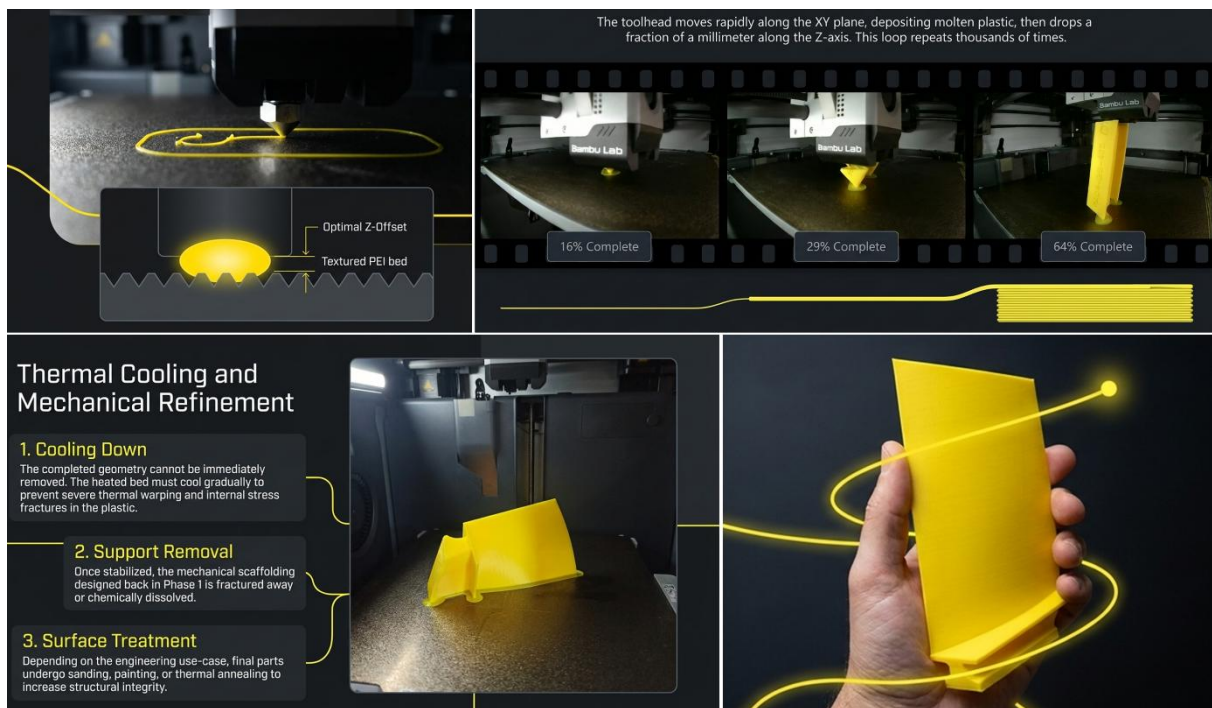


Figure 4.7 Representative stages of the printing and trimming operations.

4.5.2. 3D Printing of a Metallic Material

The aim of this case study was to design and manufacture an oil manifold component used in jet engines through 3D printing, as an alternative to conventional production methods. In addition, a comparative evaluation was conducted between the 3D printed oil manifold

component and the same component produced using traditional manufacturing techniques, in order to assess differences in design, manufacturability, and process costs.

As shown in **Figure 4.8**, the oil manifold component is a manifold assembly in which pressurized oil supplied from the oil tank is regulated and distributed. Oil pressure is controlled via two pressure adapters mounted on the component. These pressure adapters are fixed to the oil manifold at four mounting points located on two lateral surfaces. In addition, the component includes two cable inlet/outlet ports. The oil manifold operates under a maximum pressure of 50 bar and is not subjected to any additional external mechanical loads. The part is secured to a separate housing via a bolted connection through a flange region using four flange holes.

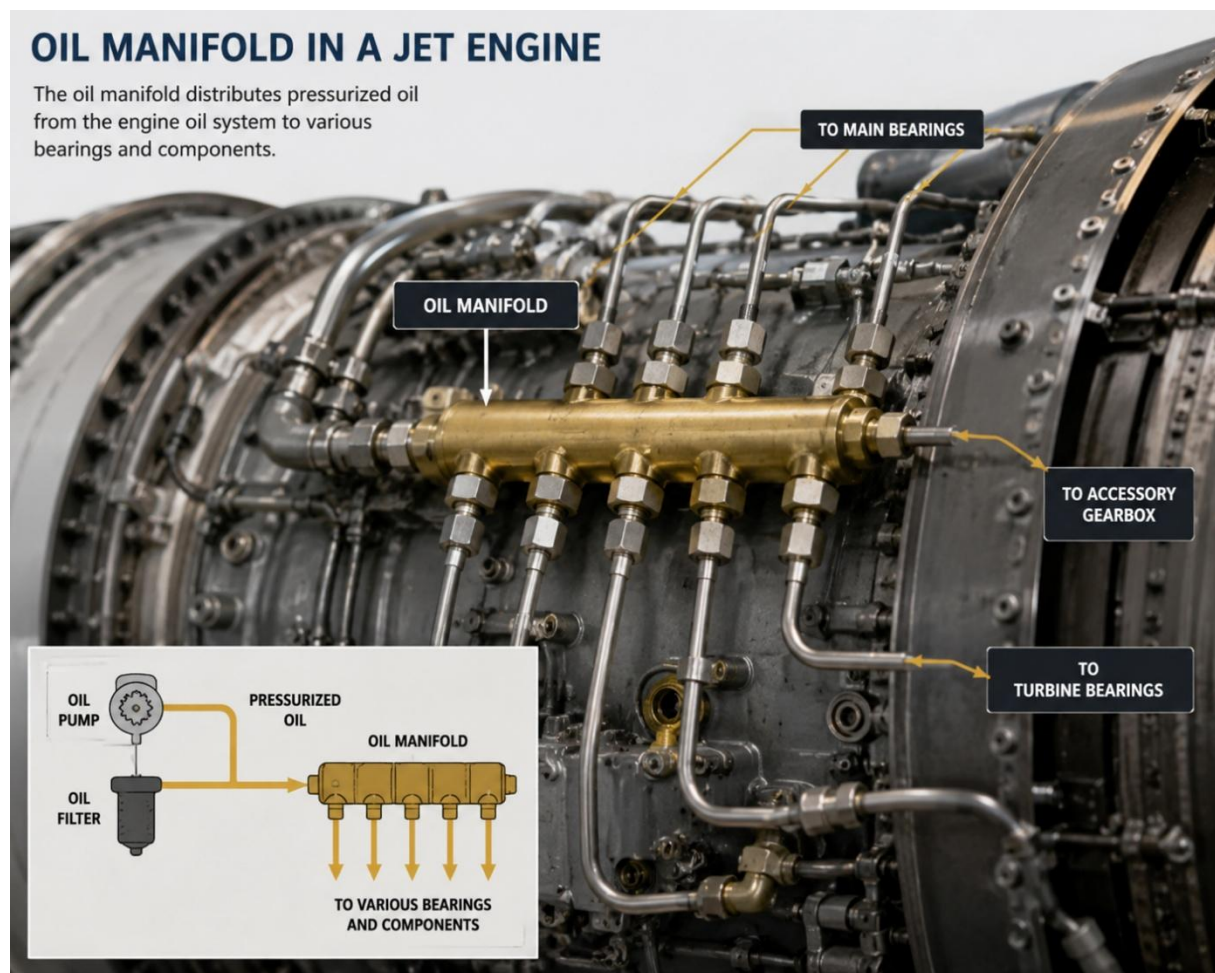


Figure 4.8 Oil manifold in a jet engine assembly.

The maximum diameter of the internal oil channels within the oil manifold component was 8 mm. This value is known to be a non-critical, self-supporting channel diameter for the additive

manufacturing system (DMP Factory 500) and the AlSi10Mg material, requiring no internal support structures. Furthermore, the amount of sagging and surface roughness expected to occur on the upper regions of the channel walls was considered to be at a level that does not adversely affect oil flow performance for this component. Therefore, these internal passages were used in the as-built condition without the need for post-process machining. Since the cable channels within the oil manifold do not impose any flow requirements, their geometry was designed for additive manufacturing by keeping the required routing volume, adopting a teardrop-shaped cross-section to improve manufacturability and reduce the need for support structures. The conventional design and the additive manufacturing-optimized design of the oil manifold component are shown in **Figure 4.9**. By benefitting from the additive manufacturing, the design was further optimized to improve flow performance, particularly in channel transitions.

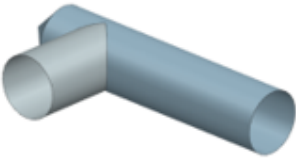
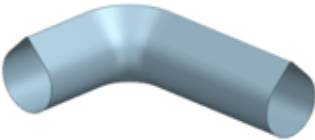
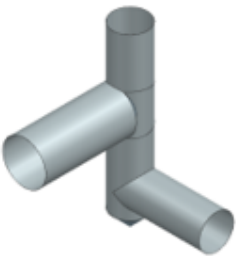
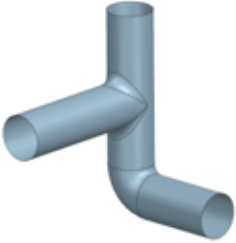
Traditional Manufacturing	Additive Manufacturing
	
Cable channels were refined by implementing teardrop-shaped cross-sectional geometries for additive manufacturing.	
	
Channel joints were refined for additive manufacturing.	

Figure 4.9 Channel designs in traditional and additive manufacturing processes.

Table 4.2 gives the material properties of AlSi10Mg alloy used in this case study. The elastic modulus and Poisson's ratio values were used as input parameters for structural analyses and topology optimization studies, while the yield strength and ultimate tensile strength values were utilized in design safety calculations. The density value was employed for weight reduction comparisons between the conventionally manufactured component and the component designed and produced for additive manufacturing. During iterative preliminary studies using topology optimization, it was observed that the stress flow was relatively low in

the regions of the oil manifold component where it is mounted onto the housing via bolts. As a result, material removal performed by the optimization algorithm led to a loss of structural integrity in these regions. To prevent this issue and to promote a smoother material distribution around the connection interfaces, additional design volume was introduced in the flange region. The modified geometry of the component is presented in **Figure 4.10**.

Table 4.2 Mechanical properties of AlSi10Mg alloy.

Properties	AlSi10Mg at room temperature
Density (g/cm ³)	2.65
Yield strength (MPa)	250
Ultimate tensile strength (MPa)	400
Elastic modulus (GPa)	76.6
Poisson's ratio	0.30

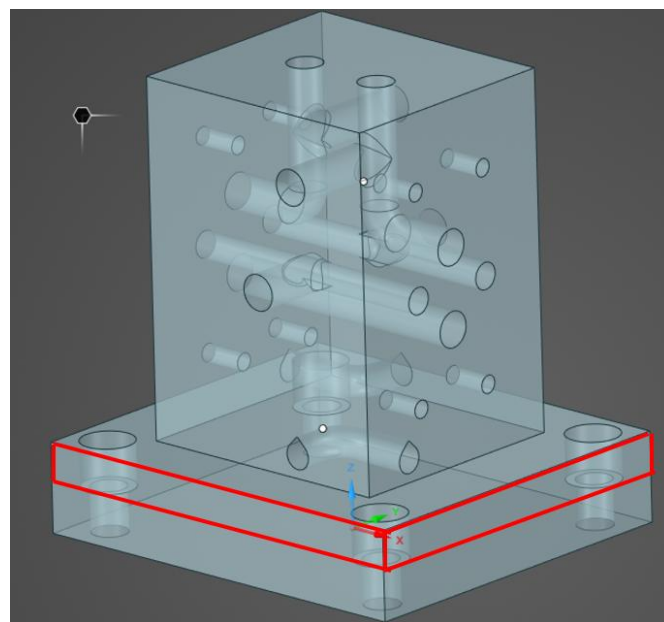


Figure 4.10 Region modified to improve material distribution within the design domain.

In order to generate the FEA model, the ANSYS Discovery software was used by selecting an element size of 0.63 mm. From the design requirements, the manifold component operates under a maximum pressure of 50 bar, which acts on the internal channels as the primary loading condition. In addition, the component is mechanically fixed to the housing through the flange region; therefore, a constrained support boundary condition is applied in these

areas. The corresponding boundary conditions and loading regions are illustrated in **Figure 4.11**. During the transition to topology optimization, additive manufacturing constraints were incorporated to ensure that the resulting geometry remained manufacturable, required minimal support structures, and minimized the need for post-processing design modifications. In this context, additive manufacturing-oriented topology optimization constraints were defined. To mitigate the formation of overhang surfaces, a critical overhang angle constraint of 45° was applied. However, this constraint does not fully eliminate local minima (i.e., locally unsupported geometries), meaning that support structures may still be required in the final design. In addition, a minimum feature size constraint of 3 mm was introduced to prevent the formation of thin structural regions that would fall below manufacturable limits. To preserve functional requirements while enabling material removal, different minimum thickness values were assigned to distinct regions of the component. Specifically, a 3 mm thickness was maintained in fluid flow regions, 2 mm in cable and port interfaces, and 4 mm in housing connection interfaces. **Figure 4.12** shows the protected regions in the component.

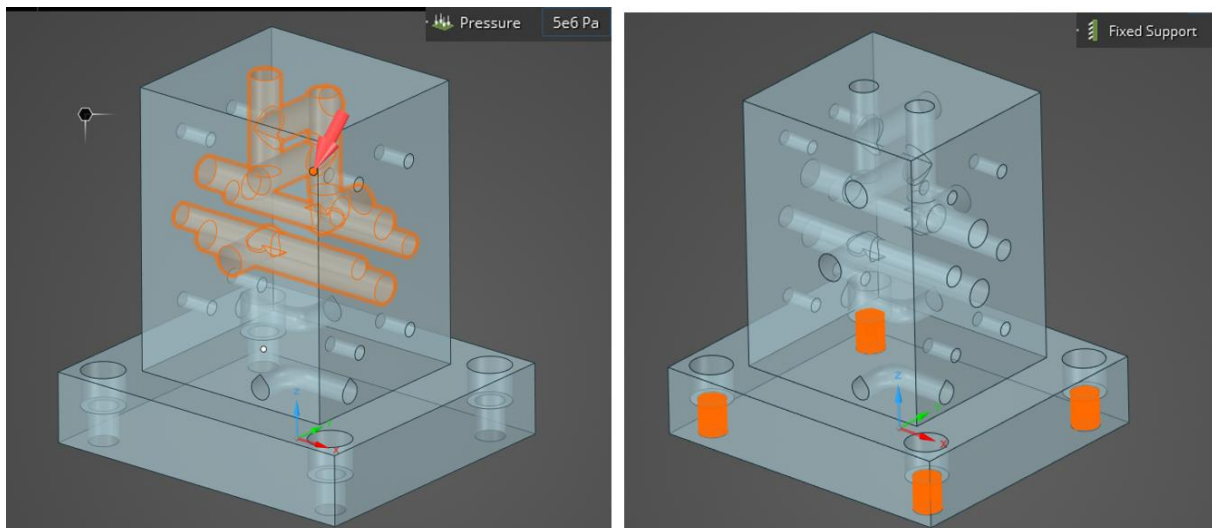


Figure 4.11 Loading regions and boundary conditions in the FEA model.

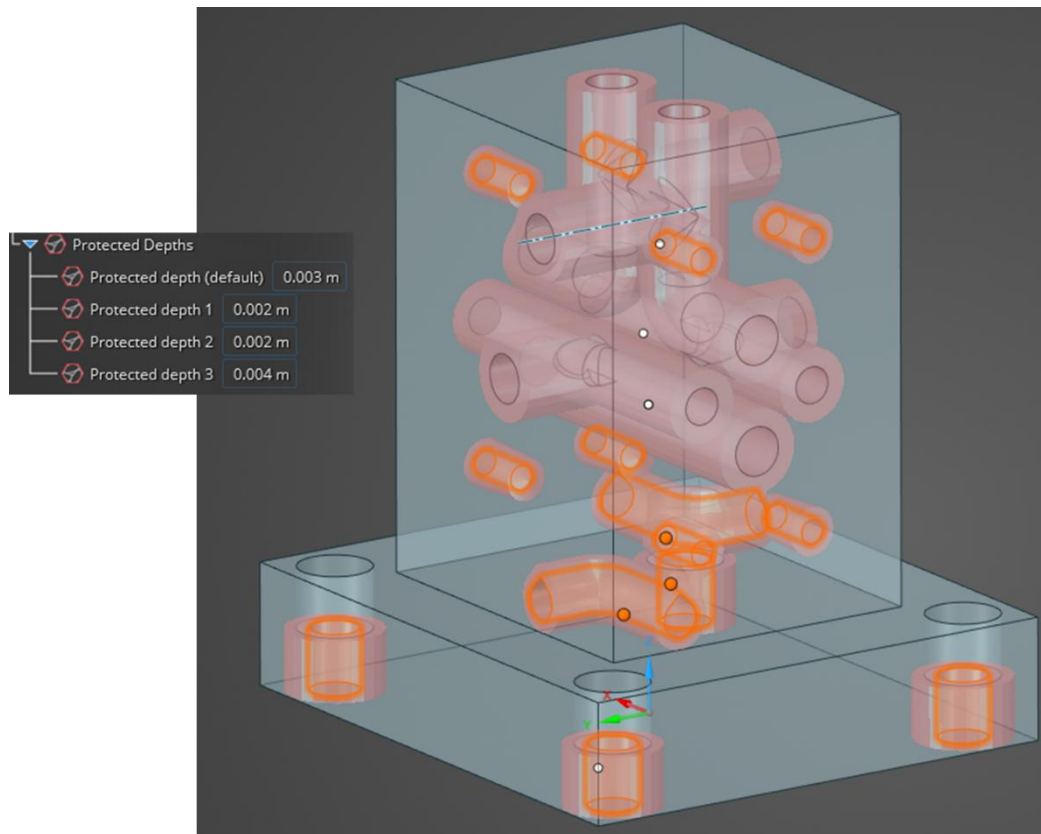


Figure 4.12 Protected regions in the component.

For the weight reduction objective, an iterative approach was adopted. Initially, a 45% mass reduction constraint was applied; however, since a higher weight reduction potential was identified during the subsequent iterations, the optimization was continued with a 55% mass reduction target. Both resulting design configurations are presented in **Figure 4.13**. Following the FEA simulations, no reduction in yield or tensile strength performance was observed, as the minimum wall thickness values defined in the design were maintained throughout the geometry. The stress distributions and corresponding values prior to weight reduction are presented in **Figure 4.14a**, while the results obtained after weight reduction are shown in **Figure 4.14b**. Structurally, no critical deformation or failure condition was observed in the model. The structural analysis performed after weight reduction was used to validate the design under the specified loading conditions.

According to the structural analyses, the design of the component for additive manufacturing did not exhibit any structural failure or critical mechanical stress. This is primarily attributed to the fact that the wall thicknesses were initially defined based on the hydrostatic loads that the component is required to withstand. As a result, significant weight reduction was achieved for a component intended for use in a jet engine, without introducing any structural deficiencies. Finally, to make the part suitable for production and application, functional holes

and interfaces were converted into appropriate CAD formats using the original CAD data. Sharp transitions and regions with potential stress concentrations were redesigned to ensure smoother geometric continuity. Following these final design modifications, a total weight reduction of approximately 39% was achieved for the component.

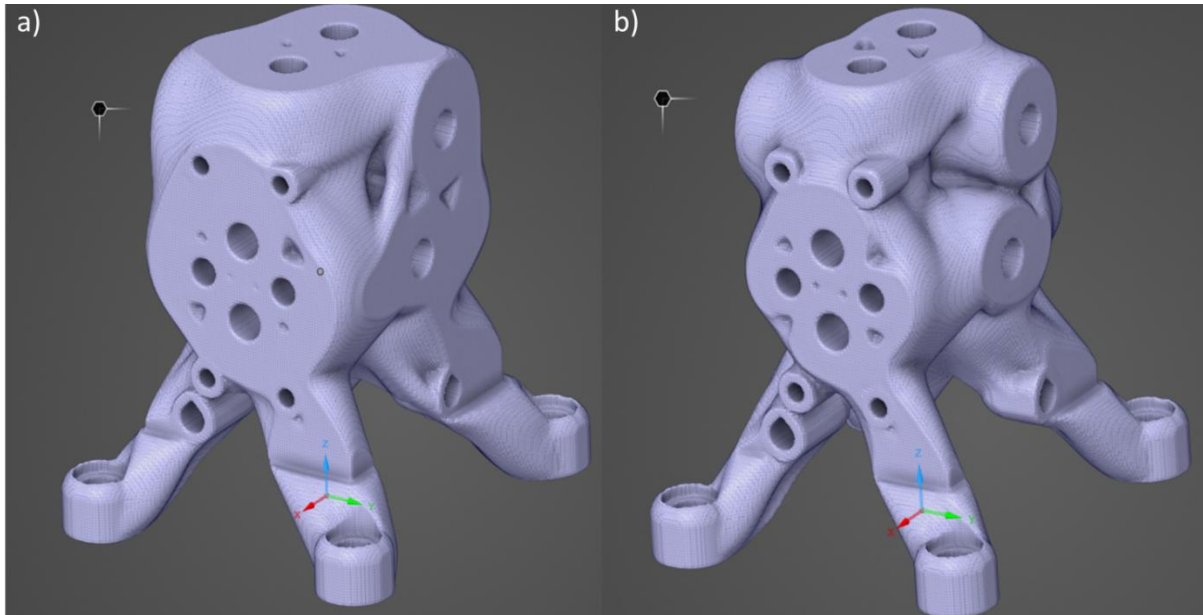


Figure 4.13 Optimized models with a mass reduction constraint of (a) 45% and (b) 55%.

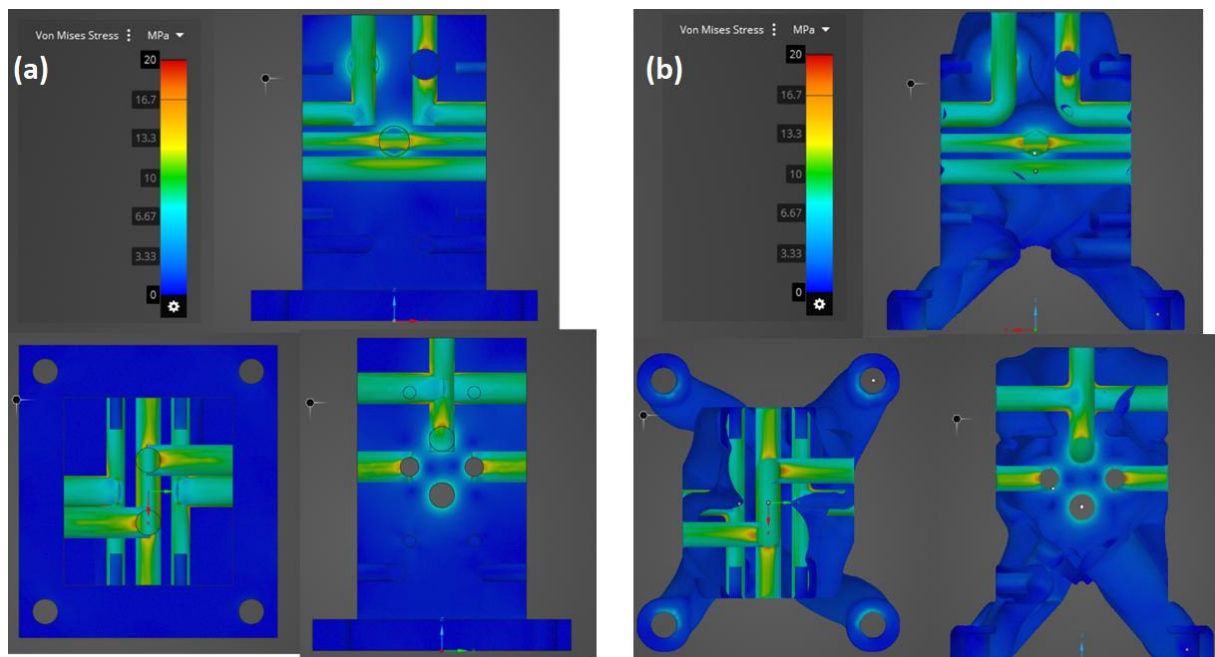


Figure 4.14 Stress distribution (a) before and (b) after weight reduction in the component.

Process modelling was carried out using the MSC Simufact Additive software. Build preparation was performed in Materialise Magics. The oil manifold component was imported into Materialise Magics, where support generation studies were conducted. Subsequently, both the part geometry and support structures were exported in STL format and imported into MSC Simufact Additive. Prior to process modelling, a mesh sensitivity study was performed for different voxel sizes to evaluate mesh dependency. Based on this study, a uniform mesh with a voxel size of 1 mm in the x/y/z directions was selected. The coarsening level was set to 0. Regarding mesh statistics, the total number of voxels was 204,902 and the number of nodes was 237,699. The voxel-based mesh structure used in the process simulation of the oil manifold component is presented in **Figure 4.15**.

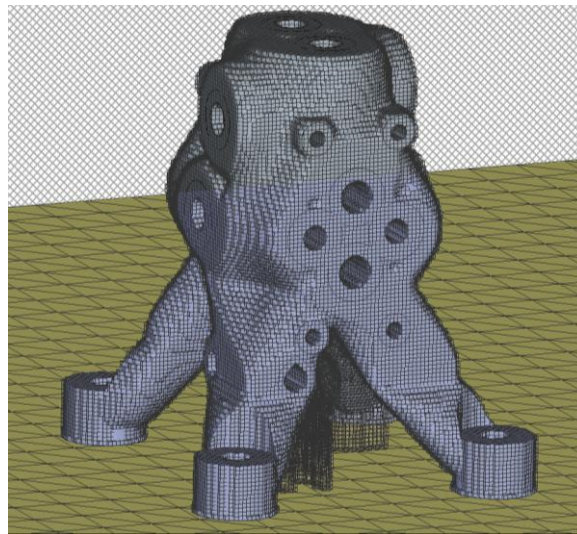


Figure 4.15 Voxel-based mesh structure for the component.

Using Simufact Additive software, potential manufacturing defects, as well as maximum stresses and deformations occurring in the part, can be evaluated. Regions exhibiting high stress and deformation concentrations can be identified, enabling necessary modifications to the part design and support structures when required. The simulation results were analyzed in two stages: first, immediately after the build process while the part was still on the build platform, and second, after the completion of all post-processing operations. This approach allows the prediction of defects that may occur directly after manufacturing as well as those that may arise following secondary processes.

As shown in **Figure 4.16**, regions on the component where potential striation lines may form are identified. In particular, a risk of striation (red lines) has been observed in areas where the cross-sectional area changes rapidly. When other manufacturing-related defects of the component are evaluated, no defects associated with recoater contact or any conditions that could lead to potential brittle or ductile failure have been observed. In addition, the equivalent stress distributions on the oil manifold component are presented in **Figure 4.17**. After completion of the additive manufacturing process, the highest stress levels were observed in volumetrically dense regions of the component. No stress concentrations that could lead to

manufacturing-related defects were identified on the part. The deformation distributions on the oil manifold component are presented in **Figure 4.18**. After the additive manufacturing process, the maximum deformation was predicted to occur in the central regions of the part, manifesting as an upward contraction (shrinkage-like deformation). At the mating interface with the pressure adapter, the average deformation level is approximately 0.2 mm. Considering that these regions are critical for assembly with other components, it is deemed feasible to produce them without the need for subsequent machining, as the observed deformation does not adversely affect assembly compatibility. However, for other critical assembly features, precautions have been taken, and holes are planned to be manufactured with machining allowances for post-processing. In the flow passage regions, the average deformation level remains below 100 μm , which is within the design requirements of the oil manifold component. To sum up, it is assessed that the observed deformations do not significantly affect the functionality or assemblability of the component.

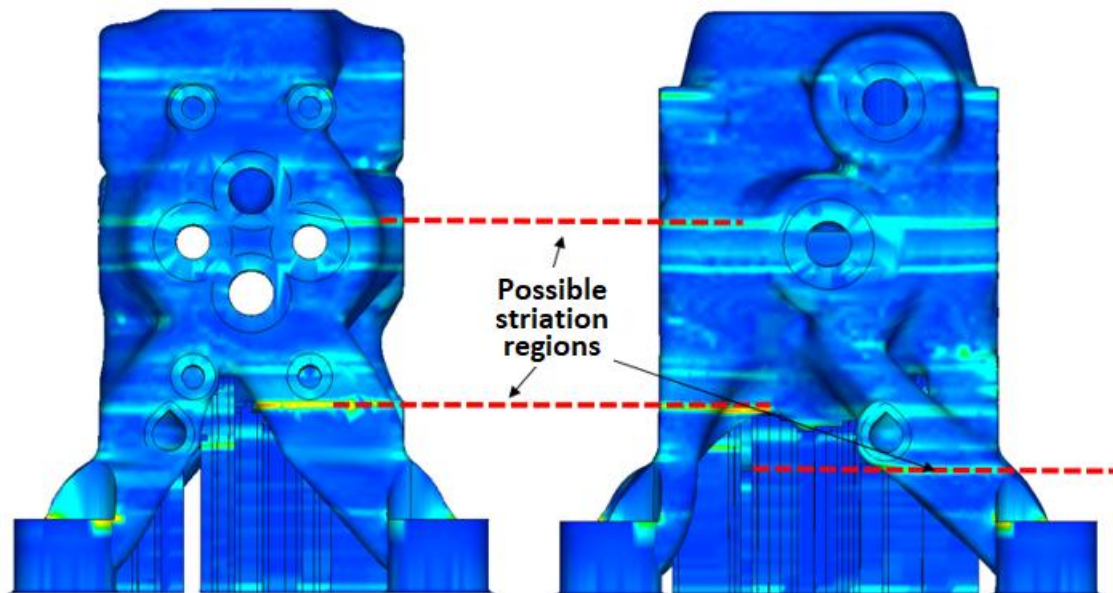


Figure 4.16 Possible striation regions on the component.

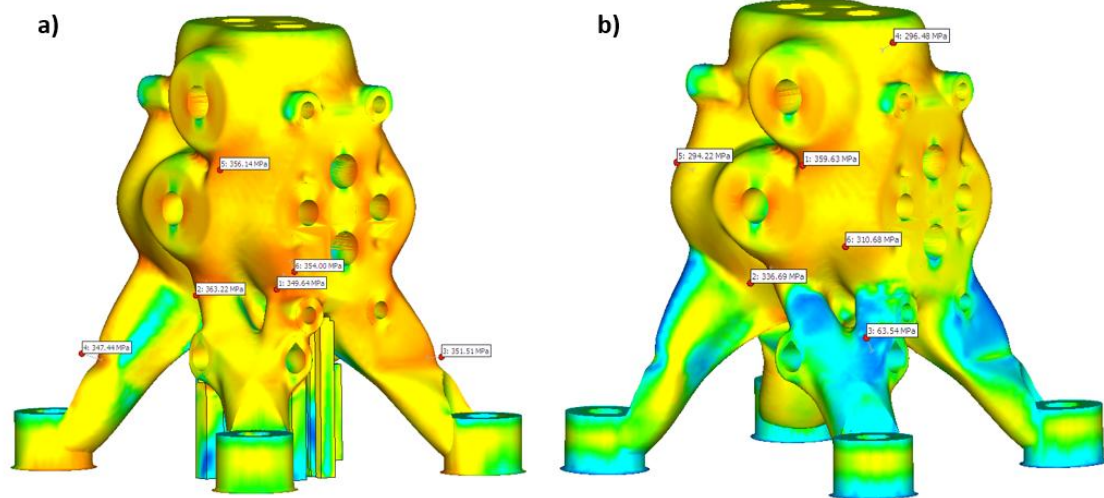


Figure 4.17 Equivalent stresses (a) after the additive manufacturing process and (b) after the part removal from the build platform.

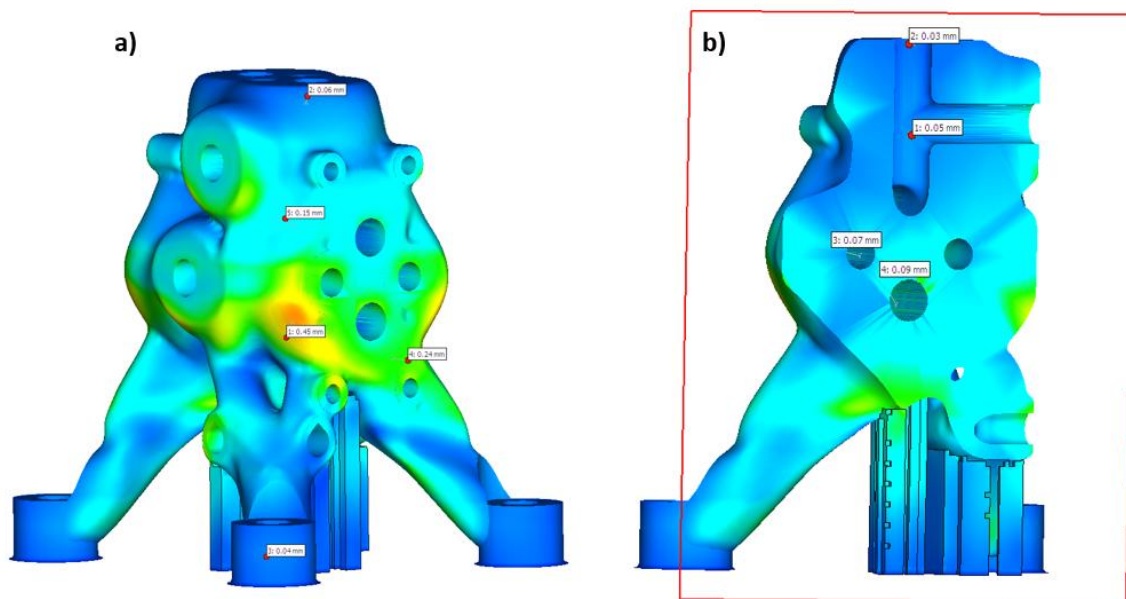


Figure 4.18 Deformations after additive manufacturing: (a) evaluation in terms of assemblability (pressure adapter mounting), and (b) evaluation of deformation in the flow region.

A production strategy was established for manufacturing a total of 12 oil manifold components on a single build platform. In addition, witness specimens were planned to be produced alongside the parts to enable mechanical and metallurgical validation testing. The

build platform prepared according to the additive manufacturing layout is shown in **Figure 4.19**. During topology optimization, a 45° overhang constraint was defined to ensure a self-supporting material distribution of the component. However, this constraint does not fully prevent locally initiated overhanging surfaces, which may still necessitate the use of support structures. Consequently, support structures were assigned to the regions of the oil manifold component that require support during additive manufacturing. The support structures used in the fabrication of the component and their corresponding parameters are provided in **Table 4.3**.

Following post-processing in Materialise Magics, the part was sliced for manufacturing using the Build Processor module of the DMP Factory 500 system. A layer thickness of $60\ \mu\text{m}$ was selected for the slicing operation. As a result, a total of 1,716 layers were generated for the component. After slicing, verification checks were performed on the discretized geometry, and the manufacturing file was prepared for transfer to the machine interface for production.

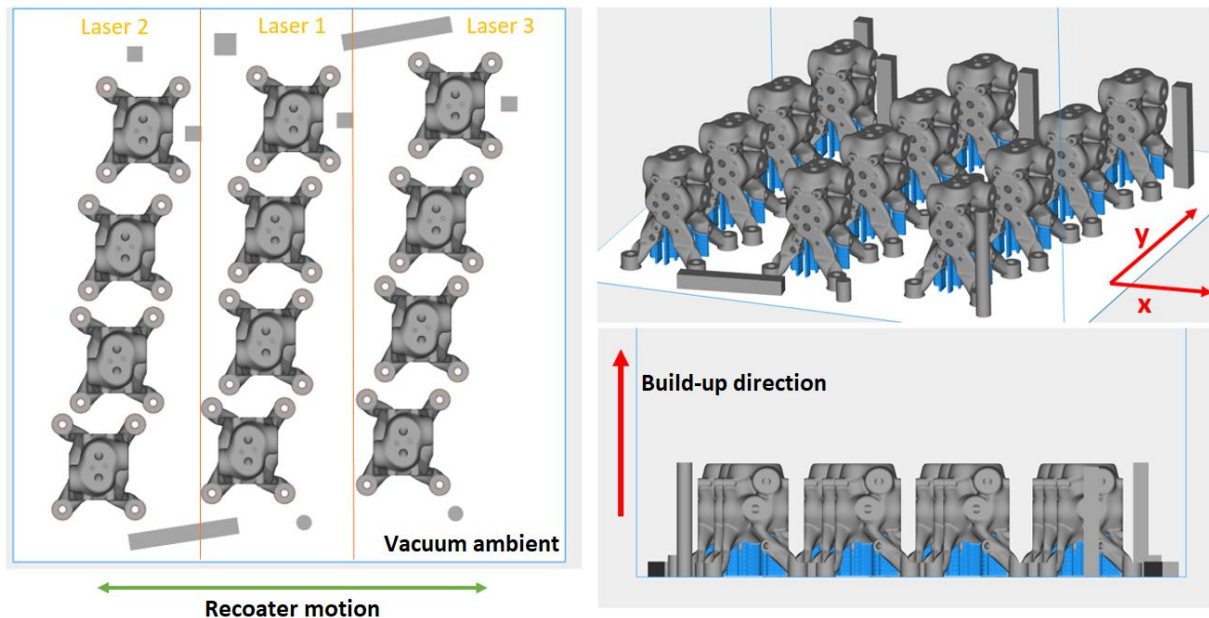
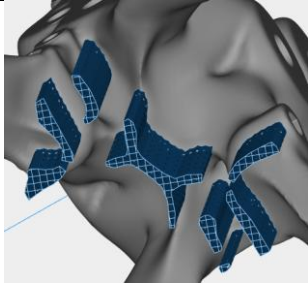


Figure 4.19 Layout of 12 components and specimens for mechanical and metallurgical characterisation.

Table 4.3 Support structure and parameters.

	
Support type	Block support structure
Perforation type and parameters	Diamond-type perforation, beam 0.6 mm, angle 60°
Hatching (x,y)	1 mm, hatch rotation: 69°
Offset	XY: 0.1 mm, Z: 0.25 mm (top and bottom)
Hatching and border parameters	Height: 0.8 mm, upper width: 0.5 mm, lower width: 1.5 mm

The additive manufacturing of the oil manifold component was realised on a DMP Factory 500 system as shown in **Figure 4.20**. The DMP Factory 500 is a dedicated laser powder bed fusion (L-PBF) system for processing AlSi10Mg, equipped with three lasers and a build volume of 500×500×500 mm³. The system is equipped with three fiber lasers operating at a wavelength of 1070 nm. In the process, the build layout was designed such that each laser scans the parts located within its designated processing area. A layer thickness of 60 µm was selected for the production process. The DMP Factory 500 operates under vacuum conditions throughout the build process. The AlSi10Mg powder used in the process has a particle size distribution ranging from 20 to 63 µm and exhibits a predominantly spherical morphology.

After additive manufacturing of the components, powder removal was performed using the Depowdering Module, which is an auxiliary system of the DMP Factory 500. Separation of the additively manufactured parts from the build plate was carried out using a wire electrical discharge machining (wire-EDM) system with a wire diameter of 0.3 mm. For enhancing the mechanical properties, T6 heat treatment was applied to the oil manifold components. Following the heat treatment, the parts were subjected to sandblasting. Threads on the fastening holes were produced using conventional machining methods. The parts were then sent to a cleaning station for final cleaning. Powder removal verification was performed using computed tomography (CT). **Figure 4.21** shows the post-processing stages for the additively manufactured component.



Figure 4.20 DMP Factory 500 system including printer and depowdering modules.

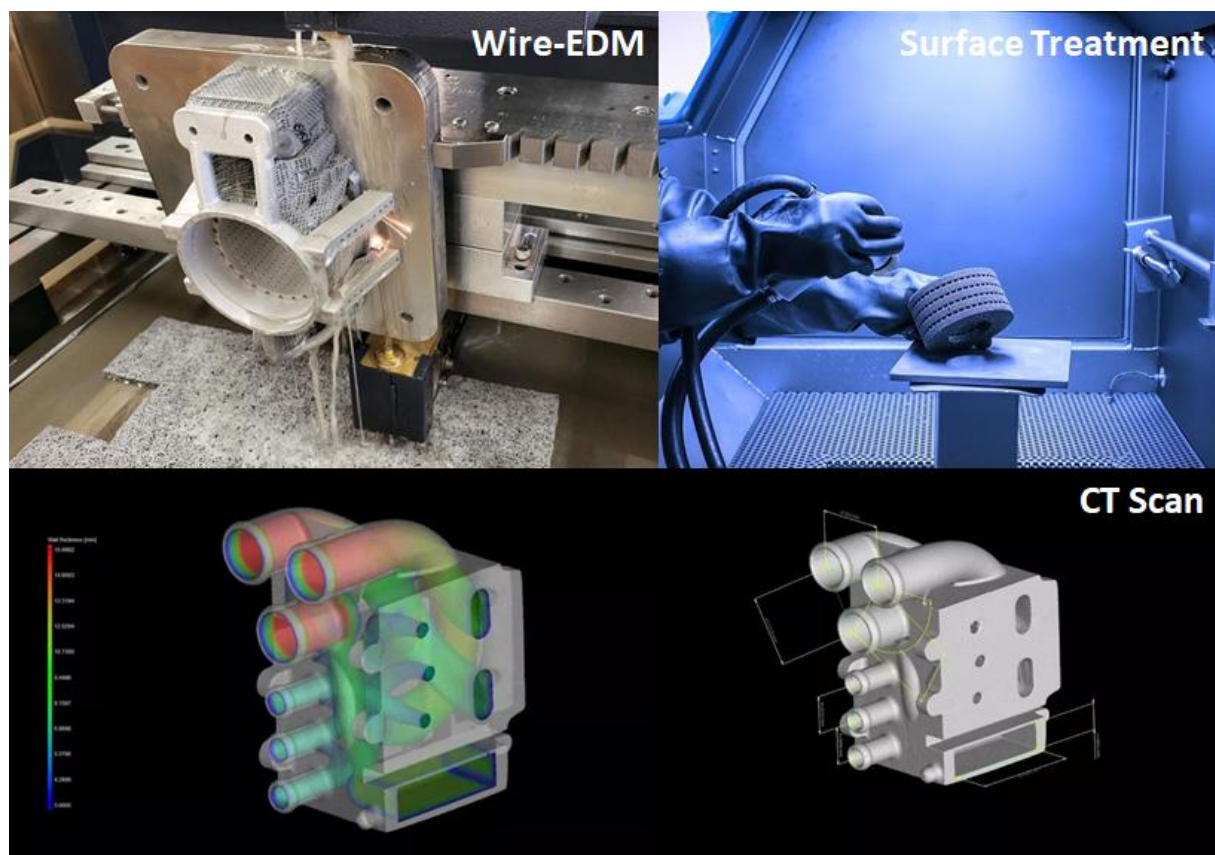


Figure 4.21 Post-processing stages for the additively manufactured component.

As a result of 3D printing process for the oil manifold component, a weight reduction of up to 39% was achieved due to the topology optimization available for additively manufactured parts. Structural validation of the topology-optimized geometry was also carried out, and it was observed that the part design requirements were satisfied. It was concluded that using this component in jet engines would reduce engine weight and result in fuel savings. Through process simulation for additive manufacturing, manufacturing defects, stresses, and deformations of the oil manifold part were predicted with an appropriate support design, and no major finding that would affect production was encountered. In addition to achieving weight reduction in the components, additive manufacturing offers further advantages over conventional manufacturing in terms of process-related costs. **Table 4.4** presents a comparison of processing costs between 3D printing and conventional manufacturing. Based on this comparison, additive manufacturing emerges as a feasible production method for small-batch manufacturing—such as producing 12 components in a single run—which is a common requirement in the aerospace industry.

Table 4.4 Comparison of processing costs for the oil manifold component.

Cost Items	3D Printing	Conventional Manufacturing
Production time including materials costs	0.83 h 10 h for 12 parts on build plate	3 h
Raw material characterisation (powder analyses)	0.25 h 3 h for 12 parts on build plate	N/A
Pre-processing (support design, slicing etc.)	0.09 h 1 h for 12 parts on build plate	N/A
CNC programming	0.5 h only for threaded holes	1 h
Post-processing (depowdering, wire-EDM etc.)	3.67 h 44 h for 12 parts on build plate	N/A
Heat treatment	0.5 h 6 h for 12 parts on build plate	0.5 h 6 h for 12 parts on build plate
Engineering cost	0.33 h 4 h for 12 parts on build plate	3 h
Labour cost	0.33 h 4 h for 12 parts on build plate	8 h
Total cost	6.5 h	15.5 h

4.6. Conclusions

This chapter presents an overview of digital production design for additive manufacturing by discussing the fundamental principles of DFAM. It outlines the sequential stages of digital product development, from initial design conception and topology-driven optimization to process planning and fabrication, while highlighting the unique capabilities that 3D printing introduces to modern digital design and manufacturing workflows. Within this framework, the chapter emphasizes how additive manufacturing enables a more integrated and iterative design approach, allowing engineers to develop geometries that are not only functionally optimized but also tailored to the constraints and opportunities of layer-by-layer fabrication. Key aspects such as lightweighting, part consolidation, design freedom, and performance-driven optimization are discussed as core enablers of this paradigm shift. To contextualize these concepts, two aerospace-focused case studies are introduced, covering the full workflow from digital design to physical production. The first case study investigates a polymer-based additive manufacturing application utilizing LW-PLA material for structural components in UAV systems. This example highlights the advantages of lightweight polymer structures, rapid prototyping capabilities, and design flexibility in low-load aerospace applications. The second case study explores the additive manufacturing of a metallic alloy component commonly used in aero-engine systems for large commercial aircraft. In this case, an aluminium alloy oil manifold is manufactured using the Powder Bed Fusion technique. Beyond the manufacturing process itself, this case study also includes a comparative assessment between additively manufactured and conventionally produced versions of the component, with particular focus on performance, weight, and production efficiency. Together, these case studies demonstrate how digital design methodologies and additive manufacturing technologies can be effectively translated into high-performance aerospace components. They also provide valuable insights into the opportunities, such as weight reduction, design optimization, and manufacturing efficiency.

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