Chapter

Optimizing Metal AM Potential through DfAM: Design, Performance, and Industrial Impact

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Abstract

Design for Additive Manufacturing (DfAM) is a transformative approach designed explicitly to optimize designs using metal additive manufacturing (AM). Exploring core DfAM principles, the chapter highlights the advantages of geometric freedom, material selection, and aligning designs with the capabilities of specific metal AM processes. It examines advanced optimization techniques like topology optimization and lattice structures to achieve high performance on lightweight metallic components. The transformative impact of metal DfAM is shown through real-world applications encompassing aerospace, healthcare, and automotive domains. The chapter acknowledges challenges inherent in metal DfAM, such as geometric limitations, surface finish considerations, and cost implications. Finally, it emphasizes the critical role of sophisticated software tools in driving design efficiency and explores future trends in AM metallic materials, technologies, and research.

Keywords: Design for Additive Manufacturing, metal additive manufacturing, topology optimization, lattice structures, lightweighting, performance enhancement

1. Introduction

Metal AM encompasses a range of technologies that build complex three-dimensional (3D) components directly from digital models by adding material layer by layer, unlike traditional subtractive manufacturing methods. AM offers unparalleled design freedom, reduced material waste, and the potential for rapid prototyping and small-batch production. Each metal AM technology offers unique characteristics, making them suitable for different applications [1, 2]. **Table 1** presents a comparison between processes regarding materials, advantages, limitations, and typical applications; it can be a valuable reference for decision-making.

1.1 Laser Powder Bed Fusion (L-PBF)

L-PBF employs a high-powered laser to melt thin layers of metal powder selectively. It is compatible with various materials, including steel, titanium, aluminum,

Technology	Advantages	Limitations	Typical applications
Laser Powder Bed Fusion (L-PBF)	High-detail resolution can produce complex geometries without specific orientation.	Support structures for overhangs are required, and post-processing is often needed.	Aerospace, medical implants, tooling industry.
Electron Beam Melting (EBM)	Can cut very thin holes of large aspect ratio, precise and distortion-free.	High capital and maintenance cost, and requires vacuum.	Aerospace, automotive, and medical industries.
Fused Filament Fabrication (FFF)	Low-cost, easy to use, wide range of materials.	Lower detail resolution compared to PBF methods and support structures often needed.	Prototyping, educational purposes, hobbyist projects.
Direct Energy Deposition (DED)	Can repair existing components, compatible with a range of materials.	Requires post-processing, less precise than PBF.	Repair and maintenance of structural components, aerospace.
Binder Jetting (BJT)	Fast print speeds, low operating costs per component.	Post-processing is often required, and less durable components.	Full-color prototypes, large sand-casting cores and molds, low-cost metal component

Table 1.
Comparative analysis of advantages, limitations, and typical applications across different AM processes for metallic materials [1–20].

and nickel-based superalloys [21]. L-PBF is recognized for its high precision, excellent detail reproduction, and the ability to produce components with superior mechanical properties [22]. However, the process can be relatively slow and requires support structures for complex geometries in customized components due to its unparalleled design freedom and material efficiency [23]. L-PBF is widely used in aerospace, medical devices, tooling, and complex production [24].

1.2 Electron Beam Melting (EBM)

EBM operates on a principle similar to L-PBF but uses an electron beam instead of a laser as an energy source. The process occurs within a vacuum chamber, particularly suitable for reactive metals like titanium and alloys [25]. EBM offers faster build speeds than L-PBF for certain materials, excellent properties for high-temperature and reactive materials, and the ability to produce components with slightly lower residual stress. However, EBM typically has a rougher surface finish compared to L-PBF, involves high equipment costs, and requires the added complexity of a vacuum environment [26]. Despite these limitations, EBM finds applications in aerospace, medical implants, and the manufacture of large or highly reactive metal components due to its precision and distortion-free nature [27, 28].

1.3 Direct Energy Deposition (DED)

DED is a versatile AM process that melts feedstock (powder or wire) as it is deposited using a laser or electron beam [29]. DED can process various metals, composites, and graded materials [30]. Its advantages include the ability to create very large components, the option to repair or add features to existing components, and faster build speeds than PBF processes for large components [31]. However, DED often has lower accuracy and surface finish than powder bed processes and usually necessitates post-processing [32]. Despite these challenges, DED is commonly used for large-scale aerospace components, repair work, and coating applications due to its compatibility with various materials and ability to repair existing components [33].

1.4 Binder Jetting (BJT)

Binder Jetting Technology (BJT) operates by precisely depositing a liquid binder onto a metal powder bed to join the particles. After manufacturing, the created components are submitted to a debinding to remove the binder, and a sintering process is performed to achieve total density. This method is mainly used with stainless steel, tool steel, and bronze [34]. Binder jetting is a cost-effective option for larger production runs, as it removes the need for support structures and permits the production of porous structures. Nonetheless, compared to fully melted techniques, binder jetting typically results in components with lower density and weaker mechanical properties. Additionally, the finishing steps involved (polishing, surface finishing, heat treatments to improve mechanical properties) can be time-consuming and require significant effort [34, 35]. Notwithstanding these limitations, BJT is utilized in prototyping, sand-casting molds, and the production of porous medical implants due to its rapid print speeds and low operating costs per component [36].

2. Design for AM (DfAM)

DfAM has revolutionized the production of metallic components by allowing intricate and complex shapes that traditional manufacturing methods cannot achieve [4]. DfAM refers to a specialized approach in engineering and design that focuses on optimizing and tailoring designs specifically for AM processes [37–40]. DfAM is centered around harnessing the unique capabilities of AM by considering the technology's constraints, opportunities, and intricacies during the design phase. There are several reasons to optimize components: lightweight design, performance increase, efficiency improvement, and decreased cost [37, 41–43]. Designing and developing components for AM can be more accessible or tougher if the designer/engineer has the experience, the requirements of the component, and the specificity of the type of component industry [44, 45]. As an example of this, **Figure 1** shows three intertwined hollow pyramids and one ring produced with FFF.

The significance of DfAM lies in its ability to leverage AM technology's capabilities thoroughly [39, 43, 46]. It enables designers and engineers to capitalize on the inherent advantages of AM, such as the freedom to create complex shapes, reduced material waste, and the production of intricate internal structures that enhance functionality [26, 47]. DfAM allows for optimizing component designs to achieve improved performance, lighter weight, increased strength, and enhanced functionality while minimizing the need for assembly [48]. Moreover, it streamlines the production process, reducing lead times and costs and making it a pivotal approach in advancing the potential and applicability of AM across various industries. By considering design intricacies specific to AM, DfAM unlocks a new realm of innovative possibilities that traditional manufacturing methods cannot match [11, 49].

It is required to evaluate which products will benefit the most from applying optimization plus AM. If companies develop optimization and AM strategies to correctly assess traditional products and processes (fabricated with traditional

Figure 1.
Three intertwined hollow pyramids with a ring were produced with FFF.

manufacturing), if they can become more efficient and achieve—at least—the same level of performance after optimization, at the same time, costs are reduced (material, manufacturing, production process, among others), companies will gain competitive advantage regarding competitors [20, 29, 50, 51].

One of the most known advantages of optimization, and one of the biggest challenges, is designing products with lower mass and similar (or better) performance under work conditions [41, 52, 53]. The manufacturing of optimized components is also a challenge, and they can often be manufactured by something other than traditional processes (like trimming, milling, drilling, and grinding). Two methods used and where DfAM can create a shape advantage for AM are topology optimization (TO) and lattice design. Both methods reduce the weight of components [41, 42], maintaining mechanical characteristics and properties. Both these strategies are widely used and are executed through Computer-Aided Design (CAD), Computer-Aided Engineering (CAE)—including Finite Element Analysis (FEA)—and Computer-Aided Manufacturing (CAM).

DfAM starts with a simple geometric shape in CAD software, ensuring it meets basic functional requirements. Distinctive design tools then optimize the components with TO and lattice structures for weight and material reduction [41, 42]. Finally, simulation software evaluates the design's performance under stress, loads, and specific operating conditions. Different methods are used to manufacture complex or expensive shapes, and traditional manufacturing is used to redesign them. The optimization software aims to create a mathematical idealization of an actual physical system; depending on the shape, material, series volume, and other criteria, series production is economically possible using metal AM [42]. It is required to determine analysis model properties, select appropriate response quantities, and choose a suitable finite element mesh to calculate the wanted responses within acceptable

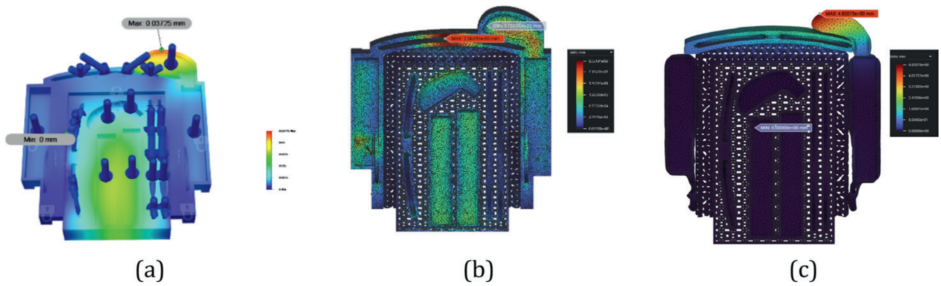


Figure 2.
Analysis of a box to store augmented reality glasses for different processing stages: (a) initial model, (b) small optimization model and (c) fully optimized model [54].

accuracy. The results achieved depend on the analysis type performed but include elements such as element stresses and modal frequencies and define materials, element thicknesses, element meshes, and other quantities needed to complete the analysis, as shown in **Figure 2** [55].

Two distinctive design methods exist. The first, process-driven shape, focuses on reducing manual interaction with a human designer to reduce design time and improve the design performance [42]. The second is the designer-driven shape, a process where a human designer controls the shape, contributing with manufacturing knowledge to avoid cost increase in fabrication. Both methods consider the AM aspect, balancing performance increase and per-component cost in series production [42, 56].

The optimization methodologies and simulation can be repeated unlimited times, based on the design methods, until a component that suits requirements is found. The only constraint is the software's time to process information and run algorithms. The previous figure shows the design strategies for redesigning AM components to improve performance and reduce costs.

3. Optimization techniques

The pursuit of optimization techniques in AM involves a multifaceted approach to maximizing the benefits of this transformative technology. This chapter investigates advanced methods such as TO, which enables the creation of structures with optimized material distribution for enhanced performance and reduced weight. Additionally, it explores the realm of designing lightweight structures to capitalize on the inherent freedom provided by AM processes. Furthermore, the study delves into generative design techniques, which leverage algorithms to iteratively generate and refine designs based on specified constraints and objectives. This research aims to unlock new avenues for innovation and efficiency in AM applications by delving into these sophisticated methodologies [57, 58].

According to Gibson et al., Design for Manufacturing and Assembly (DfMA) can be defined as the "practice of designing products to reduce, and hopefully minimize, manufacturing and assembly difficulties and costs" [59]. Theoretically, it looks easy to apply. However, it can become complex and time-consuming to apply [10], especially when the design team does not control variants well. DfMA also uses traditional manufacturing processes, which can represent significant costs for manufacturing optimized components. When AM becomes an alternative, we move from DfMA to DfAM, where the purpose is to utilize the AM fabrication capabilities best to achieve desired performance and lifecycle objectives through the combination of shapes, sizes, geometric mesostructures (such as lattice unit cells), material compositions, and microstructures [60–62].

3.1 Topology optimization (TO)

TO is a numerical approach that identifies where material should be placed in a given domain to achieve a desired functionality (e.g., stiffness) for a given set of loads and constraints while optimizing for qualities such as minimal material usage/weight or uniform stress distribution [43]. TO algorithmically determines the most structurally efficient design within a defined space and under given constraints. This process results in organic, optimized shapes that use material only where necessary for structural integrity. With AM, TO is compelling since it can create complex, load-bearing structures that are difficult or impossible to achieve through traditional manufacturing methods. These optimized designs enhance strength-to-weight ratios, reducing material usage while maintaining structural integrity, as shown in **Figure 3**, where an office stapler is shown with reduced weight while maintaining the mechanical properties and functionality [38]. TO is a process based on FEA where an algorithm is used to determine the space that provides the optimal behavior, removing material that is not required to manage the applied load to meet defined requirements and fulfill a specified optimization goal. The process requires initial inputs to determine optimization, usually boundary conditions (external loads and optimization criteria) plus component geometry [41, 42]. TO methods are commonly applied in components developed for traditional manufacturing processes, like casting and machining, which are limited—in terms of design—by the manufacturing process since it is required to compromise between an optimal form and ease of manufacture. These approaches have significant manufacturing constraints that must be considered during the design stage to ensure a feasible design [63].

TO enables mass reduction and stiffness optimization of a maximum allowed volume and a load set for a specific volume reduction goal [41]. Considering AM's ability, combining AM with TO will enable a compromise between weight and shape.

There are several software for TO, and a big part of them already take into consideration additive manufacturability. Hexagon, Siemens NX, Dassault Systèmes, and

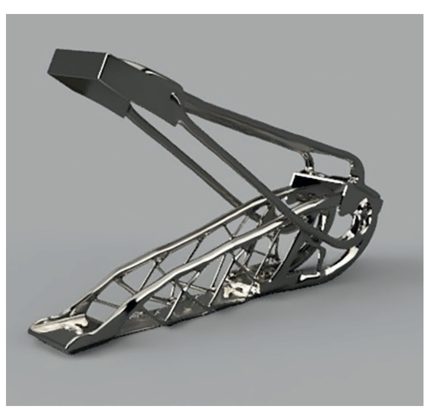


Figure 3.
Topologically optimized desk stapler [38].

Autodesk, among others, are starting to present well-developed software solutions, not only for TO but also including DfAM's perspective.

3.2 Lattice and lightweight structures

Lattice structures mimic nature by replicating the organic shapes and structures found in natural materials like wood, bone, sponge, and coral. It is made of a predefined external geometry and internal architecture, similar to cellular materials structures, referred to as lattice structures due to being inherently non-stochastic [64]. Lattice structures, likewise the TO, are an excellent way of producing lightweight, robust performance, reducing fabrication time and overall costs, which are important in industries such as aerospace and transportation. Lattice structures are intricate, mesh-like designs that feature a network of beams or struts [65]. Some examples are presented in **Figure 4**.

These structures provide strength and support while significantly reducing weight. A lattice is a cellular structure of repeated unit cells to form a larger volume, and it is like trying to mimic nature by creating organic shapes and forms like

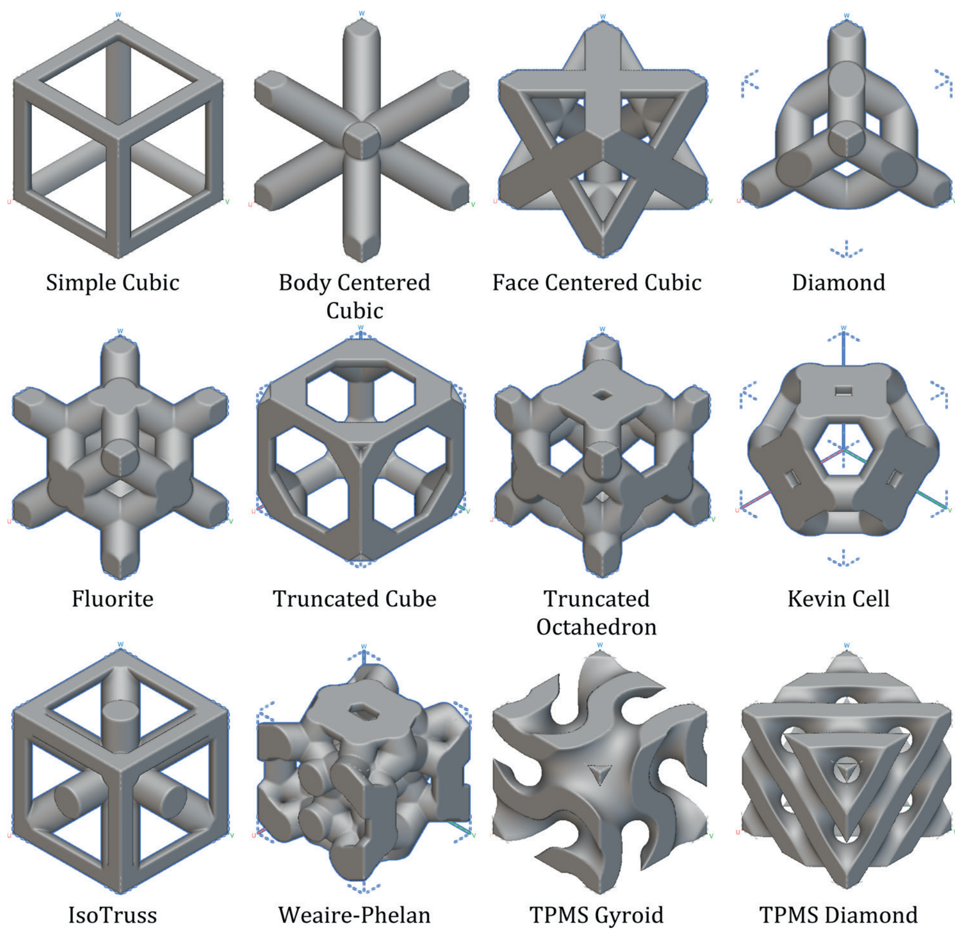


Figure 4.
Examples of lattices and lightweight structures.

wood, bone, sponge, and coral. It can be used as lightweight support structures, to increase robustness against overloading, decrease mass (less material used), and reduce production time (smaller costs) [26, 66]. There are many options for the shape and size of such lattice cells and for the pattern in which they are repeated in a conforming pattern (due to being inherently non-stochastic). Countless examples of lattice structures are used to reduce the material to improve its strength-weight ratio or replace support material in components. AM allows for the creation of these complex lattice structures easily. These lightweight structures are advantageous in aerospace, automotive, and biomedical applications where weight reduction without compromising strength is critical [67, 68]. **Figure 5** shows a gear bearing with lattice structures, which is used for the weight reduction of components, fully optimized for production through AM.

Lattice design is a designer-guided approach involving intersecting or cutting components of the design space with a consistent pattern of smaller strut-like structures and used as lightweight support structures [41], and they decrease mass and fabrication time [42]. Lattice designs can be used within components, increase robustness against overloading of the final components, and enable the utilization of less material than a solid representation of the same design space and may thus cost less to fabricate, which makes it a possible way of improving manufacturability and to lower series components cost [68]. The design-driven shape method uses lattice structures to reduce mass and decrease AM fabrication time, maintaining the performance of the components by creating self-supporting structures in the interior of the components [42]. The placement and quantities of these—lattice—structures and where they are built and disposed of are done by specific software, with appropriate algorithms running, confirmed in simulation software.

Implementing the lattice structure of AM design strategies can be beneficial when considering both the mechanical performance and manufacturing aspects [64, 69]. According to Panesar et al. [64], lattice structures are utilized in AM for various advantages, such as facilitating the production of components with intermediate densities, reducing component distortions by minimizing residual stresses through inherent porosity, and needing fewer supports due to the inclusion of self-supporting

Figure 5.
Gear bearing optimized with lattice structures.

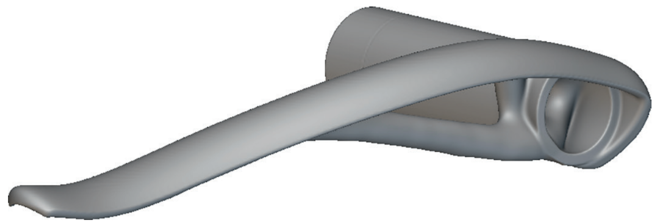


Figure 6.
Generative design of a door handle [40].

unit cells. This approach also enhances design robustness. As mentioned in the previous paragraph, the lattice structure creation is built using software where CAD files are structurally analyzed to introduce selected lattice patterns and analyzed to support stresses when an external load is applied. Again, FEA is crucial in evaluating whether the designed components support loads and stresses under work conditions [70, 71].

3.3 Generative design

Generative design utilizes advanced algorithms to explore numerous design permutations based on specified parameters and constraints, creating innovative designs by allowing optimized, efficient, creative designs that capitalize on AM's capabilities to develop superior, economically viable products [72]. This iterative approach tests and refines possibilities to optimize the final design for its intended application. Producing complex and organic shapes that traditional methods might overlook is precious in AM. This capability leverages AM's geometric freedom to encourage the development of novel, efficient designs uniquely suited to its processes. The door handle in **Figure 6** is a good example of this [40].

Generative design can refine designs in a multi-material context to meet performance criteria while minimizing material use [57]. By highlighting its role in optimizing multi-scale structures, which is crucial for applications needing varying material properties within a single component. This iterative testing ensures that designs are innovative, practical, and manufacturable [58]. Generative design in AM supports creating structures that enhance performance while reducing material waste. It enables intricate lattice structures, conformal cooling channels, and complex geometries, contributing to significant cost savings and sustainability through reduced material use and post-processing [45, 73].

4. Fundamentals of DfAM

The fundament of DfAM lies in understanding and implementing its basic principles and guidelines. This thoroughly explores various facets, including material choices and selecting appropriate AM processes [45]. As mentioned above, designing products optimized for AM entails a deeper discussion of fundamental principles, encompassing design considerations, exploitation of geometric freedom, and the reasonable selection of materials. By delving into these foundational aspects, practitioners gain insights into enhancing the efficiency and effectiveness of AM processes, leading to advancements in product design and manufacturing methodologies [54, 74]. DfAM is challenging since he must change the paradigm in which he learned and worked with familiar, safe, and proven design theories [75]. To get a new and innovative perspective and improve product performance, four areas should be considered: integrated design, individualization, lightweight design, and efficient design [69, 75, 76]. The first step identifies components and assemblies where AM offers a benefit, which—after deciding on a suitable design strategy—develops a design concept and proceeds to the design of a detailed component [75, 77]. Mass reduction assumes relevance when deciding to design for AM. Items like reduction of trimming operations, feedstock saving, complexity, and economic savings, among others, favor AM and DfAM, compared to traditional manufacturing processes [41, 42, 69]. It is not a matter of AM being able to produce components since any components—independent of design shape—are suitable to be designed and fabricated through AM; the limitations are physical (build volume enough to produce components), processability, and efficiency (time, cost, finishing), as well as post-processing operations required, functionality.

One of the most significant advantages of metal AM is that, unlike traditional methods, it allows for complex designs without driving up production costs. Traditional processes often cannot handle complex designs, and the costs are much higher when they can produce them. AM technology brought a wide range of new possibilities by allowing the production of complex components at a minor manufacturing cost [40, 63]. The production cost does not vary with the complexity since it will only increase costs marginally; however, the current fixed costs are higher when compared to the traditional process. Thus, as soon as the break-even point is reached, LPBBF will enable total cost and cycle time reduction. AM enables quick single-component manufacturing, and compared to traditional manufacturing, it is more cost-effective and flexible. Small batch sizes, highly complex forms, and designs with integrated cooling or tempering channels are not problematic for metal AM and L-PBF but are critical in traditional processes [78]. With the end of some Original Equipment Manufacturing (OEM) patent protection, plus the attention that the market is starting to show, shortly, technology will become more effective and independent of additional processes to get the same finishing as traditional manufacturing processes [77, 79].

4.1 Design considerations for complex geometry utilization

As mentioned, DfAM enables the creation of intricate and complex shapes that traditional manufacturing methods cannot achieve. Designers should leverage this capability by fully utilizing AM's layer-by-layer construction, which may involve consolidating components, creating internal structures, or optimizing designs for lightweight [38, 80]. **Table 2** provides a comparative analysis of feature types across different AM processes to enable the creation of designs fully utilizing AM's layer-by-layer construction, which involves consolidating components, creating internal structures, and optimizing lightweight, among others. DfAM allows designers and engineers to incorporate features that enhance performance and efficiency.

4.2 Design considerations for performance

The design for improved performance depends on the product. For that, the designer needs to know and understand the customer's perceived quality, performance, utilization rate, and the value that the customer gives to that component/product. The strategy depends on what is valued: performance, cost, and

Feature type	L-PBF	EBM	FFF	DED	BJT
Orientation	Allows construction of complex geometries without specific orientation.	Similar to L-PBF, it can build complex geometries without particular orientation.	Orientation affects surface finish.	Allows for multi-axis deposition, meaning the orientation can be varied.	Orientation affects surface finish.
Support angle	Supports needed for overhangs >45°.	Supports needed for overhangs >45°.	Supports needed for overhangs >45°.	Supports are not typically required due to high deposition rates.	Supports unnecessary as the unbound powder acts as a support.
Wall thickness	It can produce thin walls down to 0.2 mm.	It can produce thin walls down to 0.2 mm.	The minimum wall thickness depends on the nozzle diameter.	Wall thickness is dependent on nozzle diameter.	It can produce thin walls, depending on the binder and powder properties.
Details	Offers high-detail resolution.	Offers high-detail resolution.	Lower detail resolution compared to powder bed fusion methods.	Lower detail resolution, dependent on nozzle diameter.	Offers moderate detail resolution.
Holes and tubes	It can produce small holes down to 0.5 mm.	It can produce small holes down to 0.5 mm.	The ability to produce holes/tubes depends on nozzle diameter and layer height.	Dependent on nozzle diameter.	It can produce small holes, depending on the binder and powder properties.
Machining stock	Not typically required.	Not typically required.	It may be necessary for high-precision components.	It may be needed for high-precision components.	Not typically required.
Clearance	It can produce small clearances, down to 0.2 mm.	It can produce small clearances, down to 0.2 mm.	Clearance is dependent on nozzle diameter and layer height.	Dependent on nozzle diameter.	It can produce small clearances, depending on the binder and powder properties.
Hollowing	It can produce hollow structures.	It can produce hollow structures.	It can produce hollow structures.	It can produce hollow structures.	It can produce hollow structures.
Screw threads	It can produce fine threads down to M2.	It can produce fine threads down to M2.	Ability to produce screw threads dependent on nozzle diameter and layer height.	Dependent on nozzle diameter.	It can produce threads, depending on the binder and powder properties.

Feature type	L-PBF	EBM	FFF	DED	BJT
Surface finish	It can achieve smooth surfaces but may require post-processing.	It can achieve smooth surfaces but may require post-processing.	Surface roughness can be high and depends on layer height.	Surface roughness can be high and depends on the deposition rate.	Surface roughness can be high and depends on powder size.
Infill	It has a solid infill but can be used to design internal lattice structures.	It has a solid infill but can be used to design internal lattice structures.	It can vary in infill density and pattern.	It has a solid infill but can be used to design internal lattice structures.	It has a solid infill but can be used to design internal lattice structures.
Overhangs	Supports needed for overhangs >45°.	Supports needed for overhangs >45°.	Supports needed for overhangs >45°.	Supports are not typically required due to high deposition rates.	Supports unnecessary as the unbound powder acts as a support.
Bridging	It can bridge small gaps, depending on material and process parameters.	It can bridge small gaps, depending on material and process parameters.	It can bridge gaps, but it is dependent on material and cooling.	It can bridge gaps, but it is dependent on the deposition rate.	It can bridge small gaps but depends on binder and powder properties.

Table 2.
Comparative analysis of feature types across L-PBF, EBM, FFF, DED, and BJT [1, 2, 18, 38, 40, 54, 59–61, 80–85].

functionality [41, 42, 76, 86]. Optimization methodologies are commonly used as design tools to improve performance and fulfill the functional requirements of components. Several aspects need to be analyzed, which might vary with the application of components.

Several areas can benefit from a design and/or redesign strategy for improved performance and the use of additive manufacturability for component fabrication [42]. Areas like health, components, molding, and tooling can benefit from DfAM since all components have margins that need to be improved. In addition to cost reduction, which has been mentioned several times, there is the possibility of creating components that are 100% movable, eliminating assembly steps and production operations [41, 87].

For example, in health-related applications (medical implants and prosthetics, for instance, like the examples in the previous picture), a combination of the material's biocompatibility and the body is required to get shapes that can accommodate it. The first step is to evaluate the patient's surrounding tissue through Computer Tomography (CT) scans, data that will be used for reverse engineering (RE), enabling time-saving in development and modeling [41].

Comparing this AM strategy to traditional manufacturing, where components with standard dimensions usually exist, patients will benefit from having a 100% dedicated component. In traditional manufacturing, a 100% adapted component is expensive since that component includes development and manufacturing costs; AM enables a single production for one component only, enabling high-cost savings.

4.3 Exploiting geometric freedom

Utilizing the geometric freedom of AM technologies is a fundamental aspect of DfAM. This freedom enables the creation of intricate and optimized structures previously unfeasible with traditional manufacturing methods. TO software allows the generation of designs based on specific performance criteria such as stress distribution, weight reduction, and material efficiency. This approach helps create efficient and optimized structures for their intended function. TO can lead to innovative designs that maximize performance while minimizing material usage, as the suggestion of robotics arm gripper clamps shown in **Figure 7(a)** and **(b)** [81].

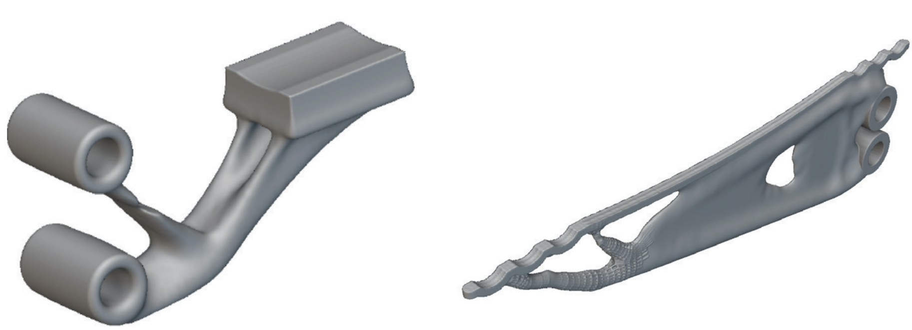
AM's ability to create shapes impossible with traditional manufacturing, such as intricate lattice structures, internal cooling channels, conformal cooling features, and complex surface textures, enhances the final product's functionality, esthetics, and performance [88, 89]. These features significantly improve thermal management, structural integrity, and overall product performance without adding unnecessary weight. By designing components to consolidate multiple components into a single structure, the need for assembly is reduced, decreasing the number of potential failure points and simplifying the supply chain. Component consolidation can also lead to significant cost savings and improved reliability [44].

Moreover, by designing self-supporting geometries, reducing or eliminating the need for support structures during printing is possible. This reduces material waste and minimizes post-processing efforts, leading to faster production times and lower costs [90]. Exploiting the geometric freedom of AM technologies allows designers to create highly optimized and functional products. By leveraging TO, complex geometries, components consolidation, and minimizing support structures, DfAM can significantly advance product design and manufacturing efficiency [81].

4.4 Material selection

Selecting appropriate metals is a crucial aspect of DfAM. The chosen metals must be compatible with the specific AM process, as different AM technologies have unique material requirements. Understanding these metals' properties and suitability for the intended application is critical to ensuring successful outcomes [45].

For instance, L-PBF typically uses metals like titanium, aluminum, and stainless steel, which are prized for their strength-to-weight ratios and are commonly used in



(a) (b)

Figure 7.
Robotics arm gripper optimized [77, 80].

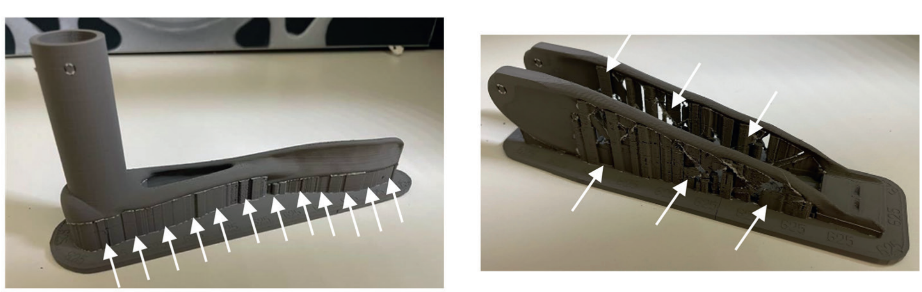
aerospace and automotive industries. Similarly, EBM is effective with materials such as titanium alloys and cobalt-chromium, which are known for their high strength and biocompatibility, making them suitable for medical implants and aerospace components [4]. Custom metal development is another critical consideration. By developing or customizing metal alloys, designers can enhance mechanical properties or achieve characteristics unique to AM, such as improved thermal stability, increased toughness, or enhanced corrosion resistance. This is particularly valuable in high-performance applications where standard metals may only meet some design requirements [23]. Focusing on creating lightweight structures without compromising strength and durability is essential. Techniques such as lattice structures and hollowing can significantly reduce material usage while maintaining the necessary mechanical properties. These strategies are crucial in industries like aerospace and automotive, where weight reduction is critical for performance and fuel efficiency [91].

By carefully selecting and possibly developing metal alloys tailored to the specific needs of the design and AM process, it is possible to achieve optimal performance, cost-efficiency, and innovative solutions that leverage the full potential of AM.

4.5 Process selection and manufacturability

Each additive manufacturing (AM) technology has its own strengths and limitations, so choosing the appropriate AM process that aligns with your design requirements is crucial, considering factors such as resolution, material compatibility, and build volume. Additionally, design with post-processing requirements in mind, planning for necessary finishing processes like heat treatment, support removal, surface smoothing, or machining to achieve the final desired properties [92].

When functional requirements are selected and the manufacturing process is chosen, it is required to confirm if the design needs to be modified to improve manufacturability. For AM, several software analyses are made, with specific software that enables the simulation of manufacturing strategy, which will allow cost reduction and quality increase and is manufacturing method dependent [41, 42, 93]. The production method and orientation of how the component is built in the AM equipment chamber influence the result of the component. An "optimal" build direction will affect how building supports are created during construction and who must be removed during post-processing, as shown in **Figure 8(a)**. Some components will be expensive or scraped if supports are in difficult or inaccessible places, as shown in **Figure 8(b)** [94].



(a) (b)

Figure 8.
Building orientation and supports required for components topologically optimized and produced through the FFF process (a) door handle [40] and (b) office stapler [38].

It is required to check different parameters, even component orientation in the building tray, to confirm that the component will not have overhangs, materials displacements, and non-conformities between what was designed and the outcome from manufacturing. Sometimes, geometry, size, and shape in specific areas are even required to improve the manufacturability. It is expected to simultaneously iterate design for function, performance, and manufacturability to improve outcomes [41, 42, 76]. When considering manufacturability, it is also required to define the post-processing operation, like trimming, blasting, heat treatment, and polishing, among others, which will increase the cost and lead time of the component; thus, this operation will increase the finishing of component, as also—many times—reduce the effective cost since it will minimize operation time in AM equipment [95].

Manufacturability also requires knowledge about the materials (availability and metallurgical properties) and equipment (different technologies, with other suppliers) since both will directly influence components' dimensional accuracy, surface roughness, and minimal building wall thickness and size [96]. It can now be realized that components that were developed through proper methods of DfAM, with a structural optimization technique that improves the material layout within a specified design space for a defined set of loads and boundary conditions, have high specific stiffness and strength through reducing (or eliminating) material wastage, which happens mainly due to AM's synergy with TO [64].

5. Benefits

As seen, DfAM is revolutionizing product development by offering unparalleled design freedom, customization capabilities, and efficiency gains. By harnessing the potential of DfAM, practitioners can unlock new avenues for innovation, streamline production processes, and achieve superior product performance. The main benefits are:

1. Design flexibility: DfAM is a cornerstone of design flexibility, enabling the creation of intricate, complex geometries unachievable by traditional manufacturing methods. This includes fabricating organic shapes, internal structures, and consolidated assemblies, empowering designers to explore unprecedented design possibilities [17, 56].

2. Lightweighting and material efficiency: DfAM allows for topology-optimized designs where the material is placed only where necessary, reducing weight without compromising strength [97, 98]. Using lattice structures and lightweight designs significantly reduces material usage, contributing to sustainability goals and cost-effectiveness [24, 99, 100].

3. Customization and personalization: AM enhances customization and personalization, allowing the production of custom, individualized components tailored to specific needs [2, 101]. This capability is particularly transformative in sectors like healthcare, where personalized medical implants can be manufactured based on a patient's unique anatomy [26, 92].

4. Rapid prototyping and iteration: DfAM accelerates rapid prototyping and iteration processes, enabling quick turnaround times for design iterations and

producing prototypes or small batches without the need for expensive tooling or setup changes [66, 86].

5. Simplification of assemblies: DfAM facilitates the integration of multiple components into a single piece, reducing the need for assembly, potentially improving product reliability, and reducing maintenance requirements. This approach is particularly advantageous in industries characterized by complex assemblies, such as aerospace and automotive [10, 102].

6. Waste minimization: DfAM minimizes material waste by using only the necessary amount of material required for the design, contrasting with subtractive manufacturing methods that often produce significant waste. This efficiency contributes to environmental sustainability by lowering energy consumption and minimizing environmental impact [37, 47].

7. Agile and on-demand manufacturing: DfAM supports agile and on-demand manufacturing, enabling production closer to the point of use. This capability is advantageous for producing spare components, reducing inventory costs, and promoting more agile supply chains [103–105].

8. Innovation and design optimization: Innovation and design optimization are intrinsic to DfAM, encouraging designers to push the boundaries of traditional design constraints and create new, improved, and more efficient products [39, 106].

9. Sustainability: DfAM's reduced waste, lighter designs, and on-demand production lower energy consumption and minimize environmental impact compared to traditional manufacturing processes [74, 107].

While DfAM offers numerous advantages, challenges such as certification, material properties, post-processing requirements, and cost considerations should be carefully evaluated during implementation to maximize its benefits.

6. Challenges and limitations

Practitioners can overcome the inherent limitations of DfAM by addressing issues such as design complexity, material selection constraints, post-processing requirements, cost considerations, and compliance with industry standards. Overcoming these challenges is crucial for unlocking the full potential of AM, enabling the creation of optimized, functional, and efficient designs that meet the evolving needs of diverse industries. The main challenges and limitations are:

1. Geometric constraints: One of the primary challenges in DfAM involves managing geometric constraints, particularly with overhangs and support structures. AM processes often require support for overhanging features, impacting surface finish, and necessitating additional post-processing efforts. Designers must strategically plan for self-supporting geometries to minimize or eliminate the need for support, optimizing production efficiency and final component quality [102, 106].

2. Surface finish: Achieving smooth, high-quality surface finishes remains a significant challenge in AM due to its layer-by-layer nature. Visible layer lines and resolution limitations can affect surface esthetics and functional performance. Effective post-processing techniques are essential to mitigate these issues. However, they add complexity to the manufacturing process and require careful integration into the initial design phase to ensure the desired outcomes [15, 108, 109].

3. Post-processing requirements: Post-processing in AM involves support removal, surface finishing, and heat treatment to achieve desired mechanical properties and surface finish. Integrating these requirements into the design phase is critical for streamlining production workflows and minimizing manual labor and equipment usage costs [15, 106].

4. Material constraints: The availability of materials suitable for AM processes varies, and not all materials are compatible with every AM technology. Designers may encounter limitations in material options or may need to compromise on material properties to align with the capabilities of a specific AM process. Balancing material selection with design requirements and performance expectations is essential for optimizing components' functionality and ensuring long-term durability and market availability [59].

5. Cost implications: While AM offers unique advantages, including design flexibility and rapid prototyping, its implementation can be cost-prohibitive compared to traditional manufacturing methods. Factors contributing to higher costs include equipment investment, material expenses, and skilled labor requirements. Managing these cost implications effectively is crucial for determining the feasibility and economic viability of adopting AM for specific applications [26, 110].

6. Complexity and design validation: Overly complex designs enabled by AM technologies often require rigorous validation processes to ensure structural integrity and performance reliability. Simulation tools and physical testing are essential for verifying design feasibility and identifying potential failure points. However, these validation processes add complexity and time to the design iteration cycle, requiring careful management of resources and expertise [11, 52, 102].

7. Regulatory and standards compliance: In aerospace, automotive, and healthcare industries, meeting stringent regulatory requirements and industry standards is imperative for certifying AM-produced components. Ensuring compliance with quality assurance protocols and safety standards poses significant challenges, influencing design considerations and manufacturing practices to achieve regulatory approval and market acceptance [49, 111].

8. Knowledge and expertise: Effectively utilizing AM technologies demands specialized knowledge and expertise across various disciplines, including materials science, engineering design, and manufacturing processes. The need for more qualified personnel and educational resources in DfAM presents a barrier to widespread adoption and implementation. Investing in training and development initiatives is essential for building a skilled workforce capable of leveraging AM's full potential in industrial applications [13, 48].

The challenges and limitations of DfAM require a systematic approach that integrates technical expertise, strategic planning, and continuous innovation. By addressing these obstacles proactively, stakeholders can capitalize on the transformative capabilities of AM, driving advancements in product design, manufacturing efficiency, and overall industry competitiveness.

7. DfAM in industrial applications

DfAM in industry offers a comprehensive exploration of the practical implementations and transformative potential of DfAM across diverse sectors. This section delves into detailed case studies and real-world applications, highlighting how DfAM principles have effectively addressed industry-specific challenges and achieved tangible outcomes. By examining these examples, valuable insights and lessons learned are elucidated, providing a deeper understanding of the impact and versatility of AM technologies in industrial settings. These case studies highlight the innovative solutions enabled by DfAM and inspire further advancements in integrating AM into mainstream industrial practices:

1. Automotive sector: DfAM has seen widespread adoption in the automotive industry, leveraging techniques such as L-PBF and EBM to streamline production processes. AM technologies have proven crucial by reducing component count, weight, and material waste while enhancing or maintaining performance standards. Key insights underscore the need for tailored metallic materials, optimized designs, and refined post-processing methods to exploit AM's benefits in mass production fully [92, 112, 113].

2. Medical sector: DfAM has revolutionized the production of patient-specific implants like cranial and orthopedic devices in healthcare. Metal AM methods such as EBM and DED enable precise customization to individual anatomies, significantly improving fit and patient outcomes. Critical considerations include precision engineering, biocompatible material selection, and strict adherence to regulatory standards, ensuring the success of personalized medical applications [6, 104, 114, 115].

3. Aeronautical industry: DfAM has made significant strides in aerospace by transforming the design and manufacturing of complex components such as fuel nozzles. Utilizing metal AM technologies like L-PBF, manufacturers consolidate multiple components into durable single-piece designs, optimizing internal geometries for enhanced efficiency. This highlights the pivotal role of design optimization in AM, reducing component counts and maximizing the creative freedom inherent in AM [98, 101, 112].

4. Aerospace industry: In space exploration, DfAM has enabled the production of lightweight, intricate structures that are impossible to achieve with traditional manufacturing methods. AM facilitates the creation of components with complex geometry and internal features, reducing overall weight without compromising strength or functionality, thereby advancing space missions' efficiency and reliability [48, 52, 53, 102].

5. Tooling/mold industry: DfAM has revolutionized tooling and mold production by enabling the creation of highly intricate, high-performance tools with shortened lead times. Techniques like FFF and BJT in metal AM technologies emphasize designing for functional performance, meticulous material selection, and effective post-processing strategies. This evolution supports the development of tools with advanced features, such as conformal cooling channels, enhancing molding processes' efficiency and product quality [39, 59, 108, 116].

6. Energy sector: In the energy industry, DfAM plays a pivotal role in optimizing the performance of components for renewable energy systems like wind turbines and solar panels. By fabricating complex geometries that improve efficiency and durability, AM technologies contribute to advancing sustainable energy solutions [50, 92, 112].

8. Materials innovation in DfAM

Materials play a crucial role in metal additive manufacturing (AM), where this technology revolutionizes material development and application by enabling the creation of components with exceptional properties such as high strength, heat resistance, and corrosion resistance. Innovations in various alloys cater to diverse industrial needs, redefining material innovation in metal manufacturing. Titanium alloys, such as Ti-6Al-4V, offer outstanding strength-to-weight ratios and are commonly used in aerospace and medical applications. Aluminum alloys like AlSi10Mg provide excellent thermal properties and are favored in the automotive and aerospace industries. Nickel-based superalloys, including Inconel 718, are known for their high-temperature performance and are essential in the aerospace and energy sectors. Specialized steels, such as maraging steel, provide high strength and toughness, making them suitable for tooling and high-performance engineering applications [49, 117, 118]. This evolution empowers practitioners to pioneer new material science frontiers using AM technologies' diverse capabilities, developing advanced alloys and composites that significantly enhance performance, functionality, and sustainability across various industries [119, 120].

Hybrid metal composites integrate different metals or blend with non-metallic materials, offering enhanced properties such as improved strength-to-weight ratios and specific thermal or electrical characteristics [121, 122]. These advancements expand applications from aerospace to electronics, underscoring AM's transformative impact in material science by enabling innovative components to meet stringent performance requirements across diverse industries.

Advancements in powder metallurgy techniques optimize metal powders' particle size distribution, flowability, and oxygen content, enhancing material performance and suitability for AM processes like L-PBF, EBM, DED, FFF, and BJT. These refinements are critical in achieving high-quality, reliable components through AM, supporting versatile applications across industries [118, 123–127].

AM's quick prototyping accelerates material development cycles, enabling rapid iteration and facilitating faster testing and validation of new alloys and composites. AM's design freedom pushes material composition and structure boundaries, fostering innovation to develop advanced materials optimized for specific processes and applications. Furthermore, AM facilitates multi-material printing, integrating multiple metals or alloys within a single print. Graded metal structures allow for tailored material properties through gradual transitions between different metals, while functional integration incorporates dissimilar metals to achieve complex geometries and multifunctional capabilities [122, 128–130].

AM materials exhibit specific properties crucial for achieving desired outcomes throughout the design process. Variations in layer adhesion and porosity impact printed components' strength and reliability. Understanding unique mechanical characteristics such as tensile strength, elasticity, and fatigue resistance ensures meeting performance requirements [92, 131, 132]. Critical thermal properties like heat resistance, thermal expansion, and conductivity are essential for high-temperature applications. Specific post-processing methods are necessary to achieve the desired surface finish and texture, impacting the final product's visual esthetics and functional integrity [67, 71, 133, 134]. These considerations underscore the complexity and importance of material selection and design optimization in AM applications.

9. DfAM software and tools

DfAM is a rapidly evolving field driven by advancements in software solutions tailored to AM workflows. These tools represent a significant progression in enabling designers to create more optimized and efficient designs suited for AM. Integrating advanced CAD software, precise simulation tools, and powerful TO techniques accelerates the evolution of DfAM [135, 136]. This integration facilitates the development of complex, high-performance, and sustainable products across various industries [52, 137].

The landscape of CAD software for DfAM has seen significant advancements. There is a noticeable shift toward solutions that cater specifically to the intricacies of AM. Software like Autodesk Fusion 360, SolidWorks, and Siemens NX offer specific modules for AM, including features like automated lattice generation and topology optimization. Specialized CAD tools facilitate more intuitive design processes that align with AM technologies' unique requirements and capabilities, integrating features with complex geometries and support from multiple materials. Specialized CAD tools facilitate more intuitive design processes that align with AM technologies' unique requirements and capabilities [39, 45].

Simulation tools have also advanced considerably, offering detailed simulations of the printing process. These tools allow designers to anticipate potential issues, optimize designs, and ensure the manufacturability of complex structures. By simulating the layer-by-layer building process, designers can identify and mitigate problems such as warping, residual stress, and support structure placement, leading to more reliable and high-quality AM components. For instance, software like ANSYS Additive Suite and Hexagon Simufact Additive provide comprehensive simulation environments that include thermal, mechanical, and microstructural analyses [59, 74, 138].

TO techniques have gained prominence in the DfAM toolkit, empowering designers to create intricate, lightweight, and highly functional designs. These techniques algorithmically determine the optimal distribution of material within a given design space. TO leverages the design freedom provided by AM to reduce material usage while maintaining or enhancing the structural integrity and performance of the component. This results in innovative designs that would be challenging or impossible to produce using traditional manufacturing methods [98, 139, 140].

By exploring advancements in CAD software, simulation tools, and TO techniques, we gain insights into the technological innovations driving the evolution of DfAM practices. Through critical analysis and evaluation of the capabilities and functionalities of these software tools, we can highlight their role in facilitating the design, optimization, and simulation of AM processes. This exploration underscores the importance of these tools in the ongoing evolution of DfAM and their potential to shape the future of manufacturing [141, 142].

10. Conclusions, future trends, and directions

DfAM empowers designers and engineers to harness the transformative potential of AM technology. Its ability to optimize designs for AM's inherent capabilities, such as geometric freedom, material efficiency, and functional integration, challenges the limitations of traditional manufacturing practices. DfAM drives innovation across diverse industries, enabling performance gains and novel product applications.

Future advancements in AM materials, software tools, design methodologies, and process control will further accelerate DfAM adoption. It is poised to become a cornerstone of modern, high-performance manufacturing, fundamentally reshaping how products are designed, produced, and utilized. This comprehensive approach to design and manufacturing represents the future of production, promising a world of products limited only by the bounds of our imagination.

Forecasts suggest a broader adoption of AM techniques across various industries, including aerospace, automotive, healthcare, and consumer goods, as companies recognize the potential for cost-effective, customized production. The trend toward on-demand manufacturing, reducing inventory, and enabling more localized and agile production will continue as AM capabilities improve.

Continued development of new materials tailored for AM, such as high-performance polymers, metal alloys, and composite materials, will expand the range of applications and improve material properties. Further advancements in multi-material and multi-color printing technologies will enable more complex and functional components, allowing graded structures and diverse functionalities within a single print.

Post-processing techniques and technologies will improve surface finish and structural integrity and integrate secondary processes within the AM workflow. Ongoing research will concentrate on developing sophisticated design software tailored explicitly for AM, focusing on optimizing and automating design processes to leverage the full potential of AM.

Integrating machine learning and AI in DfAM will assist in design optimization, material selection, and process control, further enhancing efficiency and innovation. Research will continue to advance in bioprinting for tissue engineering and regenerative medicine, aiming for complex, functional biological structures for medical use.

Research will also focus on sustainable material development, recycling techniques, and reducing waste, aligning with the principles of the circular economy. These future trends and directions highlight the potential of DfAM in reshaping the future of manufacturing, promising a world of products limited only by the bounds of our imagination.

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Conflict of interest

The authors declare no conflicts of interest.

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Abbreviations

AI	artificial intelligence
AM	additive manufacturing
BJT	binder jetting
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CT	Computer Tomography
DED	Direct Energy Deposition
DfAM	Design for Additive Manufacturing
EBM	Electron Beam Melting
FEA	Finite Element Analysis
FFF	Fused Filament Fabrication
L-PBF	Laser Powder Bed Fusion
OEM	Original Equipment Manufacturing
RE	reverse engineering
TO	topology optimization

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