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Review

Recent Inventions in Additive Manufacturing: Holistic Review

Ismail Fidan [1,*], Orkhan Huseynov [1], Mohammad Alshaikh Ali [1], Suhas Alkunte [1], Mithila Rajeshirke [1], Ankit Gupta [2], Seymur Hasanov [3], Khalid Tantawi [4], Evren Yasa [5,6], Oguzhan Yilmaz [7], Jennifer Loy [8], Vladimir Popov [9] and Ankit Sharma [10]

[1] Additive Manufacturing Research and Innovation Laboratory, Tennessee Tech University, Cookeville, TN 38505, USA; ohuseynov42@tntech.edu (O.H.); mbalshaikh42@tntech.edu (M.A.A.); ssalkunte42@tntech.edu (S.A.); mcrajeshir42@tntech.edu (M.R.)
[2] College of Engineering, Computer Science, and Technology, California State University, Los Angeles, CA 90032, USA; agupta26@calstatela.edu
[3] Harvard John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA; shasanov@seas.harvard.edu
[4] Department of Engineering Management and Technology, College of Engineering and Computer Science, University of Tennessee at Chattanooga, Chattanooga, TN 37403, USA; khalid-tantawi@utc.edu
[5] Advanced Manufacturing Research Centre, University of Sheffield, Sheffield S37AZ, UK; e.yasa@sheffield.ac.uk
[6] Department of Mechanical Engineering, Faculty of Engineering and Architecture, Eskisehir Osmangazi University, Eskişehir 26480, Türkiye
[7] Department of Mechanical Engineering, Faculty of Engineering, Gazi University, Ankara 06570, Türkiye; oguzhanyilmaz@gazi.edu.tr
[8] Department of Business Strategy and Innovation, Griffith University, Gold Coast, QLD 4215, Australia; j.loy@griffith.edu.au
[9] Department of Materials Science and Engineering, Tel Aviv University, Ramat Aviv, Tel Aviv 6997801, Israel; vpopov@tauex.tau.ac.il
[10] Chitkara University Institute of Engineering & Technology, Chitkara University, Rajpura 140401, India; ankit.sharma@chitkara.edu.in
* Correspondence: ifidan@tntech.edu; Tel.: +1-(931)-881-8436

Citation: Fidan, I.; Huseynov, O.; Ali, M.A.; Alkunte, S.; Rajeshirke, M.; Gupta, A.; Hasanov, S.; Tantawi, K.; Yasa, E.; Yilmaz, O.; et al. Recent Inventions in Additive Manufacturing: Holistic Review. *Inventions* **2023**, *8*, 103. https://doi.org/10.3390/inventions8040103

Academic Editor: Joshua M. Pearce

Received: 6 July 2023
Revised: 31 July 2023
Accepted: 1 August 2023
Published: 11 August 2023

Abstract: This general review paper presents a condensed view of recent inventions in the Additive Manufacturing (AM) field. It outlines factors affecting the development and commercialization of inventions via research collaboration and discusses breakthroughs in materials and AM technologies and their integration with emerging technologies. The paper explores the impact of AM across various sectors, including the aerospace, automotive, healthcare, food, and construction industries, since the 1970s. It also addresses challenges and future directions, such as hybrid manufacturing and bio-printing, along with socio-economic and environmental implications. This collaborative study provides a concise understanding of the latest inventions in AM, offering valuable insights for researchers, practitioners, and decision makers in diverse industries and institutions.

Keywords: additive manufacturing; invention; holistic review

1. Introduction

AM, also known as 3D Printing (3DP), has emerged as a transformative technology revolutionizing various industries including very demanding ones such as the aerospace and biomedical industries. This review paper presents an in-depth analysis of the latest inventions in AM, covering significant breakthroughs, novel techniques, and their potential implications across diverse sectors.

The paper begins by exploring the evolution of AM and its underlying principles, highlighting the latest developments in transitioning from prototyping applications to end-use production. It then delves into the advancements in materials and their compatibility with additive manufacturing processes, encompassing polymers, metals, ceramics, composites, and biocompatible materials. Moreover, the review investigates the development of multifunctional materials with improved mechanical, thermal, and electrical properties, along with advancements in material recycling and sustainability.

A crucial aspect of AM is the continuous enhancement of printing technologies and equipment. While this paper provides a generic overview of evolving AM techniques, it further explores the integration of these techniques with emerging technologies, such as robotics, artificial intelligence (AI), and automation, enabling new possibilities in design complexity, customization, and mass production.

In addition to material and technological advancements, the review discusses recent integrations of AM in key sectors, including the aerospace, automotive, healthcare, architecture, consumer products, and electronics sectors. It examines the growing impact of AM on supply chains, logistics, and inventory management, emphasizing the potential for localized production, reduced lead times, and increased product accessibility.

Furthermore, the paper addresses the challenges and limitations associated with AM, including issues related to part quality, post-processing, scaling, intellectual property (IP) management, and regulatory frameworks. It presents ongoing research efforts and initiatives aiming to overcome these obstacles and unlock the full potential of AM in industrial applications.

Lastly, the review paper explores the future directions and potential disruptive implications of AM. It highlights emerging trends, such as hybrid manufacturing, 4D printing, bio-printing, and nanoscale additive techniques, along with the socio-economic and environmental impacts that may arise from widespread adoption.

Overall, this holistic review provides a comprehensive and up-to-date understanding of the latest inventions in the field. It offers valuable insights for researchers, practitioners, and decision makers, contributing to the advancement of this transformative technology and its integration into diverse industries.

2. The Innovation Cycle

In today's fast-paced and competitive business landscape, innovation plays a pivotal role in the growth and sustainability of AM [1,2]. Since the introduction of the Bayh–Dole Act [3], which allows universities to obtain patent and grant licenses, the commercialization of university research in the USA between late 1980s and early 2000s has accelerated. This facilitated greater technology transfer and cooperation between research and industry [4]. However, according to the Wohlers Report 2023, there is still a distinct contrast in the distribution of issued patents in the field of AM. The data reveal that universities account for a mere 7% of the issued patents, while an overwhelming majority of 83% are attributed to companies [5]. This statistic emphasizes the prominent role played by companies in driving innovation and securing patent protection within the AM industry [5]. Similarly, according to Park et al., there has been a noticeable decline in the level of innovation in science and technology in universities [6]. The research group identifies several reasons for this decline and highlights that ideas too frequently remain in the research phase without progressing to commercialization. It is crucial to thoroughly examine the different components of the innovation cycle and classify inventions accordingly. The innovation cycle serves as a structured approach that enables the transformation of ideas into tangible and marketable products or services. By understanding and differentiating the various stages of the cycle, it is possible to identify bottlenecks and implement strategies for enhancing the successful transition of inventions from research to commercialization. The following section aims to elucidate the key components of the innovation cycle and their significance in achieving successful commercialization outcomes in the AM context. Figure 1 presents a visual representation of the innovation cycle, illustrating the sequential progression of stages from research and disclosure to revenue generation. The cycle is divided into three overarching headings: disclosure of an invention, IP, and commercializing an invention.

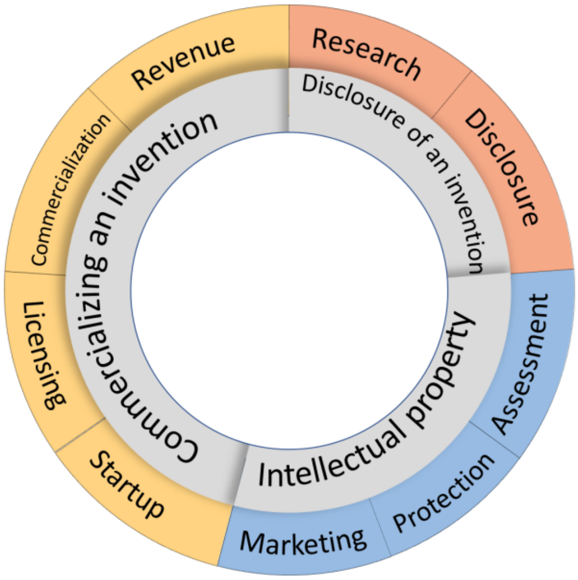


Figure 1. The Innovation Cycle: A Holistic Framework.

2.1. Disclosure of an Invention

The disclosure of an invention represents a critical phase in the innovation cycle, where inventors unveil their groundbreaking ideas to relevant stakeholders and begin the process of transforming them into tangible assets. Through disclosure, inventors share comprehensive information about their invention, including its technical specifications, unique features, and potential applications, facilitating collaboration and knowledge exchange within the innovation ecosystem. This step serves as a platform for inventors to establish ownership and legal rights over their invention, providing a clear record of their original idea and establishing a priority date, particularly in the realm of IP protection.

Research: The innovation cycle commences with the research stage, where extensive exploration and investigation are conducted to identify novel ideas and inventiveness. This stage involves rigorous literature reviews, experimentation, and ideation processes for generating inventive concepts. In the field of AM, research conducted in universities globally often places a significant emphasis on materials, processes, and quality characteristics. This emphasis stems from the origins of AM research within the engineering disciplines. However, it is worth noting that the focus on those topics may sometimes restrict attention to the broader aspects of AM, such as its applications and potential business models.

Disclosure: Following the research phase, the inventor discloses the details of the invention, thereby sharing it with relevant stakeholders and authorities. This transparent communication fosters collaboration and lays the foundation for subsequent evaluation and protection steps. In the AM research community, there is a division between events for academic and industry dissemination, with industry conferences, such as RAPID + TCT in the US [7] and Formnext—Hub for Additive Manufacturing in Europe [8], providing valuable collaboration opportunities.

2.2. Intellectual Property

The term IP refers to the legal rights and protections granted to individuals or organizations for their creations or inventions. It encompasses intangible assets, such as ideas, inventions, designs, brands, artistic works, and trade secrets. The field of IP law aims to safeguard these creations and provide exclusive rights to their creators, encouraging innovation, creativity, and economic growth. IP plays a crucial role in fostering innovation and providing incentives for individuals and organizations to invest time, resources, and expertise in creating new ideas and inventions. This is critical for AM as an emerging field. It rewards innovators by granting them exclusive rights and the ability to control and benefit from their creations. IP protection promotes a competitive marketplace and encourages the dissemination of knowledge, contributing to technological advancements and societal progress [9]. There are several forms of IP rights, each tailored to protect specific types of creations, as described in Table 1. The table provides a concise summary and comparison of various IP types, including their descriptions, protection periods, and examples.

Table 1. Different types of IP.

IP Type	Description	Protection Period	Applications	Examples from AM
Patents	Protects new and useful inventions, providing exclusive rights to the inventor	Typically, 20 years from the filing date [10]	Novel technology, processes, or products	Stratasys expiry of patent US6722872B1Proprietary heated build chamber 2021. [11]
Copyright	Protects original creative works, such as literary, artistic, or musical creations	Author's lifetime + 70 years [12]	Books, software	Things Fall Together: A guide to the new materials, Skylar Tibbets 15 June 2021—copyright valid until 15 June 2091. [13]
Trademarks	Protects brands, logos, or symbols that distinguish goods or services in the marketplace	Renewable indefinitely as long as it is in use and maintained [14]	Company logos, product names	EOS logo trademarked its logo for use in the UK via application UK00918108117 on 07 March 2019 and is due for renewal in 2029. [15]
Trade Secrets	Protects confidential business information that is not publicly disclosed	Potentially indefinite as long as the information remains secret [16]	Formulas, manufacturing processes	The protection of IP within the AM sector is a significant issue—for example, Desktop Metal highlights the costs involved in the protection and enforcement of their IP. [17]
Industrial Designs	Protects aesthetic or visual aspects of a product's shape, pattern, or ornamentation	15-year term of protection measured from the date of grant [18]	Product designs	Product Artists, such as Lionel Dean, produce unique designs via new ways of working with AM recognized by museums and galleries around the world. [19]

Assessment: Upon disclosure, the invention undergoes a comprehensive assessment evaluating its feasibility, market potential, and technical viability. This assessment stage entails scrutinizing the invention's commercialization prospects, aligning it with market demands, and conducting a thorough cost–benefit analysis. One of the challenges for AM is that the technology enables digital business innovations that are difficult to assess using conventional comparisons and represent the most difficult shift in practice when integrating the technology into business [20]. The disruptions to business models that AM creates can inhibit the uptake of investment opportunities in AM inventions or create uncertainty in pathways to commercialization.

Protection: To safeguard the IP associated with the invention, appropriate protection measures are employed. These may include patenting, copyrighting, trademarking, ensuring exclusive rights, and preventing unauthorized use or replication. Over the past three years, the number of patent applications in the field of AM has exhibited a consistent pattern, hovering around 8000. Approximately 60% of these applications have resulted in issued patents. It is noteworthy that there has been a notable shift in this trend in recent years, which could potentially be correlated with the impact of the pandemic. The cautious approach adopted by companies during this period may have influenced their reluctance to invest extensively in research and development (R&D) activities. Figure 2 below provides a visual representation of the patent application and issued patent data received from the U.S. Patent and Trademark Office [5].

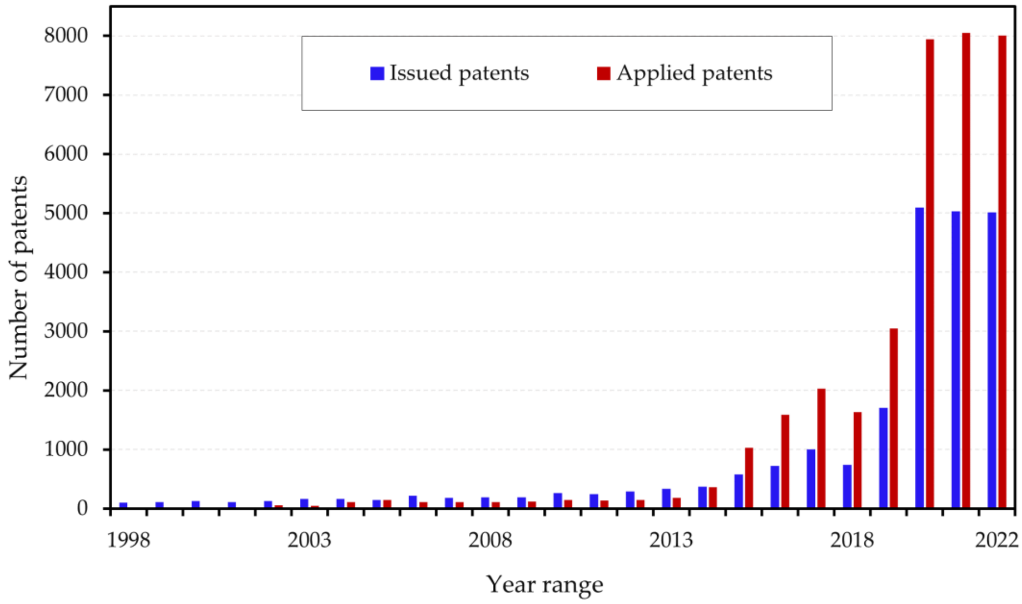


Figure 2. Statistics of patents for AM. Data Source: Wohlers Report 2023 [5].

Marketing: With the invention's protection secured, strategic marketing efforts are initiated. These encompass devising compelling marketing strategies, conducting market research, creating brand awareness, and identifying potential customers or investors.

2.3. Commercializing an Invention

Commercializing an invention refers to the process of transforming an innovative idea or invention into a marketable product, service, or technology. It involves a series of strategic steps aimed at maximizing the commercial potential of the invention and bringing it to the target market. Commercialization is a crucial stage in the innovation cycle, as it bridges the gap between invention and tangible value creation. Commercializing an invention begins with developing a comprehensive go-to-market strategy. This entails identifying the target market segments, understanding customer needs and preferences, and determining the most effective channels for product distribution and promotion. A well-defined strategy helps align the invention with market demands and enables inventors to position their product effectively. For AM, there is an additional complexity in defining a business strategy for exploiting the opportunities that inventions provide, as many AM inventions require very different ways of operating in business [21].

Startup: The startup phase marks the actual establishment of a new venture or company dedicated to bringing the invention to market. It involves securing funding, assembling a competent team, developing business plans, and setting up operational frameworks. Based on the findings of the Wohlers Report 2023, the AM industry comprises a total of 2501 startups. The majority of these startups, accounting for 55%, are situated in Europe, while 21% are located in Asia and 19% are in North America. The report also highlights that the concentration of startups primarily revolves around applications, with hardware being the subsequent focus, as depicted in Figure 3 [5].

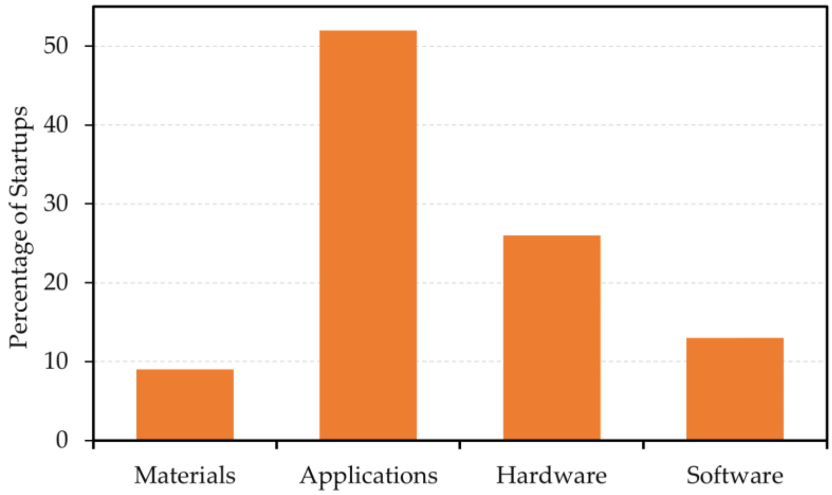


Figure 3. Share of startups by sector. Data Source: Wohlers Report 2023 [5].

Licensing: In some cases, inventors opt to license their inventions to other entities for further development, production, or distribution. Licensing facilitates a wider reach, the diversification of revenue streams, and collaborations with established market players. An example specifically enabled by AM is the licensing of spare parts based on creating and managing a digital inventory [22].

Commercialization: This stage involves executing the go-to-market strategies and launching the invention in the intended market. It includes production, distribution, customer acquisition, and adoption efforts aimed at maximizing market penetration and sales. Again, for AM, this involves creating business opportunities for the use of inventions that may not previously exist, or which may need to be serviced differently, therefore requiring new business models. Their commercial value for a company may also be less direct—for example, 3DP of building components as a sustainable practice strategy [23].

Revenue: Finally, the successful commercialization of the invention culminates in revenue generation. This can be achieved through direct sales, licensing agreements, royalties, or other monetization models, providing the inventor and stakeholders with a return on their investments.

2.4. Historical Progression of AM Inventions

AM technology emerged in the late 1970s and has experienced substantial growth and utilization across various academic disciplines since then. Numerous patents and applications have been filed for different AM techniques, contributing to the advancement of this field, as shown in Figure 4. The inception of AM technology can be traced back to 1977 when Wyn Kelly Swainson patented a technique that utilized a laser directed onto a tray submerged in liquid plastic, resulting in the fusion of a layer of solid plastic [24]. In 1981, when Dr. Hideo Kodama introduced the concept of AM, Dr. Kodama filed patents for a method that involved fabricating three-dimensional plastic models using photopolymerization, which laid the foundation for Stereolithography [25].

In 1986, Chuck Hull's invention of Stereolithography further propelled the field of AM [26]. Stereolithography employed the process of the photopolymerization of UV-curable materials to create 3D objects layer by layer, eventually leading to the establishment of the 3D Systems Corporation. Another noteworthy addition to the AM field was Selective Laser Sintering (SLS), invented by Carl Deckard and Joe Beaman in 1992 [27]. SLS utilized a laser beam to fuse powdered materials, enabling the creation of complex solid objects. This technology emerged as a prominent AM technique [28]. The widespread proliferation of AM began when 3D printers became commercially available in the late 1990s.

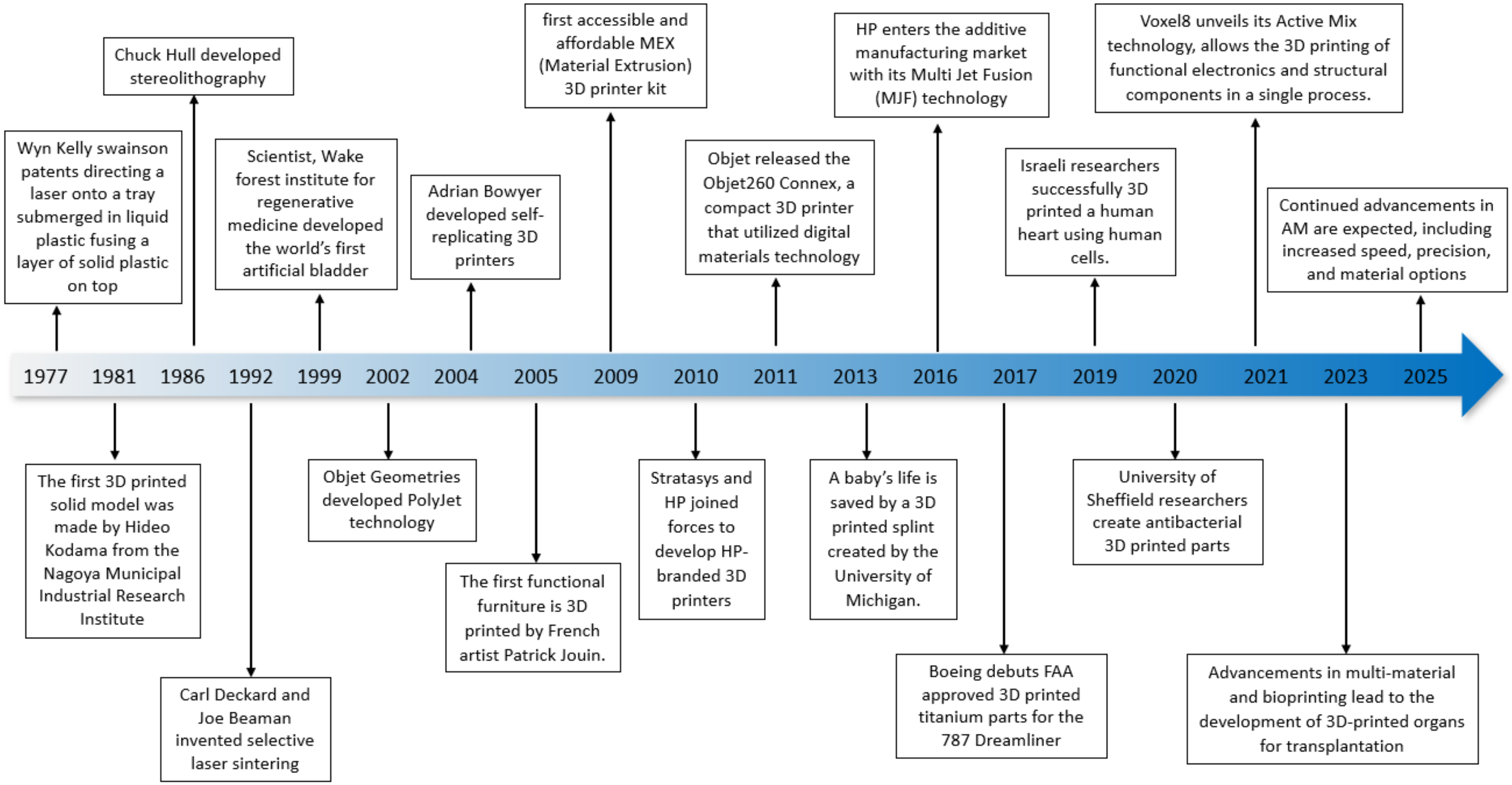


Figure 4. Historical Progression of AM Inventions from the 1970s to ~2025.

In 1999, scientists at the Wake Forest Institute for Regenerative Medicine successfully developed an artificial bladder [29], which had a significant impact on the field of tissue engineering. Subsequently, in 2002, Objet Geometries [30], developed PolyJet technology, utilized inkjet printing to fabricate high-resolution 3D models by jetting photopolymer materials that were cured with UV light. During this time, AM gained significant traction, and in 2004, Adrian Bowyer introduced the RepRap project—an open-source initiative focused on developing self-replicating 3D printers [31]. This project played a crucial role in driving the democratization of AM.

The evolution of AM technology has witnessed notable milestones and contributions from various inventors and researchers. In 2005, French Designer Patrick Jouin achieved a significant breakthrough by additively manufacturing the first functional piece of furniture [32]. Subsequent advancements took place in 2009; a groundbreaking development took place in the world of 3DP with the release of the BfB RapMan printer [33]. This innovative device marked the introduction of the first accessible and affordable MEX (Material Extrusion) 3D printer kit [34]. In 2010, Stratasys and HP joined forces to develop HP-branded 3D printers, and Stratasys also unveiled the uPrint Plus with an increased build volume and SMART Supports technology that reduced support material usage [35]. This printer offered affordable access to high-resolution printing. In 2011, Objet released the Objet260 Connex, a compact 3D printer that utilized digital materials technology [36]. This innovative printer allowed users to print objects using multiple materials simultaneously, providing enhanced capabilities for creating intricate and diverse models, introducing a new dimension to technology. In 2013, the University of Michigan made a significant breakthrough in the field by manufacturing a 3D-printed splint that saved a baby's life [37]. The medical application of AM gained recognition and showcased its potential for improving patient care. In 2016, market leader HP entered the AM market with its Multi Jet Fusion (MJF) technology, offering faster printing speeds and improved material properties [38]. Morris Technologies, founded in 1994, pioneered direct metal laser sintering (DMLS) technology, Concept Laser, established in 2000, advanced direct metal laser melting (DMLM) technology, and Arcam GE, founded in 1997 and acquired by GE in 2016, specialized in electron beam melting (EBM) technology, and all three companies have made significant contributions to the field of metal AM, leading to the advancement and adoption of industrial-grade 3DP in various industries [39].

In 2017, Boeing, a prominent aerospace manufacturer, made a notable advancement by introducing FAA-approved additively manufactured titanium parts for the Boeing 787 Dreamliner [40], further validating the capabilities of AM in the aerospace industry. In the year 2019, Israeli researchers and scientists achieved a significant milestone by successfully 3D printing a miniature human heart using human cells [41]. This groundbreaking accomplishment generated new optimism for the potential development of a fully functional additively manufactured heart that could potentially be used for human transplantation. Later, the innovation showcased in 2020 by the University of Sheffield researchers signified a substantial advancement: 3D-printed parts capable of killing common bacteria [42]. Their achievement in manufacturing 3D-printed parts with the capacity to combat common bacteria holds promise for improving hygiene standards and contributing to the development of more bacteria-resistant materials in various industries. The coupling of AM with semiconductor manufacturing was showcased by Voxel8 in 2021 when they introduced their Active Mix technology [43], allowing for the simultaneous 3DP of functional electronics and structural components in a single process. Advancements in multi-material and bioprinting technologies in 2023 have led to breakthroughs in tissue engineering and the development of 3D-printed organs for transplantation [44]. These achievements have significantly expanded the possibilities and potential of AM in the field of healthcare. Looking ahead, it is projected that AM will continue to advance in the coming years with a steep pace, with anticipated improvements in productivity, reliability, precision, and material options. Industries such as aerospace, healthcare, and automotive are expected to witness expanded applications of AM technology. The vision for 2025 entails continued progress and innovation in the AM field, fostering its integration into various sectors and driving further growth in the field [45].

3. Recent Inventions in AM Processes

In recent years, AM has witnessed significant advances in terms of technology, materials, and applications. This section reviews recent AM technology inventions that have the potential to revolutionize the field of AM and beyond.

The following trends in beam-based AM development are considered as break-through innovations:

High-Speed Sintering (HSS): HSS is a powder bed fusion (PBF) technology that uses infrared heating to selectively sinter polymer powders. It enables faster production speeds and has the potential for the large-scale manufacturing of functional polymer parts. Loughborough University has pioneered and patented the innovative HSS technology, which revolutionizes the 3DP process by enabling the cost-effective, high-volume production of intricate and customizable parts [46]. HSS competes favorably with injection molding in terms of economic feasibility. Various industries, such as the aerospace, automotive, consumer goods, healthcare, and medical industries, have embraced HSS within their end-product supply chains [47–49]. Moreover, an increasing number of global brands have embraced HSS as their preferred method for product creation.

Continuous Liquid Interface Production (CLIP): CLIP is a resin-based 3DP technology based on the original SLA/DLP process, which uses light and oxygen to selectively cure a liquid resin into solid parts continuously. It offers fast printing speeds and can produce parts with smooth surface finishes [50].

Laser Powder Bed Fusion (L-PBF) Enhancements: L-PBF, a widely used metal AM technique, has seen advancements in process monitoring and control such as melt pool monitoring, optical tomography or layer deposition/scanning monitoring, multi-laser processing technology, and new materials. These innovations have led to improved part quality, reduced porosity, enhanced mechanical properties, and increased production efficiency [51,52].

Directed Energy Deposition (DED) with wire and powder feedstock: DED techniques have been expanded to include the use of powder feedstock in addition to wire feedstock. This allows for the deposition of a wider range of materials, including metals, ceramics, and composites, enabling greater design flexibility and the production of large-scale parts. Moreover, hybrid manufacturing combining subtractive and DED AM technologies has provided unique opportunities such as an improved surface quality and dimensional accuracy in internal features of large AM components [53].

Multi-Material and Functionally Graded AM: Advances have been made in the development of AM techniques capable of printing multi-material and functionally graded structures. These technologies allow for the incorporation of different materials or variations in material properties within a single printed part, expanding the range of applications and enabling complex designs [54].

3.1. Multi-Material AM

Advances in multi-material AM technologies have allowed for the simultaneous deposition of different materials, enabling the creation of complex objects with varying mechanical, electrical, and optical properties. Multi-material AM has broad applications in fields such as the healthcare, electronics, and aerospace fields [55,56]. A voxel level is the smallest unit of a three-dimensional digital model, analogous to a pixel in a two-dimensional image. By controlling the material composition and properties of each voxel, AM can create objects with unprecedented complexity and functionality. A team of researchers from MIT developed a multi-material AM system that can print with up to eight different materials at a resolution of 50 μm per voxel [57]. The system uses an array of micro-nozzles to deposit droplets of photopolymer resin onto a moving platform, which are then cured by ultraviolet light. This technique can create objects with varying stiffness, transparency, color, and conductivity within a single print.

Multi-material AM holds significant potential and addresses the growing need for functional product design [58]. Traditional manufacturing techniques often face limitations in producing complex, customized designs that require multiple materials with distinct properties. However, with multi-material AM, designers can overcome these constraints and create functional products with enhanced performance and versatility [59]. By seamlessly integrating different materials within a single print, varied functionalities can be incorporated, such as mechanical strength, electrical conductivity, flexibility, and transparency, into their designs. This capability opens up new possibilities for industries ranging from aerospace and automotive to electronics and all Internet of Things (IoT) markets. Moreover, multi-material AM enables the optimization of material usage, reducing waste and cost while increasing design efficiency. As industries strive for greater innovation, customization, and performance, the demand for multi-material AM continues to grow, highlighting its immense potential for driving advancements in functional product design [60].

One of the modern examples of successful multi-material AM is Nano Dimension technology [61]. Nano Dimension is a company that specializes in the development of AM solutions for the production of electronic devices. Their technology, known as DragonFly, enables the 3DP of functional electronic circuits and components, including multi-layer PCBs (Printed Circuit Boards) and other intricate electronic structures. The DragonFly system combines the inkjet deposition of conductive and dielectric inks with a precise layer-by-layer printing process. It allows for the creation of complex, high-resolution electronic designs, including prototypes, custom circuitry, and small-scale production runs. Multi-material AM offers advantages such as rapid prototyping, design flexibility, and the ability to embed electronic components directly into 3D-printed structures. The applications of Nano Dimension's 3DP technology include research and development, aerospace, defense, automotive, and various other industries that require advanced electronics manufacturing capabilities.

Nano Dimension's DragonFly system enables multi-material printing by combining different types of inks. The specific combination of materials used depends on the desired application and the requirements of the printed electronic circuit or component. Here are some examples of materials that can be used in multi-material printing with the DragonFly system [62]:

Conductive inks: These inks are used to print conductive traces, pads, and interconnects. They typically contain metallic particles such as silver or copper that provide electrical conductivity.

Dielectric inks: Dielectric inks are used to create insulating layers and barriers between conductive elements. These inks have high electrical resistance and are crucial for isolating different circuit components.

Insulating inks: Insulating inks are used to create non-conductive structures, such as mechanical support or protective enclosures. They provide structural integrity to the printed object.

Functional inks: In addition to conductive and dielectric inks, functional inks can be used to incorporate specific properties into printed electronics. For example, magnetic or optical inks can be employed to add functionalities like sensors or antennas.

It is important to note that Nano Dimension's technology allows for the combination of various materials, enabling the creation of complex multi-layered electronic circuits with different functionalities and characteristics. The specific combination of materials depends on the desired design and functionality of the printed electronic device.

There have already been several papers published researching the potential of the Nano Dimension solution for various functional 3DP. For example, the work of Yang et al. [63] highlights the utilization of this solution based on piezoelectric additive fabrication for the production of single-substrate multi-metal-layer antennas. By vertically stacking metal layers in a 3D-printed single substrate, the designed antennas demonstrate wide bandwidth and ultra-low-profile advantages. The study includes the design, fabrication, and measurement of multi-layer linear polarization (LP) patch antenna elements and LP antenna arrays. The results show that the proposed LP patch antenna improves the impedance bandwidth significantly compared to traditional single-layer LP patch antennas. Additionally, the integration of the feeding network into the same substrate without increasing the size or profile of the array is demonstrated. Circular polarization (CP) patch antennas and CP antenna arrays are also fabricated and measured, showcasing wider impedance bandwidth and a broader frequency range. These antennas, designed for sub-6 GHz frequencies, exhibit great potential for applications in 5G consumer mobile electronics, combining an ultra-low profile and wideband capabilities. Sokol et al. [64] explore the use of AM technology for designing and producing planar capacitors as part of electronic circuit boards. The capacitors are constructed as pairs of conductive plates with varying geometries and layers, allowing for a wide range of capacitance values, from picofarads to nanofarads. The performance of these additively manufactured capacitors is shown to surpass that of commercially available surface mount device (SMD) capacitors by up to 20 GHz. They exhibit high breakdown voltages exceeding 1 kV and minimal leakage currents in the subpicoampere range. Additionally, the change in the RF impedance with the frequency is significantly smaller compared to that of SMD capacitors, with a reduction of three times. This demonstrates the superior performance and potential of Nano Dimension's AM technology for producing high-quality, high-performance capacitors for electronic applications.

3.2. Beam-Based Metal AM

Beam-based metal AM processes have gained significant recognition in various industries due to their immense potential. However, achieving the full industrialization of these processes still requires further efforts. To promote the industrialization of metal AM, numerous companies, research centers, and universities have been investing in comprehensive research and development activities [65].

This part focuses on the progress of metal AM technologies by examining patents. Using the Orbit Intelligence database, a search was conducted specifically for beam-based metal AM patents. The analysis began by studying the number of patents per year, revealing a substantial growth in AM patenting activities, as anticipated. Further examination of the patents aimed to identify the key players in the field. It was discovered that multidisciplinary companies, AM machine producers, end users (especially in the aerospace sector), universities, and research centers were the main contributors to this market [66].

In beam-based AM, there are several approaches for producing innovative multi-material and graded structures. The first approach to producing functionally, structurally, and compositionally graded structures in PBF was proposed via using blended powders. The application of such powder blends together with smart scanning strategies results in the possibility of producing graded microstructures. For example, Lakhdar et al. produced materials like Damascus steel with a ductile core and abrasive surface using such approach [67].

The Aerosint company, established in 2016, proposed another novel technology known as "Selective Powder Deposition" (SPD). This innovative approach enables the targeted deposition of multiple powders to form a single layer comprising two or more distinct materials. In contrast to conventional powder bed processes that utilize single-material rollers or blade recoaters, Aerosint's SPD presents an alternative solution. The applicability of this technology extends to various AM techniques, including L-PBF, Binder Jetting, and Pressure Assisted Sintering. By offering a versatile solution for selective powder deposition, Aerosint's SPD technology has the potential to enhance the capabilities and expand the possibilities of these AM processes. This innovative approach enables the selective deposition of multiple materials within a single layer of a 3D-printed object. Unlike traditional multi-material 3DP methods that typically rely on the mixing or sequential deposition of materials, Aerosint's technology allows for the precise and simultaneous deposition of different materials in a single layer. The Aerosint technology utilizes a specialized recoating system that can selectively deposit a range of powders onto the build platform. By controlling the deposition process, different materials can be placed in specific areas or patterns within a layer, enabling the creation of complex multi-material structures. This capability leads to new possibilities for designing and fabricating functional parts with graded material properties, localized variations, or the integration of dissimilar materials. By enabling the combination of multiple materials in a single AM process, it offers the ability of incorporating functionalities such as conductivity, strength, flexibility, or corrosion resistance within a single part.

3.3. Stereolithography and Microwave Sintering

One groundbreaking invention in AM is the fusion of stereolithography and microwave sintering. By using stereolithography to 3D-print objects with powdered materials and subsequently subjecting them to microwave sintering, this innovation enables the creation of complex and accurate objects with a reduced processing time. The combination of these techniques allows for the rapid consolidation and densification of the printed parts while offering a wide range of material options. This advancement expands the capabilities of AM, revolutionizing the production of intricate, functional, and diverse objects [68].

As one of the inventions in this area, the following example can be provided: Continuous Liquid Interface Production (CLIP). CLIP is a resin-based 3DP technology that uses light and oxygen to selectively cure a liquid resin into solid parts continuously. CLIP is an exclusive 3DP technique that was patented in 2014 by Carbon3D, formerly known as EiPi Systems [69]. Falling within the category of vat polymerization, CLIP shares similarities with the older stereolithography (SLA) and digital light processing (DLP) methods. Another term used to describe CLIP is digital light synthesis (DLS), both denoting the same innovative approach to 3DP.

In CLIP, a liquid photopolymer resin is selectively exposed to ultraviolet (UV) light, causing it to solidify and form parts. Although it may resemble SLA and DLP, CLIP distinguishes itself as a continuous process that eliminates the discrete steps of earlier printing methods. The breakthrough of CLIP lies in its implementation of an oxygen-permeable membrane, which creates a zone beneath the part known as a "persistent liquid interface". This interface allows for uninterrupted curing as the part is progressively drawn out of the resin. Instead of using a layer-by-layer approach, CLIP employs a digital projector and microcontrollers to project a dynamically changing image of the 3D model, streamlining the printing process into a layer-less design.

CLIP offers several advantages over other printing methods:

- Remarkable speed: CLIP prints achieve the same accuracy and surface quality as DLP/SLA prints but are completed 100 times faster.
- Superior surface finish: The layer-less nature of CLIP prints enhances their surface quality, making them comparable to parts produced through injection molding.
- Exceptional properties: CLIP parts are watertight and fully isotropic (exhibiting equal strength in all orientations) and possess increased strength compared to SLA/DLP prints.
- Versatility for prototyping and production: CLIP parts can be used for functional prototyping and are even suitable for full production runs.
- Structural integrity: This is CLIP's ability to easily integrate variable cell structures within a single part to produce different performance characteristics.
- Versality: CLIP/DLS printers offer a wide range of material options that are distinct from many other printer types.

This demonstrates that even the oldest and most well-known SLA technology still has potential for further inventions and development.

3.4. Bioprinting and Tissue Engineering

This subsection focuses on the concept of 3D bioprinting, a specific branch of AM that can be defined as the production of complex biological constructs using living cells, biomolecules, and biomaterials. Similar to inkjet-based 3DP methods, 3D bioprinting is also developed based on 2D inkjet printers by replacing ink in the cartridge with biological material (bioinks) and paper with biodegradable support material. Currently, only a few 3DP methods (MEX, inkjet printing, and laser printing) are suitable for bioprinting technology.

Bioprinting is an AM technique that uses living cells as the building blocks to create tissue-like structures for biomedical applications. Tissue engineering is a field that aims to create functional tissues and organs for transplantation or drug testing. A team of researchers from Rice University developed a bio-AM technique that integrates bioprinting and tissue engineering [65]. The technique uses a bio-ink composed of stem cells, blood vessels, and hydrogel to print vascularized tissue constructs. The technique can create tissue constructs with complex shapes and sizes, such as bone, cartilage, skin, and livers [70–72].

3D bioprinting is a promising research direction and is highly relevant in terms of economic efficiency. According to the Grand View Research report, the 3D bioprinting market was valued at USD 1.4 billion in 2020, and it is expected to grow at a compound annual growth rate of 15.8% from 2021 to 2028 [73]. By 2024, the 3D bioprinting market is projected to account for approximately 10% of the total 3DP market. Furthermore, the global tissue engineering market was valued at USD 2 billion in 2019 and is expected to reach USD 7 billion by 2027 [73].

It is worth noting that scaffold-based approaches, which involve framework-like beam structures, still face some challenges such as difficulties in uniform cell seeding, limited vascularization, and weak cell adhesion to the scaffold material. Therefore, living cells themselves or in combination with bioactive molecules and biomaterials need to be incorporated into a 3D scaffold for successful tissue or organ engineering [74].

The further expansion of 3D bioprinting finds its justification in the demand within medical sectors such as cosmetics and pharmaceuticals. The high demand for organ transplantation and the shortage of available organs are key factors driving the development of 3D bioprinting strategies aimed at reducing waiting times, the need for immunosuppression, and donor organ compatibility. This demand is expected to increase due to the large population of individuals over the age of 60 worldwide, who have a lower level of immunity and are more prone to accidents [75].

3.5. Two-Photon Polymerization

Two-photon polymerization (TPP) in AM has found diverse applications in various fields. For instance, in microelectronics, TPP enables the creation of complex microstructures such as photonic crystals and microelectromechanical systems (MEMS). These structures have unique optical and mechanical properties, making them valuable in miniaturized devices and sensors. In optics, TPP has been utilized to fabricate high-quality micro-optical components like lenses, waveguides, and diffraction gratings. These components exhibit precise control over light propagation and find applications in optical communications and imaging systems.

In the field of tissue engineering, TPP has enabled the production of intricate scaffolds with tailored architectures, which can support the growth and organization of cells for regenerative medicine applications. Additionally, TPP has been applied in microfluidics to create microchannels, valves, and pumps, enabling the precise manipulation and control of fluids at the microscale. The versatility of two-photon polymerization has led to its exploration and adoption in numerous fields, where the ability to fabricate complex, high-resolution micro- and nanostructures is crucial for advanced applications [76].

3.6. Hybrid Technologies

The concept of hybrid AM originated from the recognition that combining traditional subtractive manufacturing with AM could overcome the limitations of both processes, offering a novel approach for mass-producing medium- to large-sized components with high geometric complexity and accuracy. Lately, there have been a high number of hybrid AM practices cited; a few of them are presented below:

- Steel-based materials have witnessed significant advancements through PBF and directed energy deposition (DED) techniques, with notable efforts made to produce steel-based hybrid and composite materials using PBF methods [77].
- The integration of DED techniques with traditional computer numerical control (CNC) machining processes offers enhanced flexibility, enabling applications in hybrid manufacturing, protective coatings, and parts repair.
- Laser-based PBF enables hybrid AM, where a simple-shaped substrate component is conventionally manufactured, while a complex-shaped part is directly printed onto it, e.g., the build of the part with conformal cooling onto an existing bulk mold.

There have been recent advancements in hybrid AM technologies, where two or more manufacturing techniques are combined to fabricate 3D objects. One such hybrid AM method combines additive processes with subtractive methods such as milling or machining (see Figure 5). This approach enables the efficient fabrication of complex parts by leveraging the advantages of both additive and subtractive technologies. As a result, production is accelerated, and surface finishes are improved [78].

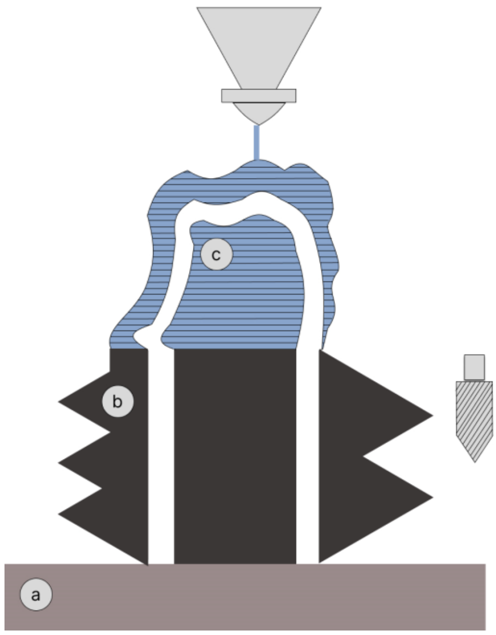


Figure 5. Schematic view of hybrid manufacturing, where (**a**) stands for the building platform, (**b**) stands for the machined part, and (**c**) stands for the printed part with complex inner cooling.

Figure 6 shows the microstructure of the hybrid AM part where the bottom wrought part was produced via subtractive manufacturing from H13 steel, and the top part was additively manufactured from MAR C300 steel using the L-PBF process. In Table 2, one can observe the diffusion of these steels from one to another and the corresponding change in the chemical composition in the interface zone. The relatively deep diffusion and blending of the initial chemical compositions of the steels result in an increased strength of the interface and, in general, an increased strength of the hybrid component [79].

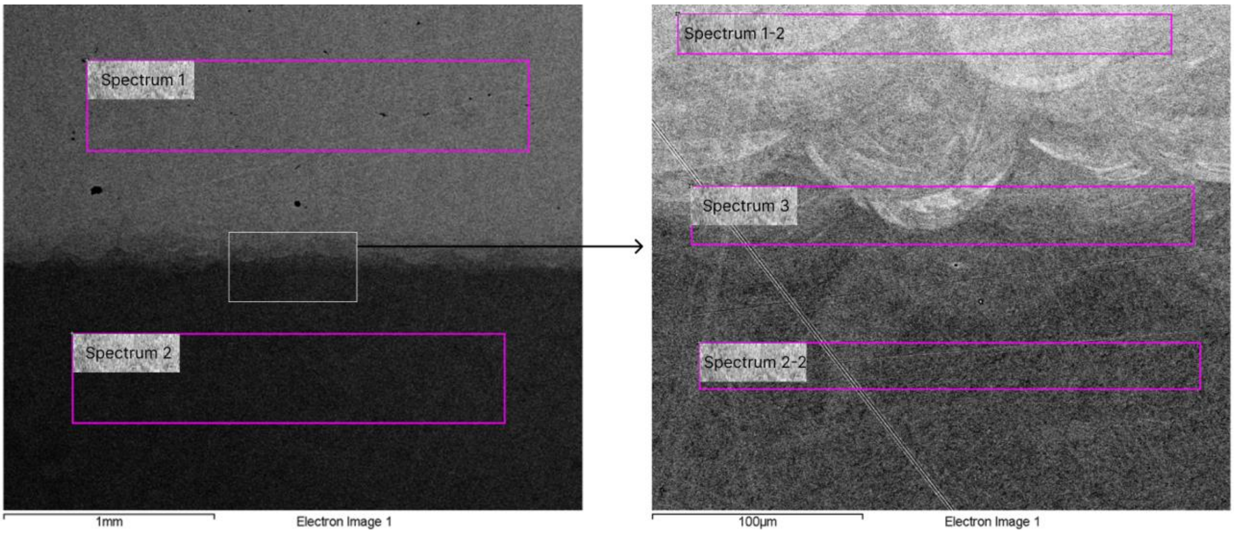


Figure 6. SEM image of the gradient structure in the interface area of the hybrid-AM part [79].

Table 2. The evolution of the chemical composition in the interface zone from the initial compositions of the H13 and maraging steel. Data of Cr, Fe, Co, and Ni in bold show changes in the content of these elements showing the gradient zone [79].

Element	Spectrum 1		Spectrum 2		Spectrum 1-2		Spectrum 2-2		Spectrum 3	
	Weight %	Atomic %	Weight %	Atomic %	Weight %	Atomic %	Weight %	Atomic %	Weight %	Atomic %
C	0.09	0.43	-	-	0.69	3.19	0.57	2.55	0.42	1.90
Si	0.96	1.90	-	--	0.30	0.58	1.03	1.98	0.87	1.71
P	0.19	0.34	-	-	0	0	0	0	0	0
S	0.15	0.26	-	-	0.12	0.20	0.11	0.19	0.08	0.13
Ti	-	-	1.00	1.23	0.72	0.84	0	0	0.17	0.19
V	0.41	0.45	0.03	0.04	0.16	0.18	0.46	0.49	0.34	0.37
Cr	**5.41**	**5.75**	**-**	**-**	**1.41**	**1.51**	**5.32**	**5.54**	**4.47**	**4.72**
Fe	**89.92**	**89.00**	**66.23**	**69.94**	**71.72**	**71.34**	**90.97**	**88.16**	**85.83**	**84.42**
Co	**0.68**	**0.64**	**9.57**	**9.58**	**7.07**	**6.67**	**0.63**	**0.57**	**2.28**	**2.13**
Ni	**0.15**	**0.14**	**18.61**	**18.70**	**14.20**	**13.43**	**0.24**	**0.22**	**3.68**	**3.44**
Cu	0.15	0.13	-	-	0.05	0.05	0.08	0.07	0.12	0.11
Nb	0.33	0.19	-	-	-	-	-	-	-	-
Mo	1.20	0.69	5.20	3.20	3.72	2.15	0.87	0.49	1.79	1.03
W	0.37	0.11	0.38	0.12	0.09	0.03	0.01	0.00	0.15	0.04
Total:	100		100		100		100		100	

In a study referenced in [80], a concept of hybridization in AM was explored. Specifically, the potential of using a PBF-fabricated part on a wrought substrate was investigated as a hybrid wrought–AM manufacturing route for Ti-6Al-4V damage critical load-bearing components. The researchers examined hybrid specimens, where the AM part was produced via selective laser melting (SLM), focusing on microstructural variations, defect presence, uniaxial tensile ductility, and fracture toughness across various configurations. It was observed that defects were present in both the AM part and the wrought counterpart of the specimens, with no discernible differences in their characteristics. This study sheds light on the feasibility of employing a hybrid approach for manufacturing components with improved mechanical properties, particularly in critical load-bearing applications.

This hybrid approach combines the benefits of additive and subtractive manufacturing, integrating AM into the traditional production chain to compensate for the limitations of AM processes and ultimately advancing the industrialization of AM. Moving forward, continued research and development in hybrid AM hold the potential to revolutionize manufacturing practices by enabling the efficient production of intricate, high-quality components on a larger scale.

Binder Jetting printing assisted with traditional heat post-processing exemplifies hybrid manufacturing [81,82]. In this approach, AM is utilized solely for shape production by printing a green body, while traditional powder metallurgy methods, such as sintering and liquid metal infiltration, are employed to achieve the desired densification, microstructure, and mechanical or physical properties [83–86]. This combination of AM and post-processing techniques proves advantageous for the manufacturing of functional parts and the design of composites [87,88]. By leveraging the strengths of both processes, this hybrid approach enables the production of components with tailored properties and complex geometries that may be challenging to achieve through conventional manufacturing methods alone. The utilization of binder jetting and traditional heat post-processing in synergy expands the possibilities for creating advanced materials and functional parts with enhanced performance characteristics [85,86]. Further research and development in this field hold promise for optimizing the hybrid manufacturing process and broadening its applications across various industries.

3.7. Open-Source Inventions in AM

Open-Source Inventions in AM refer to the technologies that are developed and shared within the open-source AM community. These inventions are characterized by their open nature, allowing anyone to access, modify, and distribute the designs, software, and documentation associated with the technology. Open-Source in AM encourages collaboration and knowledge sharing among individuals and organizations, fostering a community-driven approach to technological advancement. It enables individuals to build upon existing ideas, modify designs to suit their specific needs, and contribute back improvements or new ideas to benefit the entire community.

Open-Source AM has several advantages over traditional, proprietary approaches to technology development. First, it encourages collaboration and knowledge sharing among individuals and organizations. This can lead to faster innovation, as ideas can be freely exchanged and built upon. Second, open-source AM is more democratic, as anyone can participate in the development process. This can help to ensure that the technology is developed in a way that meets the needs of the wider community. Third, open-source AM is more sustainable, as it reduces the need for closed, proprietary systems.

On this topic, Joshua Pearce of Western University has a high number of unique contributions [89,90]. In one of his latest inventions, his team made an open-source walker, which is a customizable device, whereby the joints are additively manufactured on desktop machines and the tubing is cut to size. The goal of the project is to make a walker that is both open-source and customizable, as well as cost-effective [91].

The following list provides some of the popular Open-Source Inventions reported in recent years:

- RepRap: RepRap is one of the earliest and most well-known open-source AM projects [92]. It focuses on the development of self-replicating 3D printers, which are capable of producing most of their own components. The RepRap community has contributed to advancements in the field and has made it more accessible to a wider audience.
- Prusa i3: The Prusa i3 is a popular open-source 3D printer design created by Josef Prusa [93]. The design has been iterated upon and improved by the community, resulting in various versions and modifications. The Prusa i3 design has been widely adopted and has played a significant role in making 3D printing more affordable and accessible.
- Marlin Firmware: Marlin is an open-source firmware that controls and operates 3D printers [94]. It supports a wide range of 3D printer models and provides features

such as the precise control of stepper motors, temperature regulation, and support for various file formats. Marlin firmware has been continuously developed and improved by the open-source community, enabling 3D printer users to customize and optimize their machines.

- Slic3r: Slic3r is an open-source slicing software used in AM [95]. It takes 3D models and converts them into instructions (G-code) that a 3D printer can understand. Slic3r provides advanced options for customizing print settings and optimizing the printing process. The open-source nature of Slic3r has allowed for community contributions, resulting in new features, bug fixes, and improved performance.

Open-source innovations have played a vital role in driving the advancement and accessibility of AM technology. Through promoting collaboration and the exchange of knowledge, these groundbreaking inventions have expedited innovation, broadened accessibility, and empowered individuals and communities to explore and create novel applications for AM. Open-Source AM has the potential to accelerate innovation, democratize technology, and make AM more sustainable. As the AM community continues to grow, open-source AM is likely to play an increasingly important role in the development of this technology.

4. Inventions in AM-Related Emerging Technologies

In the realm of AM, emerging technologies have brought forth a wave of inventions that are revolutionizing various fields. In robotics, AM has paved the way for the creation of intricate and customizable components, enabling the development of advanced robots with enhanced capabilities. Digital twins, on the other hand, harness the power of AM to replicate and simulate real-world objects, leading to the improved design, analysis, and maintenance of complex systems. In the realm of virtual reality (VR), AM has facilitated the production of customized accessories and components, augmenting the immersive experience for users. Lastly, AM plays a pivotal role in automation, enabling the fabrication of specialized parts and tools that optimize processes and enhance productivity. These advancements showcase the remarkable potential of AM-related emerging technologies in shaping the future of robotics, digital twins, VR, and automation [96].

4.1. Robotics

In the field of robotics, AM has yielded noteworthy breakthroughs and progress in recent times. The subsequent instances showcase remarkable inventions and advancements achieved through the application of AM in robotics:

Multi-Material and Functionally Graded Robots: The advent of AM has facilitated the development of robots characterized by intricate designs and integrated components made from multiple materials. Through 3DP, robots can now be created with diverse properties, including variations in stiffness, embedded sensors, and actuators, all within a single structure. This is made achievable by printing robots using different materials or incorporating functionally graded structures. In their research, Li et al. employed the stereolithography process to accurately integrate multiple materials with distinct physical properties during the printing of millimeter-scale robots. They also implemented discrete magnetizations for the actuating parts, thereby offering a customizable method for producing intricate shapes with sophistication [97]. Figure 7 represents the multi-material propeller blade.

Soft Robotics: It encompasses the utilization of pliable and malleable materials to design robots that can interact safely with humans and handle delicate objects. With the aid of AM techniques like selective deposition, intricate structures of soft robots can be fabricated, complete with embedded features such as pneumatic networks, sensors, and actuators. In the area of soft robotics, Howard focused on a specific type of grippers that rely on granular jamming, which are notoriously challenging to model. Howard introduced a groundbreaking "one-shot" technique that leverages multi-material 3DP to produce entire grippers, including membranes and grains, in a single print run [98].

Figure 7. Additively manufactured multi-material propeller blade.

Hybrid Robots: Through the application of AM techniques, a new breed of robots has emerged, which blend both soft and rigid elements, known as soft and rigid hybrid robots. By incorporating soft components, these robots gain flexibility and adaptability, while the presence of rigid components ensures structural support and stability. This amalgamation empowers the robots to execute intricate tasks with finesse and interact safely with humans, all the while maintaining an overall sense of stability. Researchers at Harvard created a hybrid robot containing rigid components integrated into a soft-bodied robot [99].

Modular and Reconfigurable Robots: The utilization of AM makes it possible to fabricate modular components that can be effortlessly assembled or reconfigured to build diverse robotic systems. Researchers have harnessed the power of 3DP to create hybrid robots with interchangeable modules, enabling swift customization and adaptation to different tasks or environments. This capability allows for rapid adjustments and optimizations, empowering the robots to seamlessly tackle a range of challenges. Saab et al. presented the design and integration of a genderless coupling mechanism for modular self-reconfigurable mobile robots [100]. This paper focused on a docking mechanism called GHEFT: a Genderless, High-strength, Efficient, Fail-safe, and high misalignment Tolerant coupling mechanism that aids self-reconfiguration.

4.2. Digital Twins

There have been several recent inventions and advancements in AM in relation to the application of digital twin technology. Digital twins are virtual representations of physical assets, processes, or systems that enable real-time monitoring, analysis, and optimization. Matulis et al. presented a case study of creating and training a Robot Arm Digital Twin as an approach for AI training in a virtual space and applying this simulation learning within a physical space [101]. A virtual space, created using Unity, incorporating a virtual robot arm, was linked to a physical space, being an additively manufactured replica of the virtual space and robot arm.

The digital twin approach can influence the AM processing in various manners such as optimizing the process parameters, detecting and controlling the defects or machine health monitoring, reducing the computational burden for multi-scale modeling, and dealing with the big data in AM coming from different sources such as process monitoring sensors and material qualification [102].

It is a new area of research in AM which could unlock the full potential of AM for demanding applications [103–105]. The major research needs in the digital twins representing AM processes are developing models, databases, machine learning, the integration of the equipment, and algorithms to deal with data and predict the results.

4.3. Virtual Reality

3DP has been combined with VR technology to enhance the design, development, and user experience in various ways. Here are some notable recent inventions and advancements in AM in the field or in combination with VR:

Haptic Feedback Devices: The application of AM has been instrumental in the production of haptic feedback devices aimed at enhancing the VR experience. These devices, which encompass handheld controllers and wearable accessories, can integrate 3D-printed components to deliver tactile feedback, thereby augmenting immersion and facilitating interactive engagement with virtual environments. By incorporating AM, these haptic feedback devices offer users a heightened sense of realism and a more immersive VR encounter. Degraen et al. investigated how 3D-printed hair structures can serve as versatile passive haptic structures for VR [106].

Customized VR Accessories: The advent of 3DP has unlocked the ability to fabricate personalized accessories and components for VR systems. This encompasses a wide range of offerings, including specialized controllers, mounting brackets, ergonomic enhancements, and customizable options, all aimed at enhancing comfort and usability during VR experiences. With 3DP, users can tailor their VR setup to their specific needs, resulting in an optimized and immersive VR encounter. Lee et al. described three-dimensional-printed, personalized, multifunctional electronic eyeglasses (E-glasses), not only for monitoring various biological phenomena but also for proposing a strategy for coordinating the recorded data for active commands and game operations for human−machine interaction (HMI) applications [107]. Their overall results have provided technical insights into the associated technologies and industries such as digital healthcare and VR/augmented reality (AR).

4.4. Automation

AM has made significant contributions to the field of automation by enabling the creation of complex geometries, customization, and rapid prototyping. A mobile 3DP platform, which has omnidirectional wheels that allow for unrestricted movement along x- and y-axes, was invented [108]. The research team in this project performed a series of preliminary material tests with such a fully constructed platform. The system was tested with materials from three different industries that could benefit from mobile AM technology. A high number of inventions indicates that automation can help improve the AM processes. Recent developments in robotics, automation, and AM have shown several success stories in the construction industry [109]. Here are some recent inventions and advancements of AM in the field of automation:

Grippers and Robotic Hands: AM has enabled the creation of customized grippers and robotic hands that are lightweight, durable, and capable of complex grasping and manipulation [98]. 3D-printed grippers can be designed to match the shape, size, and properties of the objects they handle, enhancing automation capabilities.

Jigs and Fixtures: AM is used to create customized jigs and fixtures for automation processes. These tools assist in positioning, alignment, and assembly operations, improving accuracy, repeatability, and efficiency in automated manufacturing. Hiemenz [110] has showcased the utilization of AM to manufacture the fixtures used in various companies such as BMW, Thogus, Joe Gibbs Racing, and Thermal Dynamics.

Integration of Electronics and Sensors: AM techniques such as embedded printing or additively manufactured electronics (AME) allow for the integration of electronic components and sensors directly into printed parts. This enables the creation of smart and sensorized robotic systems, enhancing automation capabilities and enabling real-time data collection. Lewis et al. [111] have reported a case study of fully 3D-printed quantum-dot-based light-emitting diodes. Ready et al. [112] have outlined the creation of a rapid digital manufacturing system and considerations for building such a “printer” with the ability to integrate a structural material with functional electronic materials.

4.5. AI-Assisted AM

AI is being integrated into AM processes to enhance design capabilities, optimize part performance, identify the right process window for new material parameters, or improve process monitoring [113]. AI algorithms can generate complex geometries and lattice structures, improve material distribution, and optimize support structures, resulting in more efficient and lightweight designs [74,114]. Researchers at MIT have developed a machine learning system that utilizes AI and computer vision to improve the 3DP. By using simulations to train a neural network, the system is able to adjust printing parameters in real time, minimizing errors and improving accuracy. This approach eliminates the need for costly trial-and-error printing of thousands of objects to train the AI. The system has the potential to enable engineers to incorporate new materials with unique properties into their prints and make on-the-fly adjustments to the printing process when unexpected changes occur. This advancement represents a significant step towards intelligent manufacturing systems that can adapt and improve productivity [115]. Moreover, machine learning-centric techniques can also be used to complement the classic topology optimization approach to speed up the design optimization. In a study by Yao et al., the substitution of heavy pieces was carried out with lightweight components retrieved from a set in the initial model by using CNN to skill the in-between topologies acquired using typical topology optimization. This approach was 20 times faster than simplified isotropic material with the penalization method [116].

The application of AI techniques has emerged as a promising approach for the design and development of complex alloys, including high-entropy alloys (HEAs) [117,118]. AI methods, such as machine learning and data-driven models, offer the potential to accelerate the discovery and optimization of alloy compositions with desired properties [117]. By leveraging large databases, computational simulations, and materials informatics, AI algorithms can effectively analyze and predict the relationships between the alloy composition, processing parameters, and resulting material properties. This enables the exploration of vast compositional spaces and the identification of novel alloy formulations with exceptional mechanical, thermal, and functional characteristics [119]. Furthermore, AI-driven approaches facilitate the understanding of structure–property relationships and the identification of key alloying elements and microstructural features that contribute to enhanced performance. The integration of AI into the design process of complex alloys and HEAs holds great promise for accelerating materials discovery, optimizing alloy compositions, and enabling the development of advanced materials for a wide range of applications, including the aerospace, energy, and biomedical industries [120,121].

It can be concluded that AI has a special potential specifically for advanced materials, including HEAs, due to several factors.

HEAs are composed of multiple principal elements in roughly equal proportions, resulting in a vast compositional space to explore [122,123]. Traditional trial-and-error approaches for alloy design become increasingly impractical as the number of elements and potential combinations grows. AI-based methods can efficiently navigate this large design space and identify optimal compositions by leveraging data-driven models and machine learning algorithms.

HEAs often exhibit complex microstructures and unique property combinations, making it challenging to establish clear structure–property relationships through conventional methods alone [124,125]. AI techniques can analyze extensive datasets, including experimental results and computational simulations, to uncover hidden correlations, identify key factors influencing material properties, and predict the behavior of HEAs with high accuracy. This ability to understand and predict the complex behavior of HEAs can significantly accelerate the discovery and development of novel compositions with tailored properties.

AI can also be used in the process monitoring and control of AM processes. In a study by Scime and Beuth, multi-scale neural networks were used to train the machine learning system to correctly classify the powder-bed image patches into seven defect types, based on the images captured during LPBF images. These defect types included common problems such as incomplete spreading, super elevation, part damage, debris, etc. This approach paves the way for the in-process rectification of common problematic issues in the LPBF process when a feedback control system is implemented [126].

Furthermore, AI enables researchers to leverage the collective knowledge and expertise present in large materials databases, research publications, and experimental data. By extracting valuable insights from these vast repositories, AI algorithms can assist in the rational design of HEAs, guiding the selection of alloying elements, processing parameters, and targeted properties.

In summary, AI's special potential for HEAs lies in its ability to efficiently explore the vast compositional space, uncover complex structure–property relationships, and leverage extensive knowledge from data sources. By harnessing the power of AI, researchers can accelerate the design and optimization of HEAs, leading to the discovery of new alloy compositions with exceptional properties and advancing the field of advanced materials [117,118,124].

5. AM Inventions in Major Industries and Their Unique Aspects

This section of the holistic review article provides cutting-edge inventions in some of the major industries. Considering the length of the review, a limited number of industries are reviewed. The second part of the section is focused on the unique aspects of these inventions.

5.1. Major Industries

AM has revolutionized key sectors including the aerospace, healthcare, automotive, food, and construction industries. This transformative technology has led to remarkable inventions, driven by the ability to produce intricate shapes and cost-effective, lightweight, and high-performance products. These factors contribute to the widespread adoption and popularity of AM in various industries.

5.1.1. Aerospace Industry

AM has brought various revolutionary inventions to the aerospace industry. It has a global market size of USD 2.66 billion and is expected to reach USD 8.35 billion by 2029 [127]. Flexible designs, lower costs, faster lead times, and the lightweight manufacturing of products have popularized its adoption in this sector [128]. By leveraging these benefits, aerospace industries can enhance safety, fuel efficiency, and cost-effectiveness and foster a climate of continuous inventions. Boeing has embarked on research and collaborative ventures to explore the potential of 3DP in fabricating intricate components such as ducts, brackets, and cabin interior parts [129]. General Electric Aviation has achieved success by implementing AM technologies in the production of fuel nozzles for jet engines, resulting in improved fuel efficiency [130]. In addition, Stratasys, a leading 3DP company, has collaborated with Airbus to develop aircraft parts utilizing 3DP techniques [131]. These companies have demonstrated remarkable success in pioneering innovative AM techniques and showcasing groundbreaking inventions. However, the adoption and implementation of 3DP in aerospace also come with challenges. Key obstacles include material selection, surface roughness, scaling production, and time-consuming processes, which require focused attention and resolution.

A very different recent development for aerospace has been the 3DP of gaskets in a qualified material by PPG, based on research sponsored by the US Army Research Laboratory. PPG Ambient Reactive Extrusion (PPG ARETM) produces 3D-printed gaskets and seals on demand—for example, as ramp seals for Lockheed Martin's C-130J Super Hercules from 2021, as seen in Figure 8 [132].

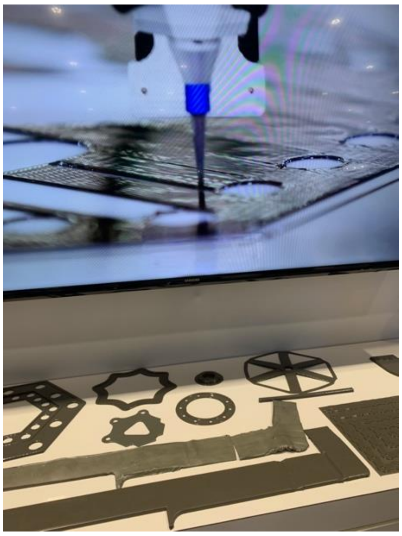


Figure 8. 3D-printed gasket for aerospace applications (PPG ARE^{TM}) [7].

5.1.2. Healthcare Industry

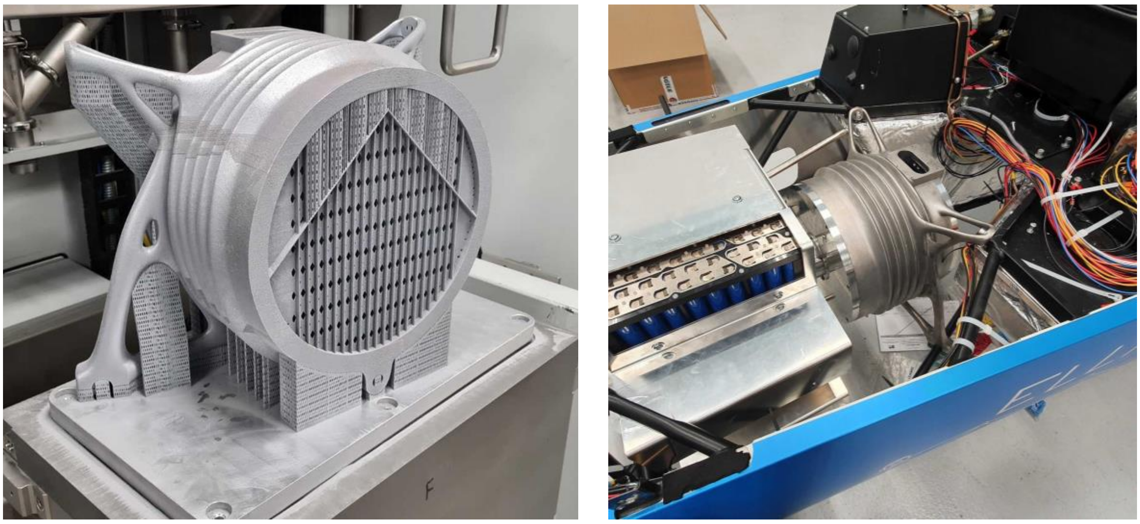
3DP in healthcare is experiencing rapid growth and is projected to reach a market growth of USD 5.59 billion by 2027 [133]. This technology stands out as the sole solution enabling the personalization and customization of healthcare products, equipment, and medications. It empowers the precise development of patient-specific healthcare products like bone replicas, organs, blood vessels, prosthetics, and drill guides using digital data and a range of materials, both locally and in research or industrial environments [133]. In Israel, scientists have successfully developed a 3D-printed heart using the patient's own cells and biological materials, although it is not yet functional [134]. Aether, a bioprinting company, has made significant progress in developing bio-inks and 3D printers capable of fabricating complex tissue structures. While 3DP in healthcare is still in the development stage, it has demonstrated promising outcomes in creating intricate functional medical structures [135]. Bioengineers worldwide are actively engaged in the pursuit of 3DPed organs, with research teams at Rice University and the University of Washington achieving a breakthrough by developing 3D-printed vascular networks crucial for artificial organ functionality [136]. In dentistry, 3DP has garnered significant interest due to its affordability, lightweight nature, acceptable mechanical strength, and ability to produce highly complex shapes [137]. Polymerization-based 3DP such as DLP, SLA, and material jetting are employed in dentistry for prosthodontic and orthodontic treatments [138].

These recent inventions highlight the transformative potential of 3DP in the healthcare industry. However, challenges such as long-term durability, the availability of biocompatible materials, surface roughness, and time-consuming processes must be addressed through collaboration, research, and advancements in material science.

5.1.3. Automotive Industry

AM has brought improvements to the automotive industry, as demonstrated by innovations such as Bugatti's Brake calipers [139], General Motors' seat brackets [140], Local Motors' Strati chassis [141], and Porsche pistons [142]. These recent inventions showcase the industry's urge for design flexibility, increased customization options, cost reduction, and improved efficiency, indicating the further integration of AM in automotive industries. However, continuous research in product development and material advancements will be necessary to tackle the challenges such as identifying suitable materials with necessary mechanical and thermal performance, addressing low production speeds, and improving the surface finish. Moreover, the use of AM in the automotive industry is still not widespread as a mainstream production route but rather more for niche applications in luxury car segments, spare part manufacturing, or die/mold manufacturing due to unique challenges in scaling AM for the serial production of automotive components.

A use case from the automotive industry is demonstrated in Figure 9 from the AMRC ELLI (Electrification and Lightweighting in Industry 4.0) project centered around a Caterham 7 sports car [143]. Using the original design space, loading conditions, and applied material, the motor casing was redesigned for AM. The optimization considered a system-level design to enable part consolidation and multi-functional use. Support brackets were organically incorporated into the motor case as a single body, and the final design used a liquid cooling circuit for better thermal control.



(**a**) (**b**)

Figure 9. A motor casing with an optimized design: (**a**) before post-processing produced by LPBF from AMRC, University of Sheffield, UK; (**b**) after post-processing [143].

5.1.4. Food Industry

The food industry holds immense economic importance and profoundly impacts people's lives. Commercially, many prominent food companies are exploring the utilization of 3DP technology to explore the customization and culinary creativity of food production. Chocolate manufacturers, for example, employ dedicated 3D printers to craft desserts with their unique artistic flair and desired quantities [144]. Barilla, an Italian family-owned food company, has ventured into producing 3D-printed pasta, offering uniquely shaped and high-quality pizza in minimum time [145]. Miam, a Belgium chocolate producer, leverages appropriate fluid ingredients to create ready-to-eat milk, dark, and white chocolates [146].

Whilst challenges related to ingredient compatibility, hygiene, production volume, taste, and more must be addressed to facilitate the widespread adoption of 3D-printed food, there has been considerable interest in the use of the 3DP of food for more specialized applications. Dysphagia, for example, is a medical condition where the patient has difficulty swallowing certain foods, and the 3DP of suitable foods has been researched for several years [147]. Protein and vegetable products that fit the texture categories of the International Dysphagia Diet Standardization Initiative are being printed. There is a concern that 3D-printed foods are "ultra-processed", and therefore, whilst easier to swallow, they can be more difficult to digest [148]. However, the negative effects on the gut microbiome are being addressed by the addition of hydrocolloids and probiotics. Recently, advances in 4D food printing incorporate responses to stimuli to change color or release aromas. These developments raise the value of technology for sectors such as aged care.

5.1.5. Construction Industry

AM embodies the ideology of maximizing productivity while simultaneously minimizing waste. Building upon this concept, numerous construction projects are embracing 3DP technology to construct low-cost houses with minimum labor hours and waste generation [149]. The application of 3DP in construction offers advantages such as design flexibility, accelerated construction speeds, and environmental sustainability. This has enabled the exploration of new material applications for construction, including for temporary shelters, as illustrated in the innovative work of the architectural firm Emerging Objects [150]. Architects can now create complicated shapes that were previously unattainable through traditional ways of construction. DUS Architects demonstrate its potential through their work on the Canal House in Amsterdam, which has since been followed up in 2021 with the demonstration AM bridge shown in Figure 10, built in the same city by high-profile 3DP Designer Joris Laarman at MX3D [151].

Figure 10. Additively Manufactured Bridge.

Dubai has already embarked on this innovative path by constructing 3DP offices, with the Office of the Future standing as the first functional office developed using the 20-feet-high, 120-feet-long, and 40-feet-wide 3D printer [152]. This innovative project achieved a 50% reduction in labor costs compared to similar-sized projects constructed conventionally, while also minimizing the waste and environmental impact, as reported by the architects involved in the project [153].

Moreover, in Europe, the utilization of 3DP in house construction is contributing to the reduction in overall CO_2 emissions [154]. The implementation of AM in the construction industry is still an evolving concept that holds the potential to revolutionize this industry. However, there are several challenges associated with 3DP in construction that must be addressed in the future, including size limitations, material selection, structure quality, and the need for a skilled workforce [155,156]. Research into the structural difficulties that can arise long-term from 3DP in various methods using concrete is ongoing [157].

5.2. Unique Aspects of AM Inventions

AM has revolutionized the manufacturing industry by introducing unique aspects that are transforming various sectors. Here are a few cases on the unique aspects of AM inventions in terms of low costs, lightweighting, recycling, sustainability, and Design for AM (DfAM):

5.2.1. Low-Cost Products

One of the key advantages of AM is its ability to produce complex parts and prototypes at a lower cost compared to traditional manufacturing methods. By eliminating the need for expensive tooling and reducing material waste, AM enables cost-effective production, making it accessible to a wider range of industries and individuals. Several researchers highlighted the significant components in regard to estimating the cost of AM and considering the factors for obtaining additively manufactured low-cost products [158]. These factors include material costs, machine costs, labor costs, build envelopes and envelope utilization, build times, and energy consumption [159].

Determining the most suitable manufacturing process for maximizing profit often hinges on the cost per part. Generally, this factor governs the decision-making process. To provide a general idea, Figure 11 illustrates the unit costs associated with three frequently employed manufacturing processes [160].

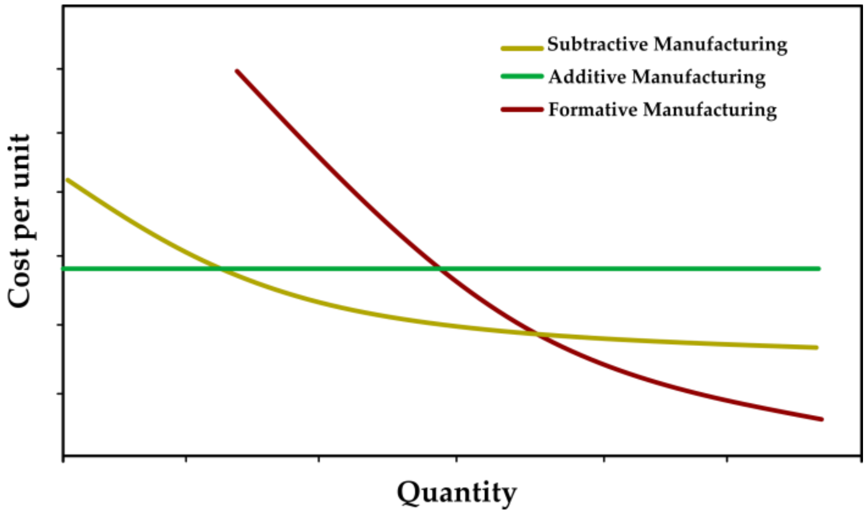


Figure 11. Cost comparison of different manufacturing techniques.

The cost of 3DP continues to decrease annually, and in certain cases, it is beginning to rival injection molding in terms of cost efficiency. However, when it comes to specific tasks, 3DP and CNC machining are typically considered interchangeable manufacturing methods based on the factors in the mechanical and quality characterizations of the fabricated parts.

5.2.2. Lightweight Products

AM allows for the creation of intricate and lightweight structures that were previously unachievable using conventional manufacturing techniques. By utilizing optimized lattice structures, hollow designs, and internal cavities, AM enables the production of lightweight components without compromising their strength or functionality. This aspect is particularly beneficial in industries such as the aerospace and automotive industries, where weight reduction can lead to improved fuel efficiency and performance.

In order to produce additively manufactured light products, a number of academic institutions, organizations, governmental agencies, and companies developed initiatives to make their current level of production lighter and also as functional as before. In a collaborative effort, the AM Standardization Collaborative (AMSC) and the Lightweight Innovations for Tomorrow (LIFT) Institute, one of the Manufacturing USA Institutes, joined forces to explore the integration of dissimilar materials using AM components. The AMSC, a project initiated by the American National Standards Institute (ANSI) in conjunction with America Makes, aims to establish AM roadmaps, define standards, and foster industry-wide coordination, quality assurance, and consistency. By leveraging this partnership, LIFT and AMSC strive to advance the capabilities of AM by enabling the successful joining of diverse materials, opening new possibilities for innovative manufacturing applications [161].

5.2.3. Remanufactured Products

AM promotes sustainable practices by enabling the recycling and reusability of materials. Unlike subtractive manufacturing, where excess material is often discarded as waste, AM only uses the exact amount of material required for the object being printed. Additionally, some AM technologies allow for the recycling of used parts or failed prints, reducing material waste and minimizing the environmental impact.

Making filaments from used filaments is important, as it promotes recycling and reduces waste in 3DP. It helps conserve resources, minimizes the environmental impact, and encourages a more sustainable approach to manufacturing. The process of making filaments from used filaments involves recycling and reprocessing the discarded or used 3DP filaments. The used filaments are collected, cleaned, and shredded into smaller pieces. These pieces are then melted and extruded to create new filament strands. This recycling method reduces waste and allows for the reuse of materials, promoting a more sustainable and circular approach to 3DP [162].

3D Systems developed and marketed the Ekocycle 3D Printer, which utilizes recycled plastic bottles as filament to construct new products through extrusion [163]. Researchers have developed the 3D Re-Printer, a cutting-edge 3D printer featuring an integrated automatic plastic waste extruder [164]. This innovative device enables the recycling of plastic bottles, transforming them into raw materials suitable for 3DP. ReDeTec's newly developed and marketed system can shred any surplus 3D prints, rafting or support material, and other 3DP waste into granules that can be used to make new filament [165]. The patented extrusion technology named ProtoCycler V3 allows for the compounding of polymers with a single screw [166]. The users can recycle PLA, ABS, PETG, HIPS, Nylon 12, etc. Overall, recycled filaments provide a sustainable and economical option for environmentally conscious makers and manufacturers, contributing to a circular economy and reduced waste generation.

According to a recent research study [167], an innovative biobased photopolymer suitable for 3DP has also been developed, which is both recyclable and reprintable. The study involved evaluating the mechanical properties of a test part made from this photopolymer derived from castor oil. Remarkably, the researchers successfully melted down the test part and reused the material to print another part. Notably, the recycled resin exhibited nearly identical properties to the original resin, including the color, viscosity, volumetric shrinkage, tensile strength, Tg (glass transition temperature), polymerization rate, and penetration depth. This breakthrough demonstrates the potential for sustainable and circular manufacturing practices within the realm of AM.

With the increased importance of green manufacturing and sustainability in today's economy, there are also a number of continuing research efforts in other AM technologies dealing with producing remanufactured products [168].

5.2.4. Sustainable Products

The design freedom offered by AM empowers engineers and designers to optimize parts for sustainability. By employing techniques like topology optimization, organic shapes, and lightweight structures, AM enables the creation of products that are more material-efficient, consume less energy during production, and have reduced carbon footprints. This aspect aligns with the growing global focus on sustainable manufacturing practices and the circular economy.

AM encompasses several key features that contribute to its sustainability and environmental advantages. First, AM enables localized and on-demand production, reducing the need for extensive transportation and associated carbon emissions. This decentralized manufacturing approach has the potential to significantly reduce the environmental footprint by minimizing transportation distances and the energy required for logistics [169,170].

Furthermore, AM enables the optimization of designs for material efficiency, leading to reduced waste generation. By employing advanced design techniques like topology optimization and lightweight structures, AM allows for the creation of complex geometries that use only the necessary amount of material. This approach minimizes material waste during production and results in lighter end-products, thereby reducing the energy consumption and environmental impact [171,172]. The ability of AM to manufacture intricate and customized components with reduced material usage aligns with the principles of circular economy and sustainable manufacturing practices.

5.2.5. DfAM Products

AM offers unique design possibilities that were previously constrained by the limitations of traditional manufacturing methods. Design for Additive Manufacturing (DfAM) leverages these possibilities to create optimized parts specifically tailored for the additive process. DfAM considers factors such as support structure optimization, part consolidation, and the integration of complex geometries, enabling the production of parts that are more functional, efficient, and customizable. DfAM is also inspired by nature, and biomimicry is one of the design approaches when considering the manufacturing flexibilities of AM.

One example of a DfAM invention central to its use is the lattice structure [173]. Lattice structures are intricate, lightweight, and highly efficient designs that are specifically optimized for 3DP. They consist of a network of interconnected struts or beams arranged in a repeating pattern, resembling a honeycomb or a mesh (see Figure 12). Lattice structures are particularly well suited for AM because they take advantage of the unique capabilities of 3DP technology, such as the ability to create complex geometries and internal structures. By using lattice structures, designers can reduce the weight of a component while maintaining its strength and structural integrity. Furthermore, the ability to design changes in performance characteristics within a single print through variations in the lattice enables a paradigm shift in the way products are conceptualized and designed.

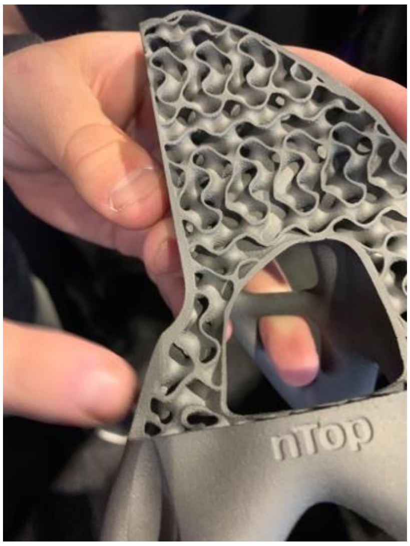
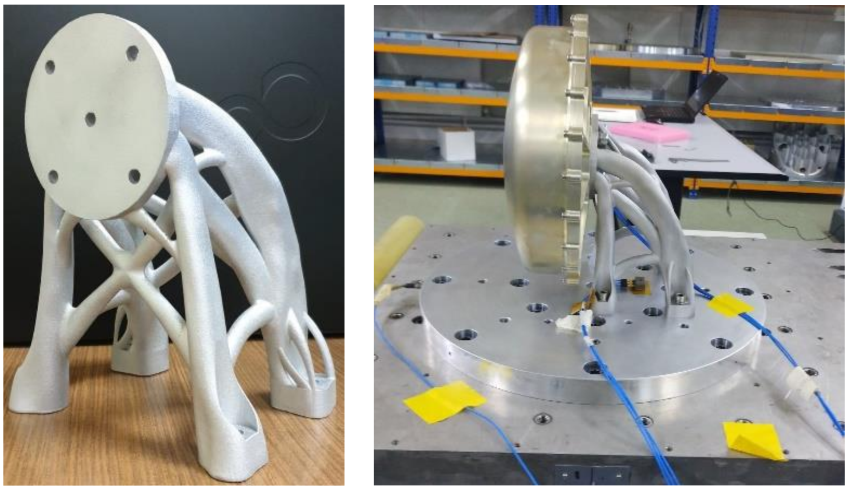


Figure 12. NASA Excite Challenge Bracket showing the variations in the lattice wall thickness within the part.

The second example is conformal cooling channels [174]. In traditional manufacturing processes like injection molding, cooling channels are typically straight and uniform. However, with DfAM, designers can create complex, customized cooling channels that conform to the shape of the part being manufactured. This enables more efficient heat transfer and faster cooling, resulting in improved cycle times, better part quality, and reduced production costs.

One of the biomimicry or bioinspired DfAM samples is the satellite reaction wheel bracket, as can be seen in Figure 13 [175]. The current design made for the machining process and all the necessary weight reductions was created. However, the biomimetic design has been adopted for the bracket, and the elephant head and foot shape and function have been considered in the design of brackets for AM. The resultant AM design is stronger, 40% lighter, and durable for all the sinus and random vibrations which occur during the take-off of the carrier rocket.



(**a**) (**b**)

Figure 13. Satellite reaction wheel bracket design for AM: (**a**) after fabrication and (**b**) vibration test set-up [175].

Topology Optimized Parts are the other type of invention in this category [176]. DfAM allows engineers to optimize the internal and external geometries of a part based on its specific load requirements. Using advanced algorithms, they can create lightweight designs with optimal material distribution, reducing material usage while maintaining structural integrity. This approach leads to weight reduction, improved performance, and cost savings, especially in industries like the aerospace and automotive industries, for applications such as lightweight brackets, e.g., satellite antennae brackets [162].

Functionally Integrated Assemblies are another example [177]. DfAM enables the consolidation of multiple components into a single, complex part. By integrating different functionalities within a single print, designers can eliminate the need for assembly, reduce the part count, and streamline manufacturing processes. This not only simplifies production but also offers weight reduction and improved overall performance by minimizing interfaces and potential points of failure.

In summary, the unique aspects of AM inventions in terms of their low cost, lightweight nature, recycling, sustainability, and DfAM have the potential to reshape industries, accelerate innovation, and promote a more sustainable approach to production.

6. Current Challenges and Future Prospects for AM

AM is emerging as a groundbreaking technology with immense potential to revolutionize various industries. It allows for the creation of three-dimensional objects by adding material layer by layer, offering unprecedented design freedom and manufacturing flexibility. While AM has already made significant strides, it also faces a range of challenges that need to be addressed. This section discusses current challenges and future directions for AM inventions, highlighting the transformative impact they can have on industries and the potential obstacles that need to be overcome.

The last decade has seen considerable advances in the process and material development for AM and a broadening of the type and number of companies engaged with the technology. According to one of the leading conference and expo providers of the technology, RAPID + TCT 2023, over 30% of exhibitors were new to the event. Post-processing equipment and future factories specific to the AM workflow were in the evidence. In addition, there was an interesting shift in profile, with a growing number of established materials manufacturers, such as 3DXTech (see Figure 14), who had now invested in 3D printers for their materials. This is a significant development, as one of the primary challenges in AM has been the limited range of materials available for printing.

(**a**)

(**b**)

Figure 14. 3DXTech provides an expansive range of materials for additive manufacturing at RAPID + TCT 2023: (**a**) fabricated sample parts; (**b**) fabricated sample rocket part using carbon fiber-reinforced PEEK material.

Although the range has expanded over the years, the AM market is still considerably smaller compared to that of traditional manufacturing processes. The development of new materials with suitable properties for AM remains a significant hurdle, especially for applications that require specific mechanical, thermal, or electrical properties. Additionally, ensuring the consistency and reliability of the printed parts across different machines and materials is crucial for widespread adoption.

Another challenge lies in the scalability of AM processes. While AM offers the potential for rapid prototyping and low-volume production, it currently struggles to compete with traditional manufacturing methods for large-scale production. The time required to print objects and the limited printing speed hinder the cost-effectiveness and efficiency of AM at a large scale. Developing faster printing techniques and optimizing the overall manufacturing workflow are essential to address this challenge. However, in addition, the industry needs to further research the value proposition for businesses in terms of the use of AM and invest in the development of new business models to exploit the opportunities the technology provides.

Despite the challenges, the future directions of AM inventions are highly promising. As research and development efforts continue, the range of printable materials is expected to expand, enabling the production of more complex and functional end-use parts. This will open up opportunities for AM to penetrate industries such as the aerospace, automotive, healthcare, and consumer goods industries on a larger scale. Furthermore, advancements in AM, including the use of multi-material and hybrid printing, will enhance the capabilities of the technology. This will enable the creation of objects with a combination of different materials, properties, and functionalities, further pushing the boundaries of design and innovation. Moreover, the integration of AM with other emerging technologies like AI and robotics can lead to automated and customized production processes, transforming the manufacturing landscape [164].

Whilst AM has made significant progress and holds immense potential, there are still challenges to overcome before it can fully realize its prospects. Addressing the limitations in the material availability, scalability, and production speed are crucial for wider adoption, as well as building strategies for increasing its integration through services complementary to established production systems [178]. However, as technology continues to advance, AM inventions have the power to reshape industries, drive innovation, and unlock new possibilities in design and manufacturing. The following sections present the current challenges and prospects of evolving AM technologies.

6.1. Bio-Printing

Bioprinting is an innovative and rapidly advancing field of biotechnology that combines the principles of 3DP with biology [179], aiming to create living tissue and organs through the precise layering of bioink, a substance composed of living cells and other biomaterials [180]. By utilizing specialized bioprinters, this revolutionary technique offers the potential to address the growing demand for organ transplants [181], tissue engineering [182], and drug testing [183], ultimately revolutionizing healthcare and transforming the approaches to regenerative medicine. Through the precise placement of cells and materials [184], bioprinting holds great promise for personalized medicine [185], improving patient outcomes [186] and reducing the reliance on traditional transplantation methods [187] while also presenting exciting possibilities for scientific research and the development of new therapies [188].

Bioprinting, despite its tremendous potential, faces several challenges that need to be overcome for its widespread implementation. First, ensuring the viability and functionality of printed tissues and organs remains a major obstacle. Maintaining the structural integrity and proper cellular interactions within the printed constructs is crucial for their successful integration and functionality in the human body [189]. Additionally, the limited availability and complexity of suitable biomaterials and bioinks pose a significant challenge [190]. Developing biocompatible and biodegradable materials that mimic the native tissue properties while also supporting cell growth and differentiation is essential. Moreover, scaling up the production of bio-printed tissues and organs to meet the demand for transplantation is a complex task, requiring advances in automation, standardization, and regulatory frameworks [191]. Lastly, the ethical considerations surrounding bioprinting, such as potential misuse or the creation of designer organs, must be carefully addressed to ensure the responsible and equitable use of this technology. Overcoming these challenges will be crucial in unlocking the full potential of bioprinting in healthcare and regenerative medicine [192].

The future prospects of bioprinting are incredibly promising, holding the potential to revolutionize healthcare and regenerative medicine. As the field continues to advance, we can envision a future where bioprinting enables the creation of patient-specific organs, tissues, and implants, reducing the waiting time for organ transplants and eliminating the need for immunosuppressive drugs [193]. This personalized approach has the potential to significantly improve patient outcomes and quality of life. Bioprinting also opens avenues for advanced drug testing and personalized medicine, allowing researchers to create realistic models of human organs for more accurate and efficient preclinical testing. Furthermore, with ongoing advancements in biomaterials, bioink formulations, and bioprinting techniques, it is possible that complex structures like blood vessels and nerve networks can be printed, enabling the creation of fully functional organs. This holds tremendous potential for addressing the global shortage of organs and revolutionizing the field of regenerative medicine, offering new hope for patients in need [194–197].

Today, there is a growing interest in making very robust, environmentally friendly, biodegradable, and easy-to-produce products with a number of AM technologies. For each production, it is always important to know the environmental restrictions regarding the use of bio-printing technologies [198,199].

6.2. 4D/5D Printing

This topic represents the next evolution in AM technology, going beyond the three-dimensional realm to introduce dynamic and shape-shifting capabilities [200]. 4D printing refers to a technology that builds upon 3DP by introducing the element of time. 5D printing is an advanced manufacturing method that utilizes complex axis movements and a combination of additive and subtractive methods. Overall, this innovation involves the creation of objects and materials that can not only be printed in three dimensions but also possess the ability to transform their shape [201], properties, or functionality over time in response to external stimuli such as heat, light, humidity, or mechanical forces [202]. By integrating smart materials and design principles into the printing process, this technology opens up a new realm of possibilities across various industries, including the aerospace [203], healthcare [204], robotics [205], and consumer goods industries [206]. This groundbreaking technology has the potential to revolutionize manufacturing, enabling the creation of self-assembling structures, adaptive devices, programmable textiles, and intelligent systems that can adapt, repair, or respond to changing environmental conditions. The advent of 4D/5D printing holds immense promise in unlocking innovative solutions, pushing the boundaries of traditional manufacturing, and driving advancements in fields that require dynamic, customizable, and intelligent materials and objects [207].

Advancements in this technology, despite its immense potential, face several challenges that must be addressed for its widespread implementation. First, the development and integration of suitable smart materials pose a significant hurdle. These materials need to exhibit reliable and predictable responses to external stimuli while maintaining structural integrity and desired mechanical properties. Ensuring the availability and scalability of such materials is crucial for the practical application of 4D/5D printing [208]. Second, achieving precise control over the transformation processes presents a challenge. Controlling the timing, speed, and magnitude of shape changes in printed objects requires advancements in design, fabrication techniques, and the understanding of material behavior [209]. Additionally, the complexity and cost of these technologies remain obstacles that need to be overcome. Advancements in printing equipment, software, and post-processing techniques are necessary to make this technology more accessible and economically viable [210]. Lastly, standardization and regulatory considerations need to be addressed to ensure the safety, reliability, and compatibility of 4D/5D-printed objects across different industries and applications. Addressing these challenges will be critical for unlocking the full potential of technology and establishing it as a transformative manufacturing technique [210–214].

The prospects of these printing technologies hold immense potential for revolutionizing multiple industries and enabling innovative applications. As technology advances, we can expect to see the creation of complex and customizable objects that can dynamically adapt to their environment [215]. In healthcare, 4D/5D printing could lead to the development of smart implants that respond to physiological changes, such as tissue growth or drug release, enhancing patient outcomes [216]. In aerospace, shape-shifting structures could enable lightweight, adaptive components, optimizing fuel efficiency and aerodynamics. The consumer goods industry could benefit from self-assembling products or programmable textiles that adjust to user preferences or environmental conditions. Additionally, in robotics and automation, the availability of this technology could contribute to the production of intelligent systems capable of self-repair, self-assembly, or adapting to different tasks. However, to realize these prospects, continued research and development are needed to overcome challenges related to material properties, process control, scalability, and cost-effectiveness. With further advancements, 4D/5D printing has the potential to transform industries, drive innovation, and offer exciting possibilities for creating dynamic, adaptive, and intelligent objects [217,218].

6.3. Micro–Nano-Scale Fabrication

This refers to the additive manufacturing and manipulation of materials and structures at the microscopic and nanoscopic levels [219], typically ranging from a few micrometers down to nanometers. This field combines the principles of engineering, physics, chemistry, and biology to create structures and devices with precise control over their size, shape, and composition [220]. By leveraging specialized techniques such as lithography, etching, deposition, and self-assembly, micro–nano-scale fabrication enables the development of miniaturized systems with unique properties and functionalities. These systems find applications in a wide range of fields, including electronics, photonics, biotechnology, medicine, energy, and environmental sciences [221–224]. With the ability to manipulate matter at the smallest scales, micro–nano-scale fabrication opens new frontiers for scientific research, technological advancements, and the creation of innovative devices that push the limits of what is possible at the micro and nano level [225,226].

Micro–nano-scale fabrication encounters several challenges that must be overcome to achieve precise and reliable manufacturing at such small scales. First, ensuring the accuracy and resolution of fabrication processes is critical. The ability to control dimensions, tolerances, and surface roughness at the micro and nano levels requires advancements in lithography techniques [227], nanomaterials, and high-precision instrumentation [228]. Second, maintaining uniformity and consistency across large-scale production presents a challenge. Variations in materials, environmental conditions, and process parameters can result in deviations in fabricated structures, hindering the reproducibility and yield. Third, integrating multiple materials with different properties and functionalities at the micro and nano scales remains a challenge. The compatibility of dissimilar materials, bonding techniques, and the precise alignment of multiple layers pose significant hurdles in achieving complex and functional structures [229]. Additionally, the cost and scalability of fabrication technologies need to be addressed. Expensive equipment, specialized facilities, and time-consuming processes hinder the widespread adoption of these techniques [230]. Moreover, ensuring the safety and reliability of micro–nano devices, particularly in the context of biomedical applications, requires thorough characterization, testing, and quality control standards. Overcoming these challenges will pave the way for advancements in micro–nano-scale fabrication and unlock its full potential in various fields [231–233].

The outlook of micro–nano-scale production holds tremendous potential for transformative advancements across diverse fields. As technology continues to evolve, we can anticipate breakthroughs in electronics, photonics, medicine, energy, and beyond [234,235]. In electronics, micro–nano manufacturing technologies could lead to the development of smaller, faster, and more efficient devices, enabling the next generation of integrated circuits, sensors, and wearable electronics [236,237]. In photonics, precise control over nanoscale structures could revolutionize optical communication, quantum computing, and advanced imaging systems. In medicine, micro–nano fabrication holds promise for personalized diagnostics, targeted drug delivery, and regenerative medicine through the creation of biomimetic structures, lab-on-a-chip devices, and implantable sensors [238]. Additionally, micro–nano fabrication could contribute to sustainable energy solutions, such as high-efficiency solar cells, advanced batteries, and energy harvesting devices. However, realizing these prospects requires addressing challenges related to accuracy, scalability, cost-effectiveness, and multi-material integration. With ongoing advancements and interdisciplinary collaborations, additively manufactured micro–nano-level products are poised to unlock remarkable possibilities, driving innovation and shaping the future of technology and scientific discovery [239,240].

6.4. Additively Manufactured Electronics

Additively Manufactured Electronics (AME) is an emerging field that combines the principles of 3DP and electronics manufacturing to create functional electronic devices and circuits directly through additive processes [241]. By integrating conductive and dielectric inks or materials into the 3DP process, AME enables the simultaneous fabrication of complex, three-dimensional structures and the deposition of electronic components [242], interconnects [243], and circuits [244]. This innovative approach offers several advantages, including the ability to create customized, lightweight, and geometrically complex electronics with reduced material waste and shorter production cycles [245]. It has the potential to revolutionize various industries, including the aerospace [246], automotive [247], healthcare [248], and consumer electronics industries [249], by enabling the rapid prototyping and on-demand manufacturing of electronic devices, sensors, wearables, and IoT (Internet of Things) components. As this technology continues to advance, it holds the promise of transforming the way in which electronic devices are designed and manufactured. New ways of interaction enabled by AME should foster a new era of flexible, interconnected, and smart electronics [250].

AME faces several challenges that need to be addressed for its widespread adoption and implementation. First, ensuring the conductivity, reliability, and performance of printed electronic components is a significant hurdle [251]. The development of printable conductive inks and materials with properties comparable to traditional manufacturing methods is crucial for achieving functional devices. Additionally, achieving high-resolution printing of fine features and interconnects poses a challenge, as it requires precise control over the deposition process and the ability to handle multiple materials simultaneously [252]. Moreover, the integration of different materials with varying thermal, electrical, and mechanical properties remains a challenge. Ensuring the compatibility, adhesion, and reliability of multi-material interfaces are essential for the successful fabrication of complex electronic devices [253]. Furthermore, the scalability and cost-effectiveness of these technologies need to be improved for mass production applications. Advancements in printing speed, automation, and material utilization are necessary to compete with traditional manufacturing techniques [254]. Lastly, addressing the standardization and certification requirements for AME is crucial to ensuring the quality, safety, and compatibility of printed electronic devices across different industries. Overcoming these challenges will be pivotal in unlocking the full potential and enabling its seamless integration into various electronic manufacturing processes [255].

The future scope of AME holds immense potential for transformative advancements in the field of electronics manufacturing. As technology continues to advance, it is possible to expect the increased integration of AME technology in various industries, including the automotive, defense, and consumer electronics industries [256]. The ability to rapidly prototype and manufacture customized electronic devices, sensors, and wearables through AME offers advantages, such as a faster time-to-market, reduced material waste, and increased design flexibility [257]. Moreover, the integration of printed electronics with 3D-printed structures opens possibilities for creating complex, multifunctional devices with improved performance and functionality. Additionally, it enables the development of flexible, conformal electronics that can be seamlessly integrated into curved surfaces and irregular shapes, unlocking new opportunities in product design and miniaturization [258]. As the technology matures, advancements in printable materials, high-resolution printing, multi-material integration, and scalability will further enhance the scope of AME, paving the way for the next generation of electronic devices and revolutionizing the way in which we manufacture and interact with electronics [259].

6.5. Wire Arc Additive Manufacturing

Wire Arc Additive Manufacturing (WAAM) is an innovative manufacturing process that utilizes electric arc welding techniques to build three-dimensional structures layer by layer [260]. This AM technique involves the precise deposition of molten metal wire onto a substrate or previous layers to create complex and customizable components. With the ability to work with a wide range of metals and alloys, it offers several advantages including high deposition rates [261], cost-effectiveness [262], and the ability to produce large-scale structures [263]. By leveraging advanced robotic systems and sophisticated control algorithms, it also enables the fabrication of functional parts with excellent mechanical properties and dimensional accuracy [264]. This versatile technology finds applications in industries such as the aerospace [265], automotive [266], marine [267], and energy [268] industries, allowing for the creation of near-net shape components, repairs, and even the integration of multiple materials. It holds significant potential for revolutionizing traditional manufacturing processes, offering increased design freedom, reduced lead times, and sustainable production methods [269]. Figure 15 presents a landing gear part made with the WAAM technology.

WAAM faces several challenges that need to be overcome for its wider adoption and successful implementation. First, achieving precise control over the deposition process presents a challenge, as factors such as the wire feed rate, arc voltage, and travel speed need to be carefully controlled to ensure proper fusion and consistent layer formation [270].

Maintaining a stable arc and achieving uniform bead geometry across complex geometries and varying part orientations is also a challenge. Second, addressing the issue of residual stresses and distortion in WAAM-produced components is crucial. The thermal cycling and rapid solidification during deposition can result in residual stresses that may lead to warping, cracking, or dimensional inaccuracies in the final product. Controlling these residual stresses and minimizing distortion is essential for achieving dimensional accuracy and mechanical integrity [271,272]. Third, ensuring the quality and integrity of deposited material is a challenge. Factors such as porosity, inclusions, and material contamination need to be carefully monitored and controlled to meet the desired mechanical properties and performance requirements. Additionally, post-processing steps such as machining or surface finishing may be necessary to achieve the desired surface quality and tolerances, adding complexity and cost to the overall manufacturing process. Lastly, developing robust process monitoring and control systems, along with standards and certifications, is essential to ensure the consistent and reliable production of components across different industries. Addressing these challenges will be crucial in unlocking the full potential of WAAM and establishing it as a viable manufacturing technique for a wide range of applications [273,274].

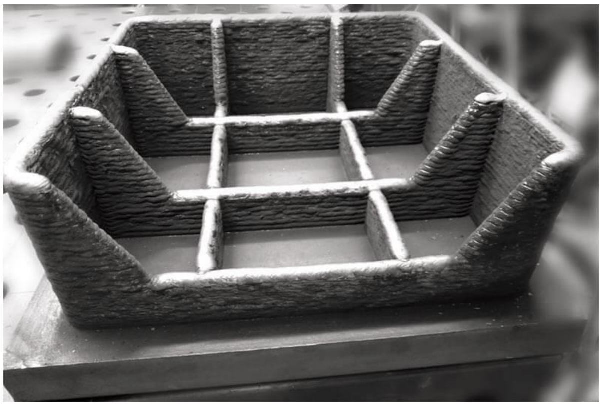


Figure 15. Landing gear made of mild steel.

As the WAAM technology evolves, expanded applications in industries such as the aerospace, automotive, and energy industries can be expected. WAAM's ability to produce large-scale components with good mechanical properties and cost-effectiveness makes it suitable for fabricating structural parts, tooling, and repairs. The future of WAAM lies in improving process control and automation to enhance precision and accuracy, addressing challenges related to residual stresses and distortion [275], and further expanding the range of materials that can be effectively deposited. With advancements in multi-material deposition, it could enable the integration of dissimilar materials in a single manufacturing step, opening new opportunities for functional gradient components [276]. The scalability and cost-effectiveness of WAAM make it attractive for rapid prototyping and on-demand production, offering reduced lead times and material waste [277].

7. Conclusions

This paper has provided a holistic review of the latest AM invention trends, showcasing the transformative impact of this rapidly evolving field. The advancements in AM have revolutionized the way we design, prototype, and manufacture objects, offering unprecedented levels of customization, efficiency, and material utilization. It becomes evident that each AM technique contributes to the diverse range of applications and possibilities in manufacturing. From the aerospace and automotive industries to the healthcare and food sectors, AM has emerged as a versatile solution, enabling the creation of complex geometries, lightweight structures, and functional parts.

Moreover, the integration of new materials, including metals, ceramics, and composites, has expanded the capabilities of AM, allowing for the production of end-use parts with enhanced mechanical properties and increased durability. Additionally, the development of multi-material printing systems has opened avenues for creating objects with intricate material compositions, introducing a new level of functionality and performance. Furthermore, the emergence of advanced software tools and AI algorithms has streamlined the design and optimization processes in AM. These tools enable engineers and designers to simulate and analyze the behavior of printed objects, ensuring their structural integrity, reducing waste, and improving overall efficiency.

In conclusion, recent inventions in AM have demonstrated significant advancements and breakthroughs, revolutionizing the manufacturing landscape. The continuous progress in materials, technologies, and software tools paves the way for a future where AM becomes an integral part of various industries, providing innovative solutions and driving unprecedented levels of efficiency and customization. As researchers and industry professionals continue to push the boundaries of AM, we can anticipate even more remarkable developments and a widespread adoption of this transformative technology in the years to come. In the future, AM operations are expected to witness remarkable advancements, with continuous improvements in speed and accuracy driven by innovative materials, enhanced printing techniques, and sophisticated control systems including AI.

Author Contributions: Conceptualization, I.F., O.H., A.G. and S.H.; methodology, I.F., O.H., A.G. and S.H.; investigation, I.F., E.Y. and J.L.; resources, all authors; data curation, I.F., O.H. and S.H.; writing—original draft preparation, all authors; writing—review and editing, all authors; supervision, I.F.; project administration, I.F. All authors have read and agreed to the published version of the manuscript.

Funding: This holistic research review received no external funding.

Data Availability Statement: Some of the data presented in this holistic review study are available at https://wohlersassociates.com/product/wr2023/ accessed on 31 July 2023.

Acknowledgments: The staff support provided by each author's lab and/or department is appreciated. The data support provided by Wohlers Associates is also appreciated.

Conflicts of Interest: The authors declare no conflict of interest.

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