Additive Manufacturing Processes and Its Applications: An Extensive Review

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Abstract — Additive Manufacturing (AM), commonly known as 3D printing, has emerged as a transformative technology with significant implications across industries. This research paper presents a comprehensive review of the current state of additive manufacturing, focusing on its diverse techniques, novel materials, and wide-ranging applications. The paper systematically examines various AM techniques, including powder bed fusion, vat polymerization, material extrusion, binder jetting, and directed energy deposition, highlighting their underlying principles and technological advancements. The exploration of materials in additive manufacturing encompasses polymers, metals, ceramics, composites, and biomaterials, each with unique characteristics and challenges. This paper delves into the ever-expanding applications of additive manufacturing industries such as aerospace, healthcare, automotive, consumer goods, and architecture have embraced AM for rapid prototyping, customized production, and complex geometries that were previously unattainable. The paper outlines specific use cases and showcases how AM is driving innovation and enabling new design paradigms across sectors. It is evident that additive manufacturing is reshaping manufacturing paradigms and fostering unprecedented opportunities for innovation across industries.

Keywords: Additive Manufacturing, Rapid Prototyping, AM Industry Trends, Additive Manufacturing Applications

I. INTRODUCTION

Additive manufacturing (AM) is a revolutionary technique that builds 3D objects by adding material layer by layer based on digital 3D design data. According to ASTM standards, AM techniques are classified into vat photopolymerization, material extrusion, powder bed fusion, sheet lamination, directed energy deposition. Vat photopolymerization solidifies liquid photopolymers using light, such as stereolithography (SLA) and digital light processing (DLP). SLA builds parts layer by layer by selectively curing liquid photopolymers with an ultraviolet laser beam. DLP uses an image projection system to cure the entire layer at once. These techniques produce high resolution and smooth surface finish but the materials are limited. Material extrusion pushes molten materials through a nozzle, such as fused deposition modeling (FDM). FDM extrudes thermoplastics to form layers and bonds them by heating. It has a wide range of inexpensive materials but limited resolution and surface finish. Powder bed fusion uses thermal energy to fuse regions of a powder bed, such as selective laser sintering (SLS) and electron beam melting (EBM). SLS sinters powdered materials with a laser, while EBM uses an electron beam in a vacuum. They produce high density and strength parts with various materials but require expensive equipment. Sheet lamination stacks and bonds sheets of materials. Laminated object manufacturing (LOM) cuts sheets and bonds them together. It uses inexpensive materials but limited resolution and surface finish. Directed energy deposition focuses thermal energy to fuse materials by melting as they are being deposited. Laser engineered net shaping (LENS) and electron beam additive manufacturing (EBAM) are two examples. They have high deposition rates but typically lower resolution and surface finish. In summary, AM techniques offer design flexibility and economic low volume production, with vat photopolymerization and powder bed fusion producing the highest resolution and quality parts, material extrusion the most inexpensive, and directed energy deposition the highest deposition rates. AM will continue to transform how we design and manufacture high performance and custom products.

II. MATERIALS USED IN AM

A. *Additive manufacturing with polymer materials*

Additive manufacturing (AM) with polymers has progressed rapidly in recent years and shows tremendous promise for transforming manufacturing. Alghamdi provides a comprehensive review of AM processes for polymers, composites, and other materials, discussing their applications in industries like biomedicine, aerospace, and electronics[1]. Omer Enaf describes a method for AM with polymers where only the surface of the material is melted, allowing the center to remain solid and maintain strength. This "monolithic attachment" produces uniform, controllable products[2]. Maguire focuses on extrusion-based AM, where polymers are dispensed through a nozzle. This enables intricate cellular architectures with improved properties like low density and high mechanical performance. Polymers used include thermoplastics, elastomers, thermosets, and composites[3]. Jafferson also reviews extrusion-based AM, discussing polymers like polycarbonate, ABS, PEEK, and nylon. They note polymers' low cost, water resistance, and versatility enable applications across industries.[4] González-Henríquez describes various AM technologies for polymers like fused filament fabrication, selective laser sintering, and stereolithography. They discuss 4D printing, where 3D printed structures change over time, enabled by shape memory polymers. Applications include biomedical uses like anatomical models, tissue engineering, and drug delivery[5]. Pal predicts exponential growth in the polymer AM market, exceeding $20 billion by 2021, enabled by functional polymers and composites. AM's customization, precision, and efficiency advantages over injection molding and thermoforming enable applications in automotive, medical, aerospace, and consumer products[6]. Yuan focuses on powder-based AM techniques like selective laser sintering that fuse polymeric, metallic, ceramic or composite powders into products. Polymeric composites provide unique properties for applications like aerospace, automotive, medical, and energy[7]. Turek reviews polymer materials used in medicine, especially for equipment, surgery, dentistry, anatomical models, surgical templates, and implants. Biodegradable polymers can regenerate or replace tissues. AM enables shorter procedures, increased precision, and progress in medical applications of polymers[8]. There have been major advances in AM with polymer materials, including extrusion and powder based techniques. Their customization, efficiency, and ability to achieve unique properties enable applications across industries, especially medicine. Continued progress in materials, processes, and applications promises to transform manufacturing.

B. *Additive manufacturing with metal alloys*

Additive manufacturing (AM) of metal alloys is an emerging technology with significant potential for producing complex parts with enhanced properties. Furumoto highlights how AM enables flexibility and customization for various industries. However, the alloys currently compatible with AM are limited[9]. Zhang reviews various metal alloys for AM, including titanium, steel, nickel, aluminum, and more complex alloys. They note that alloy development for AM requires understanding how composition and processing impact microstructure and properties. Two papers focus on aluminum alloys, which are desirable for AM but challenging to process[10]. Martin demonstrates that introducing nanoparticle nucleates during selective laser melting (SLM) enables crack free, finegrained aluminum alloy parts with wrought like properties[11]. Aboulkhair reviews how SLM of aluminum alloys has progressed, enabling more defect free parts, but notes that further work is needed to satisfy industrial needs. Other papers explore more complex alloys for AM[12]. Tammas-Williams proposes that AM is well-suited for site specific properties and reviews progress in graded materials[13]. Hofmann demonstrates radially graded metal inserts with low thermal expansion for spacecraft using laser deposition AM[14]. Kenzari introduces quasicrystal line aluminum alloys for AM to produce lightweight, high-performance parts[15]. Finally, Murr reviews the metallurgy of various alloys fabricated using electron beam melting (EBM) AM, including titanium, cobalt chromium, nickel, niobium, and iron alloys. They find that EBM produces columnar microstructures and can achieve properties comparable to wrought and cast alloys[16]. AM of metal alloys is still an emerging field, recent work has expanded the range of compatible alloys, including aluminum, titanium, and nickel alloys as well as more complex alloys. AM enables the production of site specific, graded, and lightweight high-performance metal parts with tailored microstructures and properties. Continued alloy development and optimization for AM processes will help drive industrial applications.

C. *Additive manufacturing with composite materials*

Additive manufacturing (AM) techniques show great promise for producing fiber reinforced polymer composite parts with complex geometries and tailored properties[17]–[19]. AM allows for the construction of net shape structures with complicated internal architectures without the need for multistep processing or joints. This enables ascribing specific material properties at a submillimeter scale, allowing for MultiMate rial, functionally graded designs[17]. AM of composites provides an opportunity to implement designer material properties, such as anisotropic mechanical, thermal, and electrical properties, by precisely controlling the orientation and distribution of reinforcing fibers [18]–[20]. Aligning fibers during the AM build process can be achieved through the application of mechanical forces or fields like electric, magnetic, shear, or ultrasound[19]. Combining AM and fiber alignment techniques enables the fabrication of polymer matrix composites with complex geometries and tailored, directional properties without the need for molds[18], [19]. While AM of fiber reinforced composites shows promise, there are several challenges that must be addressed. Voids can form, adhesion between fibers and matrices may be poor, fibers can cause blockages, and curing times may increase [20], [21]. Modeling and simulating the AM of composites is difficult due to the complex relationship between process parameters, material properties, and resulting microstructures [21], [22]. However, new materials, AM techniques, and fiber alignment methods are actively being developed to overcome these challenges [21], [23]. AM enables the production of fiber reinforced polymer composite parts with complex geometries and tailored properties. By precisely controlling fiber orientation during the build process, AM can be used to fabricate composites with directional properties for specific applications. While several technical challenges remain, continued progress is being made in materials, processes, and modeling to fully realize the potential of AM for composite part production.

D. *Additive manufacturing ceramics materials*

Additive manufacturing (AM) shows great promise for revolutionizing the ceramic industry by enabling the production of complex ceramic components without expensive tooling. While AM of ceramics has lagged behind polymers and metals, interest is growing in developing AM processes that can produce high-density, defect free ceramic parts. Many AM technologies can shape ceramics, but results vary based on the material, process, and part geometry. Selecting the right AM technology depends on the requirements for density, surface finish, size, complexity, and the specific ceramic[24]. Material extrusion, where material is pushed through a nozzle, shows particular promise for ceramics [25], [26]. Extrusion based techniques include extrusion free forming, robocasting, ceramic OnDemand extrusion, and freeze form extrusion fabrication. These techniques use filament or paste and differ in how layers retain their shape, e.g. through solvent evaporation or temperature control. Postprocessing and sintering can achieve high density and mechanical properties. Opportunities exist to incorporate UV-curing, gelation, and complex geometries [25]. Laser based techniques also show promise, though they remain challenging. They allow direct production of ceramic parts but require optimizing materials and process parameters [27]. Stereolithography builds 3D ceramic structures by solidifying liquid ceramic layers with a UV laser. It can achieve complex, accurate geometries and smooth surfaces but requires optimizing materials for UV curing and rheology [28]. AM could transform the ceramic industry by enabling low-cost, customized production. However, technical challenges have slowed progress, especially achieving high density and surface finish. Selecting the optimal AM technology and materials is key to overcoming these challenges. AM could open new applications and markets for ceramics if these challenges are met [29], [30]. AM of ceramics materials shows promise for enabling low-cost customized production, progress has been slow. Extrusion based and laser-based techniques are the most promising but require optimizing materials and processes to achieve high density, surface finish, and geometrical complexity. Selecting the right AM technology and materials is key to success.

E. Additive manufacturing with smart materials

Additive manufacturing, or 3D printing, has enabled the creation of complex structures using smart materials that can change their properties or shape in response to external stimuli [31]–[33]. This emerging field of 4D printing combines 3D printing with smart materials to create dynamic structures that can transform over time [34], [35]. Researchers have developed new smart materials that can respond to various triggers like heat, light, pH, and magnetic fields [31]–[33]. For example, shape memory alloys and polymers can change shape in response to temperature changes [31], [32]. Photochromic materials can change properties when exposed to light [33]. pH-responsive hydrogels can swell or shrink based on pH [31]. Magnetic materials can change shape in magnetic fields [32]. 4D printing with smart materials enables the creation of structures that are difficult or impossible to make using traditional methods. Potential applications include soft robotics, deployable structures, tune able metamaterials, and self-evolving structures. 4D printing is also enabling advancements in fields like healthcare, with applications in tissue engineering, drug delivery, and smart sutures[31], [32]. While 4D printing with smart materials shows promise, challenges remain around developing materials, improving printing processes, and modeling responsive behaviors [31]–[33]. However, continued progress in this emerging field could lead to dynamic structures with increased functionality and the ability to adapt to their environment[31]–[33]. Overall, 4D printing with smart materials represents an exciting new frontier in manufacturing that is poised to shape the future.

F. Additive manufacturing with shape memory alloy

Additive manufacturing (AM) techniques like selective laser melting (SLM) allow for the fabrication of shape memory alloys (SMAs) into complex geometries that would otherwise be difficult to achieve through conventional processing methods . SLM in particular has been applied to produce NiTi SMA parts, though issues like cracking remain [36]. A review of AM applied to various SMA systems found that process parameters and heat treatments significantly impact the microstructure, printability, and functionality of additively manufactured SMAs [37]. CoNiGa SMAs were successfully processed for the first time using SLM, resulting in a columnar grained microstructure ideal for shape memory performance, though cracking was also observed [38]. A designed processing route incorporating SLM, hot isostatic pressing, and heat treatment was able to achieve satisfactory shape memory behavior in CuAlNi SMAs [39]. Proper design for embedding SMA wires in 3D printed parts enabled the fabrication of actuated joints and a cell phone crawling robot [40]. A composite with an SMA wire/polymer skeleton was developed to create a soft morphing structure with large deformation [41]. SMA-reinforced metal matrix composites (MMCs) were reviewed, highlighting their special properties like high damping, strength, and fatigue resistance. Aluminum MMCs reinforced with SMAs were a particular focus, examining their fabrication, microstructure, interface reactions, modeling, and physical/mechanical properties. The shape memory effect was found to significantly impact the properties of these composites [42]. In summary, AM shows promise for fabricating SMA parts with complex geometries, though issues around cracking must be addressed. SLM in particular has been applied to produce NiTi and Co-Ni-Ga SMAs. Proper design and processing are required to achieve shape memory behavior in additively manufactured SMAs. SMA reinforced MMCs, especially aluminum MMCs, demonstrate unique properties derived from the shape memory effect.

III. APPLICATIONS OF AM IN VARIOUS FIELDS

A. Applications of AM in aerospace industries

Additive manufacturing (AM) has revolutionized the aerospace industry by enabling complex geometries, reduced costs, and shorter lead times. AM allows for innovative designs that provide additional space, multifunctional parts, MultiMate rial parts, part consolidation, and difficult to machine parts. The aerospace industry has installed thousands of AM parts, including nonmetallic parts, on aircraft. Boeing and Airbus are producing largescale AM metal parts and expect high production volumes [43].

The main applications of AM in aerospace are rapid prototyping, rapid tooling, repair, and direct digital manufacturing (DDM) of metal, plastic, ceramic, and composite parts. DDM is the fastest growing application. The dominant AM technologies for metal parts are directed energy deposition and powder bed fusion. For nonmetals, the main technologies are vat photopolymerization, material jetting, and material extrusion [43].

AM provides advantages for space flight, including innovative designs, mass reduction, and in space production. However, material selection, processing, postprocessing, and qualification require consideration for space applications [44].

Laser based AM, especially powder bed fusion and direct energy deposition, show promise for aerospace. They enable reduced process time, weight savings, and new materials. However, certification, cost, build size, and material properties require improvement for widespread aerospace use [45].

Metal AM is transforming commercial aviation by enabling complex parts, reduced costs and lead times, and new alloys. It provides opportunities for weight savings, part consolidation, internal features, and freeform designs. Major aviation companies have installed thousands of AM parts and are producing large structural parts. However, improvements in materials, design, cost, and certification are still needed [46], [47].

AM and 3D printing offer flexibility in geometry, materials, and time for aerospace. They enable complex, lightweight parts with little waste [48], [49]. AM is used for prototyping, tooling, repair, and enduse parts in aerospace. Technologies like laser metal deposition are used to repair components [48]. Although AM shows promise, continued progress in materials, design, and cost is required for more widespread aerospace use [49].

In summary, AM enables complex, lightweight, and consolidated parts with reduced cost and time for aerospace applications like aircraft structures, engines, and space systems. While AM has been implemented for thousands of plastic and metal parts, continued improvements in materials, design, cost, and certification will enable more widespread use of AM for enduse aerospace components.

B. Applications of AM in constructions appliances

Additive manufacturing (AM), also known as 3D printing, is revolutionizing the construction industry. Camacho review how AM can decrease labor costs, reduce material waste, and enable complex geometries in construction[50]. Paolini discusses how large 3D printers are creating building components from various materials[51]. Koralay analyzes how applicable different AM methods and materials are for construction[52]. Lim focuses on ‘concrete printing,’ an automated extrusion process for creating architectural elements. AM brings many opportunities to construction [53]. Buchanan explains how metal 3D printing can create efficient, customized structures and notes down the need for digitally savvy engineers, advanced computing, and rethinking design verification [54]. Wróbel reviews using AM for electrical components in machines. However, AM also brings challenges [55]. Mierzwiński says AM in construction requires more development and optimization and how AM reduces costs and waste in construction projects [56]. In summary, AM is revolutionizing construction through cost and time savings, waste reduction, complex geometries, and customization Metal and concrete 3D printing show particular promise. However, realizing AM’s potential demands overcoming challenges like developing digital and design skills. AM will likely complement, not replace, traditional techniques. The future is bright for this key enabling technology in construction.

C. Applications of AM in consumer goods

Additive manufacturing (AM), also known as 3D printing, is revolutionizing the way consumer goods are designed and produced. Mohajeri argues that AM enables a new "social manufacturing" paradigm where consumers are involved in all stages of design and production[57]. Bogers similarly notes that AM allows for more "consumer centric" business models and supply chains[58]. These new models provide greater design freedom and customization, allowing companies to produce highly complex and varied products OnDemand [59].

AM has been applied to fashion and jewelry, where it provides greater design freedom and allows mass customization [60]. Petrovic gives examples of AM being used for tooling, biomedicine, automotive parts, and aerospace components [61]. Venekamp notes that AM was originally used for rapid prototyping but is now being applied to final part production in various industries [62].

Haleem identifies 13 important applications of AM that are enabling "Industry 4.0," including automation, interoperability, and information transparency [63]. Guo provides an overview of the major AM processes, materials, and applications, noting progress in aerospace, automotive, biomedical, and energy applications. However, the strength and quality of AM parts remains lower than traditional manufacturing, and the equipment cost is high.[64]

In summary, AM is enabling new consumer centric and social manufacturing paradigms that provide greater design freedom and customization. AM has been applied to fashion, jewelry, tooling, biomedicine, automotive, aerospace, and other applications. AM is a crucial technology for achieving the goals of Industry 4.0, though cost and quality remain limitations. Overall, AM is revolutionizing consumer goods design and manufacturing, providing new opportunities for customization and a closer connection between companies and their customers.

D. Applications of AM in Health care and medical appliances

Additive manufacturing (AM) or 3D printing has revolutionized the healthcare sector with its ability to produce customized medical devices and components. Giannatsis provides an overview of how AM is used to fabricate custom implants, surgical models, drug delivery devices, and new AM techniques for medical use[65]. Priyadarshini argues that AM provides flexibility and innovation in healthcare, especially in times of crisis, and can be used to build resilient supply chains. AM has enabled significant advances in bioprinting, tissue engineering, dentistry, and orthopedics[66]. Sheeran reviews how AM is used to print patient specific implants, medical devices, surgical tools, and scaffolds for tissue engineering. AM also allows for virtual surgical planning and the printing of replacement organs. Despite progress, Sheoran also argues there is still potential for improvement in pharmaceuticals and drug delivery. While AM brings opportunities, it also faces challenges in healthcare applications [67]. Adugna identifies limitations like high costs, lack of standardization, biocompatibility issues with materials, and regulatory concerns [68]. Tripathi focuses on applications in cardiology and dentistry, arguing AM enables customized surgical tools, implants, and education [69]. Javaid reviews 40 applications of AM in medicine, identifying achievements and limitations in areas like implants, prosthetics, surgical planning, and education [70]. Bastin argues AM is revolutionizing medicine by enabling customized devices matched to patient anatomy and exact anatomical models for diagnosis and surgery. AM also allows for tailored mechanical properties and surface features. As AM has become better understood, there is more control and consistency, enabling medical applications. Bastin reviews the regulatory pathway for medical devices and common AM processes used in medicine [71]. Patel argues AM played a key role in India's COVID19 response by enabling quick local production of crucial parts, reducing waste and reliance on global supply chains. Various groups collaborated to develop opensource 3D printed products [72]. These papers show how AM is transforming healthcare through customized and innovative medical devices, implants, surgical tools, and anatomical models. While challenges remain, AM provides flexibility and resilience, as evidenced in the COVID19 crisis. With more advanced and consistent processes, as well as a regulatory framework, AM will continue enabling significant medical advances.

E. Applications of AM in education sector

Additive manufacturing (AM) has become an increasingly important technology in education. Several papers discuss how AM is being integrated into engineering curricula at universities to prepare students for careers in this growing field. Keaveney details how an undergraduate engineering program incorporated AM into their curriculum through a project where students designed and 3D printed a turbocharger turbine part. This hands-on experience with AM improved student engagement and learning [73]. Alabi provides an overview of AM research and education efforts at several South African universities, arguing these show the potential for AM education in developing countries. Two papers specifically focus on simulation tools for AM education[74]. Anand discusses how the University of Cincinnati is developing curriculum around Siemens AM simulation software to teach students the entire product lifecycle and prepare them for Industry 4.0 careers [75]. Serdar argues students need to learn sophisticated AM design skills and tools, like simulation and topology optimization software, to take advantage of AM's capabilities. They discuss modifying an engineering design class to improve students' skills with complex AM geometries. Several papers point out the interdisciplinary nature of AM and the need for collaboration across engineering fields [76]. Mehta reviews literature on AM education, especially at the graduate level, to develop a specialized AM workforce. They argue AM education requires expertise crossing all engineering backgrounds and that foundational engineering education research can help develop interdisciplinary and agile AM experts [77]. Alabi and Ramdhani also note the interdisciplinary possibilities of AM in education [74], [78]. The papers show AM education is crucial to prepare students for AM careers and take advantage of this new technology's potential. AM education requires an interdisciplinary approach, hands-on experience, and knowledge of simulation and design tools. Integrating AM into engineering curricula, especially at the graduate level, can develop the agile, specialized workforce needed for the future of this technology.

IV. TESTING OF ADDITIVE MANUFACTURING PARTS

A. Mechanical testing of AM parts

There are many methodologies discussed across these papers for mechanically testing additively manufactured components. Dongare proposes using Mini tensile testing, a scaled down tensile test, to evaluate the anisotropic properties of AM parts. This is a cost-effective method for understanding how cooling rates and build orientation affect mechanical properties [79]. Warad discusses using finite element analysis (FEA) to validate the strength of AM tooling components. They found that for some applications, isotropic material properties can provide acceptable results, simplifying the modeling [80]. Agarwal provides an overview of various mechanical tests used for AM, including tensile, fatigue, torsion, hardness, and impact testing [81]. These tests are critical for determining the performance parameters of AM components. Schnittker proposes integrating digital image correlation (DIC) into tensile testing of large AM parts. They used this method to measure Poisson’s ratio and elastic modulus of glass filled ABS parts, finding poor adhesion between the ABS and glass fibers [82]. Reddy performed small-scale tensile testing on various metal AM alloys, including IN718, CoCrMo, Maraging steel, SS316L and Ti6Al4V. They found this method viable for quality control and building hybrid parts [83]. Merklein also performed tensile testing on AM stainless steel parts, finding high potential but need for further optimization [84]. Agostinis provides an overview of experimental studies on the mechanical properties of both metal and polymer AM materials. Studies looked at how porosity, layer linkage, surface roughness, build orientation, layer thickness, infill percentage, and other factors affect properties [85]. Aleshin proposes using nondestructive testing (NDT) methods like ultrasonics and computed tomography to evaluate AM parts during the build process. This could enable layer by layer quality control [86].

B. Thermal testing of AM parts

The papers show that thermal testing is critical for understanding and improving additive manufacturing parts. Eyerc found that the interface temperature between layers in a 3D printed ABS part exceeded the glass transition temperature, indicating poor interlayer bonding. They suggest thermal monitoring and control is needed for high quality parts [87]. Carvalho used simulations and experiments to study how heat transfer affects defect detection in 3D printed nylon parts. They found simulations provide insight into optimizing nondestructive testing parameters [88]. Merklein also studied how process parameters affect mechanical properties in metal 3D printed parts. They found properties depend on controlling porosity, layer linkage and surface roughness, showing the need for thermal testing [84]. Billah embedded thermocouples in 3D printed polycarbonate parts with embedded wires to measure temperature during high current testing. They found heat-treating reduced porosity and increased breakdown strength and heat dissipation [89]. Xiong used simulations and experiments to study how preheating the substrate affects thermal behavior in metal 3D printed parts. They found preheating smoothes thermal cycles, decreases cooling rates, and reduces temperature gradients, suggesting it could reduce defects Xiong. Yavari validated a graph-based model for predicting thermal history in directed energy deposition additive manufacturing of titanium parts. Their model closely matched experimental temperature measurements, showing promise for predicting distortion and microstructure [90]. Kenderian embedded thermocouples in metal 3D printed parts to monitor temperature during the build process. They found temperature accumulation, dissipation, and drops can indicate defects, allowing for real-time adjustments [91]. Finally, Sehhat studied how temperature and material affect mechanical properties of FDM 3D printed polymer parts for space applications. They found temperature significantly impacts tensile strength, while material type does not. ABS showed the best properties across temperatures due to its high glass transition temperature [92]. The multiple studies about thermal testing of AM parts show that thermal testing and monitoring of additive manufacturing parts provides critical insights into defects, mechanical properties, and process improvements for high quality parts. Simulations and experiments have been used to understand thermal behavior, and real-time monitoring shows promise for defect detection and correction during the build process.

V. CONCLUSIONS

In summary, while AM enables design flexibility and sustainability, its full potential is limited by technical obstacles. With further development, AM may transform manufacturing through customized, optimized production. Overall, the reviews indicate AM is an emerging set of technologies with both opportunities and challenges that, if addressed, could revolutionize manufacturing.

The researchers have explored NDT methods, specialized test specimens, standardized test artifacts, physical testing, and postprocessing techniques to evaluate the quality, properties, and reliability of additively manufactured parts. These methods help ensure that AM parts will function as intended for their enduse applications. Continued research and development of testing procedures will be crucial as AM becomes more widely adopted for production of functional components.

For thermal testing simulation, modeling, experimental methods have all been used to explore the complex thermal phenomena in AM processes. A deeper understanding of thermal behavior can help improve process monitoring, control, and part quality.

The future of additive manufacturing holds significant potential for growth and innovation. Additive manufacturing will likely involve continuous innovation, collaboration between industries, and a greater focus on sustainability, customization, and efficiency. As technology advances and new applications emerge, AM is poised to play a central role in reshaping manufacturing and product development processes.

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