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Advances in Nanocomposite Materials for Additive Manufacturing: A Review of Materials, Methods, and Applications

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Abstract: Additive manufacturing (AM), or 3D printing, has rapidly advanced from prototyping to functional part fabrication, driven by its ability to produce complex geometries with minimal material waste. A critical enabler of next-generation AM applications is the integration of nanocomposite materials — engineered by incorporating nanoscale fillers into polymeric, metallic, or ceramic matrices. These nanocomposites offer enhanced mechanical, thermal, electrical, and biological properties, unlocking multifunctional capabilities for a wide range of industries, including aerospace, biomedical, electronics, and energy. This review provides a comprehensive overview of the types of nanocomposites and nanofillers used in AM, examines their compatibility with various AM techniques, and explores the functional enhancements they bring. Key application areas and the associated challenges in processing, scalability, and safety are discussed. The article concludes with insights into future trends, emphasizing the transformative role of nanocomposites in advancing AM toward high-performance, intelligent, and sustainable manufacturing solutions.

Keywords: Additive Manufacturing, Nanocomposites, 3D Printing Materials, Functional Materials, Advanced Manufacturing Technologies.

1. Introduction

3D printing or additive manufacturing (AM) is one of the revolutionary technologies to create objects starting with a layer-by-layer manufacturing based on a digital model. Unlike traditional subtractive manufacturing methods in which material has to be removed off a larger piece to form the desired shape; material is added only where it is necessary in AM. Such special system will enable remarkable design flexibility, customizability and material savings. Originally used in prototyping and low-cost plastic products, AM has grown slowly since its inception two decades ago and is currently used in the mass production of complex and functional components used in various industries such as aerospace, healthcare, automotive, and consumer electronics [1-3]. Although these improvements have been made, functional constraints of the conventional materials involved in AM have continued to cut-short full potential of the technology. The AM materials with the best performance characteristics e.g., thermoplastics, photopolymers, and metal powders are unlikely to be used in applications, demanding high performance unless customized. This has led to the need to find stronger materials that have the capacity of delivering not only mechanical capabilities but also multifunctional applications that can be used including electric conductivity, thermal management, chemical resistivity, and biocompatibility. A possible way out is the producing of nanocomposites by adding nanomaterials to regular

AM feedstocks. Nanocomposites can be defined as intermittent materials comprising a matrix (polymeric, metallic, and ceramic) layer impregnated with free nanomaterials (carbon nanotubes (CNTs), graphene, metal and metal oxide nano particles, nano clays, or silica). The reinforcements have a large surface area-to-volume ratio and special physical, chemical, and mechanical characteristics that make it possible to enhance the performances notably even with low filler concentrations. Through nanomaterial inclusion in standard matrices, nanocomposites have potential to enhance their tensile strength, rigidity, tensile rigidity, impact performance, thermal stability, conductivity, flame resistance and even biologic activity. This goes ahead to make them suitable candidates in taking AM to the next level where it can become a means to developing high-performance, functioning end-use parts [4,5].

The combination of nanocomposites and AM technologies is particularly attractive because of a number of reasons. First, the very computational character of AM allows high resolution of control over part geometry, to position nanomaterials in particular areas of a component to optimize their localized properties. Second, AM can facilitate the production of light shelves with internal characteristics and complex shapes, which could not be produced easily or even at all, within relevant manufacturing tools. These geometries may facilitate multifunction behavior (when used with nanocomposites) e.g. embedded sensors, thermal management or smart responsiveness. Third, AM provides a versatile route to the creation of new materials with in-situ mixing, multi-material printing, and optimization of the process that increases the extent of possible applications. Nevertheless, the introduction of nanocomposites in AM processes is not devoid of difficulties. The addition of nanomaterials will considerably modify the rheological behavior of feedstocks that make material supply, printing, and adhesion of layers much trickier. Moreover, the uniformity in the dispersion of nanoparticles in material processing and printing is imperative in maintenance of performance consistency. They can cause problems in the structure leading to structural defects and variation in properties of printed parts due to agglomeration, poor interfacial bonding and sedimentation of nanoparticles. In addition, nanomaterial compatibility with different AM processes and matrix is also a point of serious inquiry. To some degree, all AM methods (construed as fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), or direct ink writing (DIW)) present distinct demands of material formulation and behavior [6-8].

Regarding such opportunities and challenges, this review article attempts to present the overall overview of its current state in nanocomposite materials in additive manufacturing. It starts with the description of the types of nanocomposites and nanofillers, and then the description of various AM technologies applicable to nanocomposites processing. Then the article draws attention to the major functional improvements that become possible when using nanocomposites, including reinforcement, conductivity, and biocompatibility. Recent uses in industries such as aerospace, biomedical and electronics are discussed, as well as key processing and safety issues. The review is also made complete with the discussion of the new trends and research directions, which may define the profession in the future in this quickly developing area. With this discussion, we hope to highlight the way nanocomposite materials in additive manufacturing can revolutionize the industry and give a guide on the future study and industrial application [9].

2. Materials and Methods

Types of Nanocomposites and Nanofillers

- Nanocomposites are made in engineering by adding reinforcements at the nanoscale-level usually less than 100 nanometers into an ordinary bulk material. These reinforcements improve greatly the physical, mechanical, thermal as well as the functional properties of the host matrix. Depending on the type of the matrix product, the antimony nanocomposites most often applied in the additive manufacturing (AM) can be divided into three major groups: polymer matrix nanocomposites (PMNCs), metal matrix nanocomposites (MMNCs), and ceramic matrix nanocomposites (CMNCs) [10].

2.1 Nanocomposites (PMNCs)

The PMNCs are the most studied type of nanocomposites in relation to AM as this type of nanocomposites can be easily processed, and polymers correlate with most of the current AM techniques. Polymer matrices used commonly are thermoplastics and thermosets. By adding nanofillers, mechanical strength, thermal stability, flame retardancy and functional behavior of these materials become more enhanced.

- **Carbon Nanotubes (CNTs)**: CNTs offer exceptional tensile strength and electrical conductivity. They can be integrated into thermoplastics like PLA, ABS, and nylon to create conductive filaments suitable for FDM. However, achieving uniform dispersion is challenging and critical for performance.

- **Graphene and Graphene Oxide**: These 2D nanomaterials improve mechanical, thermal, and barrier properties. They also enable the development of smart or responsive polymer systems.

- **Nano clays**: These are layered silicate structures that enhance barrier properties, flame retardancy, and stiffness.

- **Silica and Metal Oxide Nanoparticles**: Nanoparticles like SiO_2, TiO_2, and ZnO improve UV resistance, strength, and antimicrobial properties.

The key challenge in PMNCs lies in ensuring homogeneous dispersion and strong interfacial adhesion between the nanofillers and the polymer matrix, which determines the overall composite performance [11].

2.2 Metal Matrix Nanocomposites (MMNCs)

MMNCs are composed of a metal matrix—such as aluminum, titanium, or nickel—reinforced with ceramic or carbon-based nanoparticles. These materials are processed using high-temperature AM methods like selective laser melting (SLM) or directed energy deposition (DED).

- **Ceramic Nanoparticles (e.g., SiC, Al_2O_3, TiC)**: These reinforcements significantly enhance hardness, wear resistance, and high-temperature strength.

- **Carbon-Based Nanomaterials (e.g., CNTs, Graphene)**: These improve mechanical strength and electrical conductivity, although compatibility with metal matrices can be more difficult.

- **Intermetallic Nanoparticles**: These can contribute to improved high-temperature performance and oxidation resistance.

Dispersion and wettability of nanoparticles in molten metal are major challenges, often requiring the use of ultrasonic mixing, mechanical alloying, or surface modification techniques.

2.3 Ceramic Matrix Nanocomposites (CMNCs)

Ceramic matrices are inherently brittle and have poor fracture toughness, which limits their application. Nanocomposite strategies aim to overcome these limitations by introducing reinforcements that can deflect cracks and improve energy absorption.

- **ZrO_2 Nanoparticles**: Enhance toughness and thermal shock resistance.
- **Carbon Nanotubes and Graphene**: Improve mechanical resilience and thermal conductivity.
- **SiC and AlN Nanoparticles**: Provide improved hardness and wear resistance.

CMNCs are typically fabricated using binder jetting, robocasting, or stereolithography of pre-ceramic polymers, followed by high-temperature sintering. Controlling shrinkage and porosity during sintering is a critical challenge in achieving high-performance parts [12-14].

2.4 Hybrid Nanocomposites

There are also instances to employ nanofillers of more than one category with the objective of exploiting synergetic effects. Another example is given in connection with CNT in which a combination of CNT with graphene or ceramic nanoparticle would result in enhanced multifunctional effects, including being both mechanically and electrically reinforced.

2.5 Major Concerns on Selection of Nanofillers

Aspect Ratio: High aspect ratio fillers (such as CNTs and nanofibers) have more efficient contributions toward mechanical conductive properties. Silane modification, the process of adding a silane, may enhance the interaction between nanofillers and the matrix as well as their dispersion.

Loading Content: The ideal filler content should be able to provide performance advantages and improve processability as well as overloading can negatively affect extrusion or curing.

In brief, the choice and combination of nanofillers depending on their properties and compatibility with AM technologies play a very critical role in shaping nanocomposite materials in terms of their performance. The matrix and nanofiller interaction is the basis on which the next-generation materials for the additive manufacturing can be developed [15,16].

3. Results

Additive Manufacturing of Nanocomposites

The need to integrate nanocomposite materials in the additive manufacturing (AM) has required alterations and developments in the processing strategies to manage the peculiarities and characteristics of the advanced material. The level of compatibility of different AM processes with the nanocomposite feedstocks varies based on many factors including viscosity, thermal stability, filler content and resolution demands. This section goes into the details of the key AM methods used in processing nanocomposites and their mechanism of action, benefits, drawbacks, and the application areas.

3.1 Fused Deposition Modeling (FDM)

FDM is among the commonest AM methods to fabricate nanocomposites because of accessibility and cost effectiveness. It entails extrusion of thermo plastics filaments into a heated nozzle and extrudes material on top of another to create the final product.

Nanocomposite Integration: Composite filament usually is created by embedding the nanoparticles (carbon nanotubes, graphene and metal oxides) into thermoplastic resins (PLA, ABS or nylon) as nanocomposites.

Pros: Easy to set up, high compatibility of material, and the ability to be used in rapid prototyping.

- **Difficulties:** Nanoparticle dispersions are hard to achieve evenly and their agglomeration might lead to clogged nozzles or non-uniform flow. The rheology and thermal properties of the filament are also influenced by the presence of nanoparticles, and thus great attention should be paid to the parameters during the printing process [17].

3.2 Stereolithography (SLA)

SLA applies a laser or digital light projector to cure a layer of photopolymer resin selectively layer by layer. The resolution of this technique is also high and surface finishes are smooth so this method is more viable in complex and fine nanocomposite structures.

Nanocomposite Integration: Nanoparticles are mixed into UV based resins in order to increase mechanical strength, wear resistance or electrical features.

Pros: Very accurate and finish; applicable to functional features with stringent tolerances.

Challenges: Adding nanoparticles has drawbacks that alter the print depth and resolution due to the rise in resin viscosity. It is important to maintain a stable state of nanoparticles with homogeneous dispersion in the resin.

3.3 SLS and Selective Laser Melting (SLM)

The SLS processes as well as the SLM are methods of powder bed fusion whereby powder is sintered or melted employing a laser. SLS applies best to polymers whereas SLM focuses on metals.

Nanocomposite Integration: Nanoparticles get mixed with polymer or metal powders to make reinforced materials. That is, metal powders containing ceramic nanoparticles enhance wear rates and mechanical strength.

Strengths: Capability to manufacture complicated geometries and functional components that have good mechanical characteristics.

Problems: It is hard to attain homogenous powder commingling and nanoparticle dispersion. Nanoparticles may change the energy absorption and melting characteristics of powders and proper laser power, scan velocity and layer thickness will have to be optimized 18].

3.4 Direct Ink Writing (DIW)

DIW or also called robocasting or extrusion-based printing is the process of building structures in layers by extruding through a fine nozzle a highly viscous ink or paste. It is also very helpful in ceramics, hydrogels and functional materials.

Nanocomposites: Combinations of nanomaterials can be integrated into the ink to give multifunctional and responsive nanoparticle types.

The strengths: the flexibility in material design, the capability to print viscous and functional materials, and the availability of applications that deal with embedded electrics and applications that utilize bio applications.

Issues: The rheology of the ink is of prime importance in being printable and maintaining shape. Nanomaterials might agglomerate and sediment, which may undermine stability and flow homogeneity of inks [19].

3.5 Other processes Binder Jetting

Binder jetting uses a binding agent picked out on to a bed of powder selectively. It is applied on metal as well as ceramic nanocomposites which are then sintered to obtain final properties. Nanocomposite Integration-Nanoparticles may be introduced into the binder or the powder to enhance mechanical or thermal properties.

Benefits: No heating when printing, this minimizes the thermal stresses; can be used with tender materials.

Challenges: Parts have to be densified and strengthened after printing and this means they might shrink or warp.

3.6 Major Processing Factors

In all the AM processes, effective fabrication of the nanocomposites relies upon:

- **Quality of dispersion:** it is important that the nanoparticles be well dispersed within the matrix so that it has uniform properties without defects.
- **Material Rheology:** Nanomaterial presence affects the viscous flow of inks, resins or filaments and it must be optimized to ensure an easy extrusion or deposition.
- **Interfacial Bonding:** A good bond between the matrix and nanofillers is essential towards the mechanical performance.

Print Parameter Optimization: Factors such as temperature, laser power, print speed, and layers height should be optimized with each nanocomposites-based formulation.

Overall, the incorporation of nanocomposites in AM manufacturing is being used to make high-performance and multifunctional components. Nonetheless, it needs profound knowledge of material science and process engineering to face the challenges of nanomaterial behavior in printing that are unique [20].

4. Discussion

Potential functional performance improvement along a broad spectrum of properties is one of the greatest arguments to add nanomaterials to additive manufacturing (AM) feedstocks. Such improvements can be made due to the specific properties of nanoscale fillers including their large surface area and strong mechanical, high electrical and good thermal conductivity. This segment discusses major functional gains that have resulted due to the integration of nanocomposites into AM structures with the nature of the associated gains, especially in different application scenarios.

4.1 Strength improvement of mechanical property

One of the most important determinants of the AM part applicability is the mechanical performance especially in the structural and load bearing applications. The base matrix can be enhanced in tensile strength, stiffness and impact resistance to a substantial degree in case of nano powders like carbon nanotubes (CNTs), graphene, silica and nano clays.

- **Strength and Stiffness:** The use of long aspect ratio fillers such as CNTs and nanofibers enhances the modulus and strength through transfer of load to the matrix thus augmenting the stiffness and yield strength.
- **Toughness and Impact Resistance:** Nanoparticles have the capacity to block crack propagation through crack deflection, particle pull-out, and energy dissipation.
- **Fatigue Resistance:** Nanocomposites have been found to be more durable in a cyclic loading situation than pure materials because of increased interfacial bonding and energy dissipation ratings.

The levels of mechanical improvements really depend on few factors i.e. the type of filler, dispersion quality, interfacial bonding and the quantity of filler to be added. Agglomeration and defects can be formed due to overloading with nanoparticles which eliminate the advantages [21].

4.2 Electrical conductivity

Electronic applications Traditional AM materials, particularly polymers, are insulators. Adding CNTs, graphene, carbon black or metal nanoparticles (e.g. silver, copper) in form of conductive nanofillers allows fabrication of conductive nanocomposites material appropriate as an electronic material

- **Percolation Threshold**: When the filler concentration exceeds a critical level, a conductive network forms, allowing electrical conduction through the matrix.
- **Applications**: Printed electronics, flexible circuits, antennas, and electromagnetic interference (EMI) shielding components can be fabricated using conductive nanocomposites.

The performance of conductive nanocomposites is influenced by the type and shape of the nanofiller, its dispersion, and the orientation of conductive pathways during printing [22].

4.3 Thermal Conductivity

Thermal management is essential in electronics, aerospace, and automotive applications. The inclusion of thermally conductive nanomaterials such as graphene, boron nitride, aluminum nitride, or metal nanoparticles improves the heat dissipation capability of AM parts.

- **Enhanced Heat Flow**: Nanoparticles form conductive pathways that facilitate efficient heat transfer, reducing hotspots in functional components.
- **Thermal Stability**: Nanocomposites often exhibit higher resistance to thermal degradation, making them suitable for high-temperature environments.

Proper alignment and dispersion of thermally conductive fillers are critical to achieving isotropic or directionally controlled thermal properties [23].

4.4 Biocompatibility and Biofunctionality

Biomedical AM applications increasingly rely on nanocomposites to meet the complex demands of tissue compatibility, mechanical performance, and biological activity.

- **Bioactivity**: Ceramic nanofillers like hydroxyapatite and bioactive glass promote cell adhesion, proliferation, and bone regeneration.
- **Antibacterial Properties**: Silver, zinc oxide, and copper nanoparticles offer antimicrobial functionality, essential for implants and surgical tools.
- **Customized Mechanical Behavior**: Nanocomposites can be tailored to mimic the mechanical properties of natural tissues, enhancing the integration and performance of implants and scaffolds.

Ensuring the long-term biocompatibility and non-toxicity of nanocomposite components remains a research priority in this domain [24].

4.5 Smart and Responsive Behaviours

The way to 4D printing is through nanocomposites where the printed structures aerometric or can transform into changing shapes or capabilities based on external external stimuli such as heat, light, moisture, or magnetic fields.

- **Shape Memory:** Nanocomposite polymers can memorize their initial form by using certain triggers to allow them to work in deployable and actors' applications.

Self-Healing: Certain nanocomposites also contain healing agents or reversible bonding modes that allow local healing of small damages to take place autonomously.

- **Sensing and Actuation:** Printed parts with positioned piezoelectric or magneto strictive nanoparticles act as sensing or actuation elements that are applied in the field of soft robotics, wearable devices, etc.

These intelligent attributes give a dynamic quality to conventionally inert AM parts and form critical components to the future generation of multifunctional devices [25].

4.6 Photophysics and Magnetism

Optical Tuning Nanoparticles options like quantum dots, TiO_2, and rare-earth oxides make it possible to tune optical characteristics of photonic devices and displays.

Magnetic functionality: By including magnetic nanoparticles (such as Fe3O4 or NdFeB), it is possible to construct magnetically responsive or rather actuated components.

These capabilities increase the use of the AM parts to sophisticated optics, data storage and biomedical imaging. To sum up, nanocomposites are set to provide a paradigm shift in expanding the capacity of AM materials. Maximising the functional properties by optimising the type, concentration, and dispersion of nanofillers it is possible to create a wide range of functional properties, allowing the fabrication of parts that are far beyond the limits imposed by conventional materials. This puts nanocomposite-based AM to be a pillar technology to high-performance, multifunctional and intelligent systems [26].

5. Apps and Issues

Additive manufacturing (AM) has provided significant opportunities in a broad market because of the inclusion of nanocomposite materials. Combining nanoscale tailoring of material properties with the design freedom inherent to AM is providing the ability to make highly functional, application specific parts. But the shift between the development at a laboratory scale to an implementational scale of the industry presents certain challenges. The section gives an elaborate description of the existing applications and primary impediments of large-scale use.

5.1 Possible Uses of Nanocomposite Materials in AM

Aviation and Automotive Industry

Weight saving with retaining the structural integrity is one of the major targets in the aerospace and automotive industries. This would be addressed squarely by nanocomposites that improve the mechanical capability of lightweight materials.

- **Lightweight Structural Parts:** It is possible to greatly enhance stiffness and strength with carbon nanotubes or graphene polymer base nanocomposites, but which are relatively light weight.
- **Thermal Protection Systems:** Nanocomposites (Ceramic and metal matrix nanocomposites with enhanced thermal resistance) can play a role in enhancing thermal protection in high-temperature equipment parts or heat shields, as well as in engines.
- **Electromagnetic Interference (EMI) Shielding:** Enclosures and housings of a sensitive electronic device can be made of conductive nanocomposites [27].

Biomedical Applications

The biomedical field benefits greatly from the customization and bioactivity of nanocomposites in AM.

- **Implants and Prosthetics**: Bioactive ceramics (e.g., hydroxyapatite) reinforced with nanoscale fillers enhance bone integration and mechanical properties.
- **Scaffolds for Tissue Engineering**: Porous nanocomposite scaffolds support cell attachment, proliferation, and differentiation. Nanofillers can also provide antimicrobial properties.
- **Drug Delivery Systems**: Nanoparticles embedded in AM-produced matrices enable controlled drug release profiles and localized delivery.

Electronics and Wearables

Nanocomposite AM enables the fabrication of flexible, lightweight, and functional electronic components.

- **Conductive Tracks and Circuits**: Carbon-based nanocomposites allow for the printing of circuits on flexible substrates.
- **Sensors and Actuators**: Piezoelectric and conductive nanocomposites can be used to create sensors for strain, pressure, or temperature.
- **EMI Shielding and Antennas**: Printed components with embedded nanoparticles provide effective shielding and signal transmission [28].

Energy Devices

Energy storage and conversion systems benefit from nanocomposites through enhanced electrochemical properties and design optimization.

- **Batteries and Supercapacitors**: Nanostructured electrodes printed via DIW or inkjet printing offer high surface area and improved conductivity.
- **Fuel Cells**: Nanocomposite membranes and catalysts improve performance and durability.
- **Solar Cells**: AM-printed nanocomposite layers are used in lightweight and flexible photovoltaic devices.

Smart and Responsive Systems

- **4D Printing**: Nanocomposites responsive to stimuli such as temperature, light, or moisture are used to create structures that change shape or function over time.
- **Self-healing Materials**: Encapsulated nanoparticles or nanostructured networks enable the restoration of mechanical properties after damage.

5.2 Challenges in Nanocomposite AM

While the applications are promising, several challenges hinder the widespread adoption of nanocomposite materials in AM.

Nanoparticle Dispersion and Agglomeration

Achieving uniform dispersion of nanoparticles in the matrix is critical for consistent performance. Nanoparticles tend to agglomerate due to high surface energy, leading to weak spots and property variability. Methods like ultrasonication, surface functionalization, and in-situ synthesis are used to address this issue but often add complexity to the fabrication process.

Printability and Rheological Behavior

The addition of nanofillers alters the rheology of inks, resins, and filaments. Increased viscosity can hinder flow, cause nozzle clogging, or affect layer adhesion. Optimizing material formulations for specific AM techniques is a continuous challenge requiring extensive trial and error [29,30].

Interfacial Compatibility

The bonding between nanofillers and the matrix material significantly influences the mechanical and functional properties of the final product. Weak interfacial bonding can lead to debonding or crack propagation. Chemical modification of nanoparticle surfaces is often required to improve compatibility.

Health and Environmental Risks

Nanoparticles, particularly when airborne or in free form, pose potential health risks during handling and post-processing. Concerns about environmental impact, recyclability, and long-term stability of nanocomposite components must also be addressed. Regulatory guidelines and safety protocols are still evolving.

Process Standardization and Scalability

Compared to research related to human beings or animal models, the non-uniformity of the characterization of materials, testing procedures, and performance measures restricts comparability of research and prevents application in the industry. Moreover, there is the issue of increasing the scale of printing, learn to print in the lab to mass production with quality and consistency being maintained.

Price and Material Supply

Good nanomaterials can be costly and they might not be produced in mass enough to adopt in industries. Also, the expenditure of coming up with tailored formulations and keeping the control of the process raises the total price. Conclusively, the nanocomposite-strengthened AM has revolutionized high performance as well as multifunction applications in the wide range of industries. Yet, in order to achieve its full potential in commercial and industrial areas, technical and economic obstacles have to be overcome [31].

6. Conclusions

The Nanotechnology and additive manufacturing (AM) have become an irrevocable trend in the world of material science, a trend that has allowed the production of not merely geometrical, but also functional high-tech components. Submerging nanoscale fillers in polymeric, metallic or ceramic matrices to form nanocomposite materials, realize enormous potential in improving structural and functional properties of AM-printed components.In this review we first illustrate the basic categories of nanocomposites and the great variety of nanofillers that are presently used in AM. These fillers range in type of nanoparticle, such as carbon nanotubes and graphene (carbon-based nanomaterials) to ceramic nanoparticles and metal oxides and are chosen specifically with regard to application and the intended property. The fact is that nanocomposites are potential candidates in numerous fields, such as aerospace, biomedical engineering, electronics, and energy, due to their capability to enhance considerably the mechanical strength, thermal, electrical conductivity, and even biocompatibility.

Further, the nanocomposites compatibility with the numerous AM technologies, including fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering/melting (SLS/SLM), and direct ink writing (DIW) processes, likewise widened the perspective of high-performance, multifunctional, and even smart materials. The development of sophisticated materials by design, tuning of rheologies and dispersion mechanisms of nanoparticles also have been important in providing reliability in printing and part quality.

Although this technology has demonstrated appreciation, there are a number of challenges through which full industrial potential of nanocomposite materials in AM needs to be met. These include:

- The nanoparticle dispersion must be even to prevent their agglomeration and defects occurrence.
- Parameters optimization of the printability and process parameters in various AM platforms.
- Increasing the interfacial bonding between the nanofillers and the matrix to allow better transfer of loads.
- Health and environmental issues of handling and disposal of nanoparticles.
- Even the development of universal methods of testing and material data banks to speed the progress of commercialization.

The future studies are proposed to cover scalable production of high-quality nanocomposites, real-time control of the print process, and predictive models' development by using artificial intelligence and machine learning. Also, materials scientists, engineers, biologists and industrial designers will have to work in an interdisciplinary capacity as innovations made in a lab are turned into products that are brought to market. With the ever-developing AM industry, nanocomposites are ready to become the key to next-generation manufacturing. It will lead to the development of smart systems, dynamic Materia their capability of integrating the mechanical robustness with multifunctional operation.

Conflicts of Interest

The authors declare no conflict of interest.

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