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The Significance of Additive Manufacturing within the Context of Industry 4.0

[1]Kamal Dalal (student at GITAM), [2]Mr. Bhoop Singh (Asst. Professor at GITAM)

Abstract

Industry 4.0, the latest industrial revolution, promotes the integration of advanced information technologies and intelligent production systems. Additive manufacturing (AM) is recognized as a crucial element in driving this transformative shift. This paper presents a comprehensive examination of AM technologies, highlighting their significant contributions to Industry 4.0. The review centers around three key dimensions of AM: recent progress in material science, advancements in process development, and improvements in design considerations. The primary goal of the paper is to categorize the existing knowledge and technological trends in AM, while emphasizing its potential applications. The paper explores how AM plays a pivotal role by enabling the creation of complex objects layer by layer, directly from digital designs. It investigates recent advancements in material science, including the development of new AM-compatible materials such as metals, polymers, ceramics, and composites. The study also focuses on the continuous refinement of process development, such as enhanced machine capabilities, faster printing speeds, and improved precision. It underscores the need for optimized designs that leverage the unique capabilities of AM technology, allowing for the production of lightweight structures, intricate geometries, and functional integration. These design enhancements not only facilitate the realization of innovative products but also enhance efficiency while minimizing material waste. This paper offers a comprehensive overview of AM technologies in the context of Industry 4.0. By examining recent advances in material science, process development, and design considerations, it aims to categorize the current knowledge and technological trends in AM while highlighting its potential applications. This review provides valuable insights for researchers and industry professionals, fostering further advancements in this transformative field.

1. Introduction

Industry 4.0, the fourth industrial revolution characterized by intelligent automation technology, emphasizes the integration of modern manufacturing techniques and advanced information technologies to enhance economic competitiveness. Illustrates how Industry 4.0 facilitates the collaboration of cyber and physical systems, aiming to establish smart factories and redefine the role of human workers. The virtual realm of Industry 4.0 encompasses concepts such as the Internet of Things (IoT), Big Data, and Cloud Computing, while the physical realm includes Autonomous Robots and Additive Manufacturing. In the context of cyber-physical systems, IoT involves gathering information from physical objects through computer networks or wireless connections. This data, derived from products, machines, and production lines, contributes to a significant amount of statistical information that is exchanged and analyzed. Additional sources of data include design records, customer orders, supplier deliveries, and logistics-related information. Collectively, this vast quantity of data is referred to as Big Data, a pivotal concept in Industry 4.0. Cloud computing, which involves the processing of this abundant information, is also a crucial term in the virtual industrial domain. These cyber technologies collectively contribute to the effective utilization of available information for future smart manufacturing.

On the physical side, the capabilities of existing manufacturing systems limit the development of smart factories. This is where Additive Manufacturing (AM) plays a vital role as a key component of Industry 4.0. As Industry 4.0 demands mass customization, unconventional manufacturing methods need to be developed. AM has the potential to become a significant technology for producing customized products due to its ability to create intricate objects with advanced characteristics, such as new materials and complex shapes. Currently, AM is being used in various industries, including aerospace, biomedical, and manufacturing, due to its ability to improve product quality. Although concerns remain regarding its applicability in mass production, the utilization of AM in the industry is increasing due to technological advancements. As AM technology continues to develop, offering accurate and robust fabrication of complex objects at increased production speeds, it may eventually replace conventional manufacturing techniques. This paper reviews recent literature related to the physical aspects of Industry 4.0, with a specific focus on AM, aiming to assist researchers in categorizing and organizing fundamental knowledge in this field. Given its significant role in Industry 4.0, AM is the primary focus of this paper.

2. Materials

Material science plays a crucial role in comprehending the advancements in Additive Manufacturing (AM) technologies. Researchers in this field are particularly interested in exploring new materials that are suitable for 3D printing applications. While a wide range of plastic and polymer materials are already available for AM, certain specific materials have captured the attention of the industry, as depicted in Fig.1. In this section, we will delve into a detailed discussion of the properties of prospective materials anticipated to emerge in the era of Industry 4.0, while identifying their potential applications.

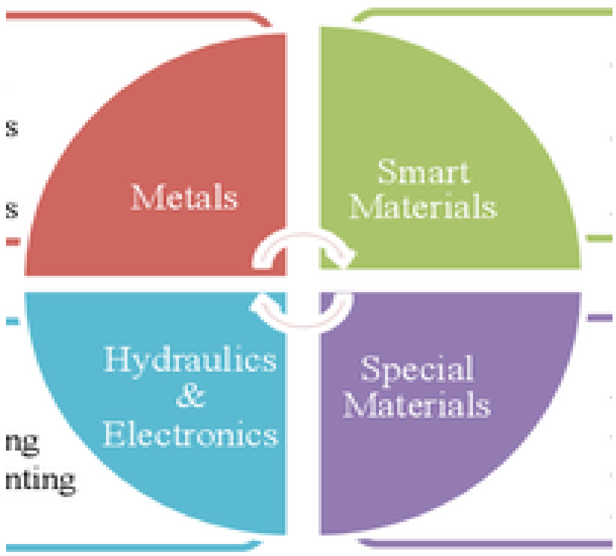

Figure 1: Overview for ongoing research materials for AM

2.1. Metal additive manufacturing

Given their favourable mechanical properties, metals have been widely used in engineering applications. However, the 3D printing industry is actively seeking innovative solutions to produce metallic parts that can serve as substitutes for conventionally-manufactured counterparts. The advancements in 3D printing technology have given rise to a burgeoning research field known as Metal Additive Manufacturing (MAM). In recent years, various metals, such as aluminum, titanium, and stainless steel, have been successfully utilized as primary constituents in the AM process to manufacture metallic components. Metal powders are commonly employed in commercial metal 3D printers, although alternative material mixtures have also been under scrutiny for MAM.

The microstructure resulting from AM has a significant impact on the mechanical properties, including tensile and fatigue behaviour, of the printed parts. Consequently, issues related to microstructure, phase composition, and heat treatment have garnered attention within the AM research community. For instance, Tang et al. conducted an investigation into the mechanical properties of components fabricated through a laser-based MAM process, uncovering insights into the cracking mechanism. However, despite these advancements, there is still much progress to be made as the manufactured parts have yet to meet the industry's expectations. Some key challenges that need to be addressed include cost-effectiveness, production speed, improved tensile/fatigue/hardness behaviour, enhanced surface quality, and the attainment of a homogenous microstructure.

In the new era of Industry 4.0, MAM is poised to become a significant player, provided it overcomes these existing barriers through advancements in both material science and MAM processes. The realization of Industry 4.0's potential heavily relies on the continued development and improvement of MAM, enabling the production of high-quality metal parts at a competitive cost with desirable mechanical properties.

2.2. Smart Materials

Smart structures are characterized by their ability to change shape or material properties in response to external conditions, earning them the classification of 4D printing materials. The integration of smart materials into the additive manufacturing (AM) industry offers advantageous features such as reconfigurability and the ability to achieve desired material properties over time. Shape memory alloys (SMA) and shape memory polymers (SMP) are commonly used as 4D printing materials for creating functional parts in applications such as soft robotic systems, self-evolving structures, and controlled sequential folding. SMAs, like nickel-titanium, are extensively employed due to their properties of super-elasticity and thermal shape recovery, finding applications in biomedical implants and micro-electromechanical devices. SMPs, on the other hand, exhibit sensitivity to external stimuli such as light, humidity, and temperature gradients. The biocompatibility of SMPs has led to increased interest in their application in medical engineering. Additionally, digital light processing of SMP materials has found use in the clothing industry and jewelry applications.

Piezoelectric materials also hold promise as alternative options for 3D printing. Their applications span energy harvesting, actuation, and nanofabrication for creating functional structures. In the era of Industry 4.0, all these sectors are likely to leverage AM technologies with further improvements in the quality of produced parts.

Soft robotics is one area where smart materials have recently found application, with researchers discovering that electro-active polymers can be externally stimulated to alter their stiffness in a controlled manner. For instance, Ge et al. introduced the concept of "active origami," showcasing the controllability of active hinges produced through multi-material printing using 3D printed SMPs. One potential application of active hinges is self-opening satellite components activated by external stimuli. Similarly, Raviv et al. explored multi-material printing with hydrophilic polymers, demonstrating self-evolution of 3D shapes generated through imposed deformations when exposed to water. These studies lay the foundation for research on self-assembled structures. In the future, smart materials could be utilized in extreme environments such as deep-sea or space travel, where activation by water or UV light, respectively, becomes feasible. 3D printing technology is poised to accelerate the integration of smart materials, enabling potential applications in self-assembling structures, compact configurations, stimuli-activated mechanisms in extreme environments, and programmable materials, which will be widely adopted in the near future. However, further research is required to explore new material combinations, innovative manufacturing processes, and design improvements in the realm of smart materials.

2.3. Printable hydraulics and electronics

In a study by MacCurdy et al., a novel innovation in multi-material additive manufacturing (AM) was investigated, introducing the concept of printable hydraulics. This approach involved simultaneously printing solid and liquid materials using fused deposition modelling (FDM) with multiple nozzles. The process allowed for the fabrication of structures consisting of rigid, flexible, and support materials, while also incorporating fluid components. The outcome of this research enabled the production of hydraulically actuated working mechanisms, such as soft robotic grippers, in a single stage without the need for additional assembly steps. This demonstrates the potential of 3D printing as a means of instant robotic fabrication, leading to the creation of ready-to-use functional systems.

The introduction of conductive materials in AM opens up possibilities for incorporating electronic circuitry directly into printed objects. This concept of embedded electronics has become a significant area of interest. MacDonald et al. focused on an intelligent embedded electronic application by integrating LEDs and electronic printed circuit boards (PCBs) into a 3D printed electronic gaming dice. Additionally, Ota et al. explored the 3D printing of customized objects for rehabilitation purposes that housed electronic devices. A state-of-the-art study on 3D printed functional components highlighted further applications of printed electronics, including quad-copters, stretchable tactile sensors, and micro batteries. These works demonstrate the potential of AM in fabricating smart objects across diverse fields. AM presents opportunities for the simultaneous fabrication of products and their accompanying electronics. In the era of Industry 4.0, there is the potential to enhance the packing efficiency of electronic systems, enabling the creation of more innovative designs in a single step using multi-material printing technology.

2.4. Special material and applications

The previous sub-sections provided an overview of innovative materials for additive manufacturing (AM). In this section, we will briefly discuss additional materials that are expected to be utilized in the near future. One prominent area of exploration is additive construction, which focuses on the use of AM technology for building future structures and infrastructures. Concrete and other specific materials are being investigated as the foundation for 3D printing in civil engineering applications. In the fashion and jewellery industries, AM practices have been gaining momentum, particularly with advancements in textile printing. AM offers advantages such as a rapid design process, shorter fabrication time, and reduced costs associated with packaging and transportation.

Another gripping application of 3D printing is in the food industry, where edible materials are being examined for creating various products with desired surface textures and multiple nutritional contents. While challenges related to process productivity, durability, and serviceability of edible materials still need to be addressed, AM holds potential for the future of food fabrication. An unconventional and exciting area where AM technology is being explored is space exploration. Studies are investigating the possibility of 3D printing using lunar regolith (Moondust) to construct habitats and infrastructures for space colonies. The feasibility of utilizing AM technology to make use of in-situ resources on Mars for future manned exploration missions has also been proposed as a means to reduce the need for transporting resources from Earth. This section highlights the implications of special materials and associated processes in construction, food, garment, and aerospace industries. AM presents immense potential to be further explored in the future, leading to increased competitiveness across a wide range of industries.

3. Processes

In this, we will explore novel additive manufacturing (AM) processes, with a particular focus on those related to metal additive manufacturing (MAM) and hybrid manufacturing. While the number of innovative AM processes is rapidly increasing, they are rooted in well-established fundamental technologies, as shown in Figure 2. As technology continues to advance, we can expect the development of more enhanced processes in AM. However, many of these processes have primarily been developed for printing conventional materials such as polymers, which are commonly used for non-industrial applications. In the context of Industry 4.0 and the needs of heavy engineering applications, specific AM processes have gained significant attention, particularly in the realm of metal materials.

It is anticipated that the future of manufacturing will involve the integration of different processes. Known as hybrid manufacturing, this emerging field combines additive methods with subtractive methods to fabricate superior products with improved surface quality, fatigue strength, and other desirable attributes. The growing interest in hybrid manufacturing has led to the exploration of various combinations of manufacturing processes beyond traditional AM approaches. MAM and hybrid production methods will be further discussed in the following subsections as key technologies for future intelligent manufacturing.

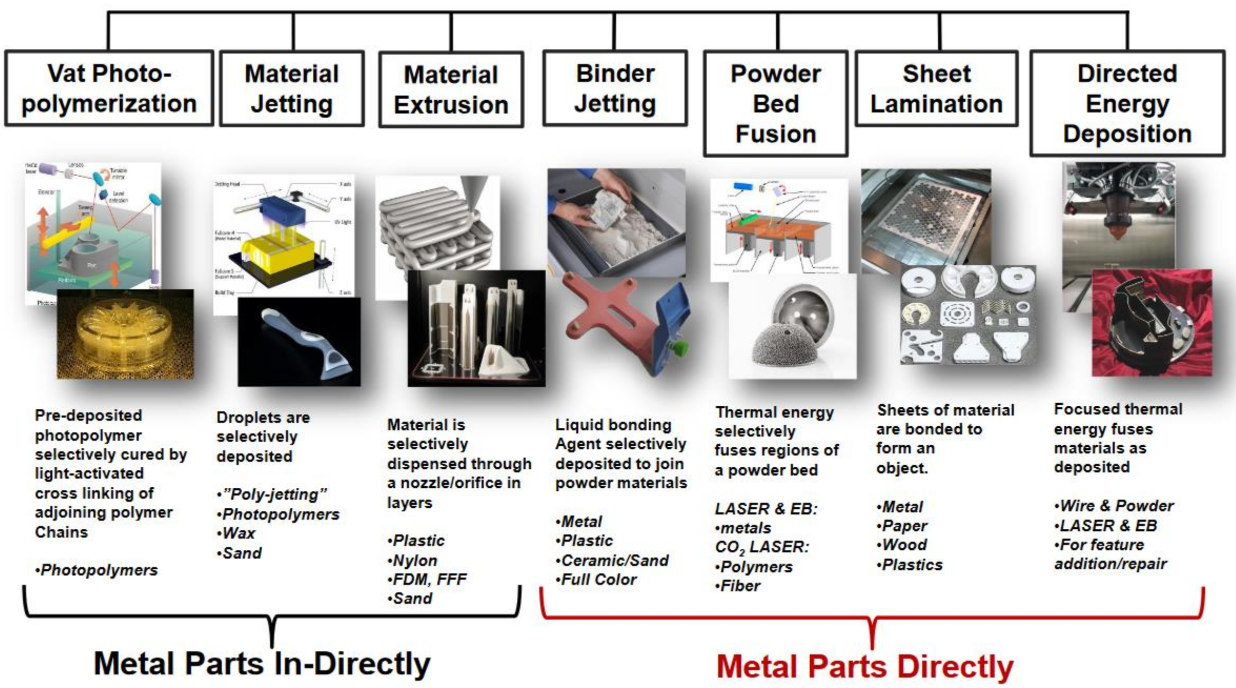

Figure 2: Classification of AM Processes

3.1. Processes for Metal Manufacturing

Metal additive manufacturing (MAM) plays a crucial role in Industry 4.0, given the widespread use of metallic materials in various engineering fields. Among the different types of printing methods, MAM processes hold dominance due to their relevance to metal constituents. There are four fundamental approaches to achieving AM of metals: i) powder bed fusion, ii) direct energy deposition, iii) material jetting, and iv) binder jetting. The first two approaches, selective laser sintering/melting (SLS/SLM) and electron beam melting (EBM), are the most commonly used in the industry. They involve the use of an energy source to heat the metal material in a powder pool, with the naming based on the specific energy source employed. Direct energy deposition techniques, such as laser engineering net shape (LENS), utilize thermal energy for melting while depositing fused metal. Indirect MAM methods also exist, involving molding for metal parts and subsequent casting. Wire and arc additive manufacturing (WAAM) is a novel MAM process that combines arc welding with wire feeding, enabling the additive fabrication of large components from all weldable metals. WAAM has found applications in the aerospace industry due to its ability to produce large components and shape a variety of metals. Another recent patented MAM process is Nanoparticle Jetting (NPJ), which involves jetting heated metal nanoparticles suspended in a special liquid medium to form thin layers of the manufactured part. NPJ claims to offer superior surface finish, high accuracy, and metallurgical properties comparable to solid counterparts, while providing safer manufacturing conditions by eliminating hazardous powder.

Atomic diffusion additive manufacturing (ADAM), introduced by Mark forged, is another novel process where dense metal parts are printed layer by layer using metal powder confined in a plastic binder. The plastic binder is progressively removed, followed by sintering to achieve the final product with excellent mechanical characteristics due to the simultaneous sintering of the entire part. Similarly, Desktop Metal Company has introduced a novel MAM technology called Single Pass Jetting (SPJ). In the SPJ process, metal powder is deposited and compacted using sequential binder jetting. The bi-directional movement of the printing head enables the process to be a hundred times faster than regular laser-based metal additive technologies. SPJ is touted as facilitating mass production with competitive manufacturing cost per part capabilities.

In spite of the advancements in MAM, extensive research is ongoing to address challenging issues such as process stability/repeatability, limited part size, high unit cost, and suboptimal mechanical properties of finished products. Researchers are exploring parameter optimization, precise sintering operations, suitable powder compounds, and other remedies to overcome these challenges. In-process monitoring and inspection have also gained importance in breaking barriers for future metal manufacturing. Given the indispensability of MAM in smart factories of Industry 4.0, the development of novel processes and accompanying technologies is expected to accelerate in the near future.

3.2. Hybrid Manufacturing Process

Hybrid processes involve the sequential or integrated combination of additive manufacturing (AM) and subtractive manufacturing (SM) processes, incorporating proper fixturing and orientation control to produce parts. This approach is employed to improve dimensional accuracy and accelerate production processes. Hybrid techniques are particularly useful for fabricating complex geometries that cannot be achieved using a single manufacturing process, whether additive or subtractive. Over the past decade, researchers have proposed hybrid solutions to create products with specific engineering attributes.

Past studies have focused on developing hybrid rapid prototyping systems. For example, Lee et al. developed a system where fused deposition modeling (FDM) was used as the additive process, allowing the extruder to switch seamlessly from AM to SM without compromising workspace. In a similar study, FDM was followed by CNC machining, taking into account the FDM deposition angle to achieve lower surface roughness without compromising the surface morphology. In the case of metals, a hybrid process combining electron beam melting (EBM) and rapid CNC machining has been proposed to improve process efficiency. This approach involves using milling as the SM method, supported by appropriate process planning. Similarly, Du et al. introduced a combination of selective laser melting and precision milling to achieve the desired surface finish. Another hybrid approach, known as hybrid deposition and micro-rolling (HDMR), has been utilized for producing metal aircraft parts with exceptional mechanical properties.

The performance of hybrid manufacturing can be further improved through advanced process planning that integrates design and production. Zhu et al. proposed a framework that combines AM, SM, and inspection processes. The framework includes an algorithm for organizing manufacturing operations and sequences with optimized parameters to reduce production time and material consumption. A similar concept was applied in a notable application where a hybrid process was used to reuse existing products by adding material and subsequently machining them. With the advancements in information technology and the efficient utilization of available data following the fourth industrial revolution, further progress in hybrid technologies is expected.

The combination of novel hybrid processes and effective process planning is likely to satisfy industrial needs by enhancing product quality.

4. Design related issue

As Additive Manufacturing (AM) is a relatively new technology, engineers and designers often have limited experience and knowledge about its capabilities and limitations. However, the advancement of digitalization in the context of Industry 4.0 has provided opportunities to overcome design-related barriers associated with these emerging production technologies. The development of computational tools for simulation, visualization, and instant analysis plays a crucial role in modern fabrication.

The focus has shifted towards Design for Additive Manufacturing (DfAM) as a supplementary design approach. DfAM encompasses two branches: a general design framework and methods for achieving improved functionality in specific products. The general design framework offers inexperienced designers a comprehensive perspective for making optimal decisions during the design and manufacturing stages of AM. For example, Salonitis proposed a DfAM methodology that evaluates customer needs, functional requirements, design parameters, and process variables simultaneously. Another study introduced a DfAM framework that considers manufacturing and assembly issues in the early stages of product development, assisting designers in selecting suitable materials and processes.

The second branch of DfAM focuses on achieving superior products for specific objectives, often at the expense of other factors. Topology Optimization (TO) is a key component of this approach, aiming to obtain the best possible geometry while satisfying certain requirements. Examples include optimizing product volume while maintaining minimum compliance of parts and exploring novel TO applications for achieving lower weight-to-stiffness ratios. Two methods have also been investigated for optimizing heat transfer in structures fabricated through AM, and studies have explored the use of Solid Isotropic Material with Penalization in hybrid AM. Other design optimization studies have focused on parameters such as slice thickness, geometric information of CAD models, part build orientation, and support structures. CAD software-related issues have garnered significant interest in recent years. Researchers have explored the limitations of the STL file format and proposed alternative digital file types such as AM File format (AMF) and 3D manufacturing format (3MF). The use of open-source CAD software projects has also been reviewed. Additionally, various slicing algorithms and efficient process planning techniques have been proposed, including methods that minimize printer head movements by capitalizing on the coherence of inhomogeneous interiors. The importance of design-related issues will continue to grow as the industrial and academic research community gains experience through successful implementation of novel computational technologies and design methodologies. This will enable more effective management of the capabilities and restrictions of AM in the near future.

5. Drawbacks and future direction

In the past decade, Industry 4.0 has garnered significant attention from academia and industry as it represents a major paradigm shift in future factories. Additive Manufacturing (AM), as a key technology in this upcoming revolution, holds immense potential for development, provided that current barriers are overcome. In this section, we will outline some foreseeable predictions about AM and discuss potential drawbacks along with recommendations to address them. AM may not be the preferred choice for mass production of regular parts in conventional industrial factories due to its drawbacks in manufacturing speed, accuracy, repeatability, and cost. However, it offers distinct advantages over conventional manufacturing methods when it comes to fabricating intricate and customized objects. AM enables a wide range of possibilities in terms of materials (from polymers to metals), size (from nanoscale to large parts), and functionality (from self-assembling to optimum heat transfer). The strength of parts produced through AM is another area that requires improvement. This can be addressed through the development of novel materials and processes that enhance microstructures, as well as the implementation of proper design and topology optimization techniques. Hybrid manufacturing can also help mitigate certain drawbacks, such as improving product surface quality and providing opportunities for repairing or reshaping existing parts. Looking towards the future, decentralization may become possible by leveraging cloud services to distribute workload across factories and machines. Sustainability is another important aspect, where AM can play a significant role in reducing waste resources and energy consumption through just-in-time production. Additionally, the emergence of 3D printing and digital manufacturing is expected to impact society in various ways. First, the role of employees in the industry may be redefined, shifting towards management, design, and analysis roles rather than manual labor. Second, platforms like do-it-yourself and maker movements enable users to actively participate in the design and manufacturing stages. For example, students can design their own products by transforming the classroom into a hands-on laboratory with the help of affordable 3D printers. In the era of Industry 4.0, there are several popular research fields related to additive manufacturing. These include the development of new material compounds for enhanced microstructures, innovative design frameworks for parameter estimation, improved CAD utilities for optimization, simulation, and modeling purposes, as well as the exploration of novel AM and hybrid processes with real-time process control and inspection. The main recommendation is to foster collaboration among the research community, industry, and governments to overcome current barriers in AM. Furthermore, the relative novelty of AM as a technology highlights the need for standardization efforts and appropriate certification processes.

6. Conclusion

The integration of cyber-physical systems enables the development of highly efficient smart factories capable of producing high-quality customized products. The advancements in information technology play a crucial role in driving the transition to the upcoming industrial era, with Additive Manufacturing (AM) being a key enabler. This paper has focused on three specific topics: materials, processes, and design issues. However, in the future, it is anticipated that more interdisciplinary research efforts will be needed to further advance AM.

The roles of designers, factories, and customers will undergo significant redefinition as manufacturing becomes distributed across various locations, including small workplaces and homes. This shift towards personal and customized fabrication will overcome the current barrier of mass production in centralized locations. Looking ahead, there is a growing trend towards the development of new materials for AM, including smart materials and metallic constituents, to achieve specific desired characteristics. Another prominent trend is the pursuit of creating functional parts and machines in a single step of fabrication. With the opportunities presented by emerging AM technologies, the design and production challenges are now limited only by the imaginations of individuals.

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