Digital Manufacturing of Composites Using Additive Manufacturing in Industry 5.0

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***Abstract*—Industry 5.0 has revolutionised manufacturing by combining human-centric, sustainable and resilient production systems with advanced digital technologies. Composite materials are increasingly manufactured by additive manufacturing (AM) techniques. These materials are valued for their superior strength-to-weight ratio, corrosion resistance, and customisability to desired properties. Digital manufacturing facilitates the integration of computer-aided design (CAD), simulation, digital twins, artificial intelligence (AI), and cyber-physical systems for the optimal fabrication of composite structures. This paper investigates the role of additive manufacturing in the digital manufacturing of composites within the framework of industry 5.0. It reviews the state-of-the-art technologies, materials, applications, challenges and prospects. The study shows that smart manufacturing environments can improve customisation, production efficiency, sustainability, and human-machine collaboration, while overcoming limitations in material performance, process reliability, and standardisation.**

***Index Terms*—Industry 5.0, Digital Manufacturing, Composite Materials, Additive Manufacturing, Smart Manufacturing.**

I. INTRODUCTION

The manufacturing industry has evolved rapidly from mechanisation to automation and digitalisation. Industry 4.0 gave rise to intelligent factories with interconnected systems, automation and real-time data analytics. Industry 5.0 extends this idea to include cooperation between humans and intelligent machines, as well as sustainability and resilience [1]. Industry 4.0 is a concept that is concerned with the integration of information and communication technologies and physical elements in industrial settings. This idea is slowly gaining traction in many economies, and some sectors are already moving towards Industry 5.0. The next phase is about focus on human-cantered development, sustainability and resilience. Additive manufacturing (AM) is one of the main technologies that are driving the next Industrial Revolution. AM has radically changed the product development cycle by allowing fast prototyping and manufacturing of complex components with high precision and similar visual quality to traditional methods. Industry 5.0 is based on the collaboration between human ingenuity and advanced digital technologies, and AM and 3D printing are uniquely positioned to offer unprecedented customisability, efficiency, and sustainability [2].
Composite materials have become indispensable in the aerospace, automotive, healthcare, construction, and energy industries due to their high mechanical performance and lightweight features. Composites are usually manufactured using traditional manufacturing techniques that require complex tooling, produce large amounts of waste material, and offer limited design flexibility. Additive manufacturing has emerged as a revolutionary solution by allowing the layer-by-layer manufacture of complex geometries directly from digital models [3].

The conventional ways of manufacturing composites, from hand lay-up to filament winding, generally involve a trade-off between the degree of automation and the freedom of design. These processes require expensive moulds to produce the resin and fibre architecture. Tooling and equipment costs have to be written off over large production volumes. In contrast, additive manufacturing (AM) or 3D printing has been developed as a revolutionary method for composite fabrication with unprecedented freedom in the material composition and geometrical complexity.AM eliminates the need for Moulds and reduces the cost per part significantly, even at low volumes of production [4].

II. INDUSTRY 5.0 AND DIGITAL MANUFACTURING

Industry 5.0 is the subsequent phase of industrialization that follows from Industry 4.0 and incorporates not only technological advances but also human innovation, sustainability, and resilience. In contrast to the previous phases which were mainly associated with automation and efficiency, Industry 5.0 aims at cooperation of human beings and smart machines to generate custom-made manufacturing that is efficient and sustainable [5]. Digital Manufacturing can be defined as a manufacturing approach that employs computer-aided technologies and digital data for designing, simulating, monitoring and optimizing the manufacturing process through the entire life cycle of a product [6].

2.1. Concept of Industry 5.0

Industry 5.0 focuses on:
- Human-centric manufacturing
- Sustainable production systems
- Resilient industrial operations
- Human-robot collaboration
- Intelligent decision-making using AI

Unlike Industry 4.0, which emphasizes automation, Industry 5.0 seeks to combine human creativity with machine precision.

2.2. Digital Manufacturing

Digital manufacturing refers to the integration of digital technologies throughout the product lifecycle, including:
- Product design
- Process planning
- Manufacturing execution
- Quality control
- Maintenance and lifecycle management

III. ADDITIVE MANUFACTURING OF COMPOSITES

Additive Manufacturing (AM), popularly known as 3D Printing, is a manufacturing technology that builds components in layers from digital models. Composites are developed through the combination of two or more materials, where one of them acts as a reinforcement (carbon fibres, glass Fibers, ceramics) and other acts as a matrix (polymers, metals, ceramics), to improve mechanical, thermal, or electrical characteristics of the resulting material. Additive manufacturing of composites combines the freedom of additive manufacturing with the advanced performance of composite materials. Additively manufactured composites are a new class of materials that offer unique benefits such as customizable composition of materials, functional reinforcements, phase distribution, and 3D shapes [7].

3.1. Types of Composite Materials Used in Additive Manufacturing

The additively manufactured composites represent one of the newly emerged families of materials, which have distinct characteristics, such as tailorable material composition, functional reinforcing agents, controlled arrangement of phases, and complicated 3D shapes. For example, additively manufactured bio-composite, polymeric composite, and polymer-derived ceramic composite show their distinct characteristics in comparison to the composites manufactured through conventional techniques, such as joining, tooling, cutting [8]. The below-mentioned list represents the classification of composites used in additive manufacturing processes.

3.1.1. Polymer Matrix Composites (PMCs)

Carbon fibre-reinforced polymers (CFRP)
Glass fibre-reinforced polymers (GFRP)
Kevlar fibre-reinforced polymers

3.1.2 Metal Matrix Composites (MMCs)

Aluminium reinforced with silicon carbide
Titanium reinforced with ceramic particles

3.1.3 Ceramic Matrix Composites (CMCs)

Silicon carbide reinforced ceramics
Alumina-based composites

3.2 Additive Manufacturing Techniques for Composites

3.2.1. Fused Deposition Modelling (FDM)

- Uses thermoplastic filaments mixed with short or continuous fibres.
- Materials include PLA, ABS, Nylon, and PEEK reinforced with carbon or glass fibres.
- Widely used due to low cost and ease of operation.

3.2.2. Stereolithography (SLA)
- Uses photosensitive resin mixed with nanoparticles or ceramic fillers.
- Produces parts with high accuracy and excellent surface finish.

3.2.3. Selective Laser Sintering (SLS)
- Uses powdered polymers mixed with reinforcement particles.
- Suitable for producing complex and durable components.

3.2.4. Direct Ink Writing (DIW)
- Deposits composite pastes or inks layer by layer.
- Used for advanced composites, biomedical devices, and electronics.

3.2.5. Continuous Fiber Reinforcement Printing
- Incorporates continuous carbon, glass, or Kevlar fibres during printing.
- Produces components with significantly improved strength and stiffness.

IV. DIGITAL FRAMEWORK FOR COMPOSITE ADDITIVE MANUFACTURING

The digital manufacturing workflow consists of the following stages:

4.1 Digital Design
- CAD software
- Topology optimization
- Generative design algorithms

4.2 Simulation and Process Planning
- Structural analysis
- Thermal analysis
- Process parameter optimization

4.3 Smart Manufacturing
- IoT sensors
- Machine vision
- Real-time monitoring

4.4 Digital Twin Technology
Digital twins create virtual replicas of manufacturing systems.
- Real-time monitoring
- Performance prediction
- Process optimization

4.5 Artificial Intelligence Integration
- Defect detection
- Process optimization
- Material characterization
- Production scheduling

V. CONCLUSION

The concept of Industry 5.0 is an innovative manufacturing model that integrates human knowledge, sustainability, and smart automation. Additive manufacturing technology offers unmatched flexibility in the fabrication of composite products by facilitating unique geometries, customization, and resource efficiency. Digital manufacturing tools like artificial intelligence, digital twin, Internet of Things, and cyber-physical systems improve the efficiency and reliability of composite fabrication.
Despite the challenges that exist with regard to materials, process control, and standardization, improvements in this field can be anticipated to fast-track the adoption of the technology in industry. This will be fundamental in meeting the goals of Industry 5.0.

REFERENCES

[1] M. T. Islam, K. Sepanloo, S. Woo, S. H. Woo, and Y.-J. Son, "A review of the industry 4.0 to 5.0 transition: Exploring the intersection, challenges, and opportunities of technology and human–machine collaboration," *Machines*, 2025.
[2] C. Shen, Y. Guo, Z. Shen, F. Yan, and N. Zhong, "Additive manufacturing of aerospace composites: A critical review of the material–process–design interplay and prospects for application," Materials, 2025.
[3] K. Yu, M. L. Dunn, H. Jerry Qi, et al., "Recent advances in design optimization and additive manufacturing of composites: From enhanced mechanical properties to innovative functionalities," npj Adv. Manuf., vol. 2, Art. no. 26, 2025.
[4] A. Haleem, M. Javaid, S. Rab, R. P. Singh, R. Suman, and L. Kumar, "Significant potential and materials used in additive manufacturing

technologies towards sustainability," Sustain. Oper. Comput., vol. 4, pp. 373–384, 2023.

[5] M. K. Sott, "Industry 5.0: Revolution or repackaging? Unveiling the ambiguities of the new industrial era," Sustain. Futures, vol. 11, 2026.

[6] P. K. Paritala, S. Manchikatla, and P. K. D. V. Yarlagadda, "Digital manufacturing—Applications past, current, and future trends," Procedia Eng., vol. 174, pp. 982–991, 2017.

[7] S. Yuan, S. Li, J. Zhu, and Y. Tang, "Additive manufacturing of polymeric composites from material processing to structural design," *Compos. Part B: Eng.*, vol. 219, Art. no. 108903, 2021.