Twinning the future: Implementing digital twin technology in the optimisation of fibre-reinforced polymers

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Abstract. Optimisation of fibre-reinforced polymers (FRPs) is critical for engineering a sustainable future. This review paper explores the potential of digital twins (DTs) in enhancing the characteristics, performance, and sustainability of synthetic and sustainable FRPs. DTs provide a virtual space for real-time monitoring and predictive analysis and have revolutionised the traditional limitations of FRP production. Recent case studies, like the FASTIGUE project and advances in fibre-reinforced thermoplastics, showcase the DT's powerful role in addressing issues during production. The paper also discusses the unique challenges of developing sustainable "green" composites that balance performance with biodegradability to meet the Sustainable Development Goals. It highlights the benefits of utilising DTs to scrutinise the manufacturing processes of both synthetic and natural FRPs. Modern DTs have demonstrated the capacity to optimise the curing kinetics and mechanical properties of these materials. Furthermore, case studies such as the 3D-printed continuous carbon fibre composites, overmoulded fibre-reinforced thermoplastics, and recyclable Elium®-based composites authenticate the capabilities of DTs in enhancing the sustainable manufacturing of FRPs. Acknowledging future challenges, the paper recommends integrating production and sustainability metrics into modern multi-tier DT systems for holistic benefits.
Keywords: Digital Twins, Composites, Fibre Reinforced Polymers

1 Introduction

In pursuing a sustainable future, the optimisation of composite materials is a pivotal challenge in the engineering and manufacturing sectors. Among different types, fibre-reinforced polymers (FRPs) have emerged as a promising solution due to their superior physical and mechanical properties [1]. However, optimising such composites for performance and sustainability poses significant challenges. Recent advancements in digital technologies offer potential solutions to these challenges. The use of digital twins (DTs) has emerged as a transformative approach to enhance the efficiency and sustainability of composite materials.

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A DT is a virtual replica of a physical system that allows for real-time monitoring and predictive analysis. This enables composites to be optimised in a previously unattainable way [2, 3]. Recent publications have highlighted the potential of DT in revolutionising the production of FRPs. For example,

- The FASTIGUE project has empowered the DTs of large-scale composite structures and enabled real-time analysis of issues during the production process [4].
- Application of DT technology in fibre-reinforced thermoplastics production enables innovation and optimisation of production machinery [5].

Sustainable FRP composites made from natural or biodegradable materials have drawn significant interest due to their potential to reduce environmental impacts. The methods of processing these biobased materials have seen improvements but most of them are still underdeveloped due to their highly variable characteristics [6]. As a result, the overall properties of these composites are still inferior as compared to the high-performance conventional glass or carbon FRPs. Therefore, a balance between composite performance and biodegradability is required to fulfil the Sustainable Development Goals [7].

This paper discusses the challenges posed by the manufacturing techniques of synthetic and green FRPs. It also aims to explore how DTs can be used to optimise FRP-based composites by enhancing and addressing the prevalent issues in their manufacturing processes. The current challenges to large-scale commercial implementation of DTs in the composites industry and future perspectives are also a part of this review.

2 History & evolution of DTs in composites industry

The concept of digital twins has been evolving since the early 21st century. The term "digital twin" was first used in the context of the aerospace industry, but its roots can be traced back to practices from the 1960s [8]. It gained significant traction in the mid-2010s and was initially adopted for tangible industrial products, such as aircrafts. Since then, it has expanded to various applications, including the composite industry [9].

DTs in the composite industry represent a convergence of various technologies such as IoT, data analytics, AI, and more. These technologies have propelled DTs from a conceptual stage to practical, real-world deployments [10]. They serve as virtual replicas of a physical system and enable the prediction or optimisation of performance. In this way, they have become integral in the shift towards Industry 4.0 [11].

3 Challenges in optimising FRPs

Polymer composites have been widely applied across numerous industries, including aerospace, aviation, biomedicine, automotive components, electrodes, packaging, and more. Traditional manufacturing techniques like injection moulding, roll moulding, extrusion moulding, and hot pressing have limitations in meeting the full range of requirements for these advanced composites. Some of the key challenges posed by traditional and modern manufacturing or processing methods are shown in Table 1.

Table 1. Challenges or issues posed by traditional and modern manufacturing techniques for FRPs [12-17]

Manufacturing Technology	Challenges/Issues
Injection Moulding	Volume flow profile and processing temperatures pose significant challenges in curing and maintaining final part quality
Surface coating technology	• Induction of residual stresses compromises mechanical performance • Weak interfacial quality between the spraying and base material
Additive manufacturing (3D/4D)	• Generation of pores and thermal stresses during printing can lead to defects • Weak interfacial bonding strength between layers
Magnetic pulse powder compaction	Occurrence of non-uniform density distributions in the compacted parts

Unlike conventional synthetic polymer-based composites, green composites have gained prominence due to their eco-friendly nature. Consumers have raised concerns about the leaching of contaminants and chemicals from plastic consumer goods. The development of adequate recycling infrastructure and greener alternative materials will be necessary to reduce the environmental footprint of synthetic polymers. These alternative materials include biobased composites composed of natural fibres and biodegradable polymer matrices. They find applications in various industries, including automotive, construction, and consumer goods [18].

However, the development of these green composites is hindered by several challenges that must be addressed to make them viable for widespread use. A key issue is ensuring these materials can withstand high temperatures while eliminating the unpleasant odours emanating from natural fibres (e.g. kenaf, hemp, jute, etc.). Likewise, the compatibility between natural fibres and polymer matrices is also crucial for achieving the desired mechanical characteristics of biocomposites [19].

Given the immense variety of possible ingredient combinations, there is still much to be learned about how sustainable green composites function. The determination of optimal manufacturing conditions and material selections are crucial steps toward creating quality composites. In most cases, the inferior properties of natural fibres pose a fundamental obstacle to their integration into green composites. The knowledge of energy consumption, product lifetime, weathering resistance and service quality is critical to the sustainable development of these composites [20, 21].

The defects introduced during processing can seriously degrade the failure behaviours and lifetimes of FRP components. Finite element analysis (FEM) has emerged as an effective tool for simulating manufacturing processes. This allows for assessing failure behaviours and predicting damage evolution to reduce costs associated with physical testing. While research on correlating process defects to composite performance is still limited, FEM techniques undoubtedly provide a powerful means of analysing composite microstructures and anticipating failure modes [22-24].

4 Optimising synthetic & sustainable FRPs using DTs

The integration of DT in the processing and manufacturing of synthetic or natural polymer composites represents a transformative approach to optimisation. DT can create a conceptual framework that allows for the real-time monitoring and adjustment of parameters in modern manufacturing methods like 3D or 4D printing [25]. This framework includes a virtual representation of the manufacturing environment with sensors and IoT devices that collect data from the physical environment. The data is then used to simulate and analyse the behaviour of composites during processing. It can enable the identification and correction of potential issues before they occur [26].

As discussed, controlling curing kinetics in processes like moulding (extrusion, injection, compression, etc.) is crucial for manufacturing desired composites. DT can be used to optimise these processes through multiscale cure analysis. It involves simulating the curing process at different scales to understand its impact on the composite's properties. By adjusting the parameters in the virtual world, manufacturers can achieve the desired cure kinetics and achieve optimal mechanical properties [27].

For natural fibre-based polymers, a lightweight yet durable design is crucial [28, 29]. The DT can ensure a continuous and unambiguous flow of variation information from part design to assembly. Integrating manufacturing data can predict variations and deviations during assembly. The surrogate models of DT can represent fabric permeability and pressure fields. These models enable real-time monitoring and optimisation to make a lightweight yet robust composite assembly [30]. Likewise, DT can also be used to optimise the mechanical properties of such composites via various optimisation paths. These paths include accounting for the variability in natural fibres, compactness of phases, and developing an optimised process. These factors can be simulated using DT, and their impact on the performance of composites can be assessed [9, 22].

5 Case studies of DT implementation in composites industry

5.1 3D-printed continuous carbon fibre composites

The study [31] was based on implementing a hierarchical DT framework for 3D microwave printing of Continuous Carbon Fiber Reinforced Composites (CCFRP). The prime focus was mitigating issues related to belt slippage during the printing process. The research aimed to predict and prevent malfunctions from belt slippage by utilising core and basic DTs. The core of the study revolved around monitoring real-time acceleration data from the printing bed to detect any instances of belt slippage.

Abnormal vibrations were a key indicator of potential issues. Therefore, core DTs leveraged MATLAB Simscape models to predict vibration patterns and adjust the G-code paths proactively before printing. It enabled the pre-emption of errors linked to belt slippage. Another significant finding of the study was that the ability to perform real-time monitoring of filament temperature and microwave power enabled efficient wear and tear assessment. It can facilitate timely maintenance measures that reduce printing risks associated with component degradation. Likewise, the predictions derived from the DT framework were also validated. It was done via a comparative analysis of measured and calculated data. The outcomes verified the efficacy of the core DTs in accurately forecasting vibration patterns and detecting belt slippage.

5.2 Overmoulded fibre-reinforced thermoplastics

In a recent study [32], the intersection of simulation and machine learning was focused on creating a DT model for the manufacture of composites. These composites were over-moulded fibre-reinforced thermoplastics (FRTP) and were selected for their balance of manufacturing speed, mechanical performance, and lightweight properties. Such properties make these composites highly relevant in automotive construction. Even minor variances in the manufacturing process (e.g., temperature adjustments) can lead to substantial differences in the bond strength during the synthesis of these composites. The researchers proposed a cyber-physical production system (CPPS) based on a DT framework to tackle this variability and improve precision in manufacturing. They utilised a combination of finite element method (FEM) simulations and machine learning. A complete framework of the cyber-physical production system is shown in the following figure,

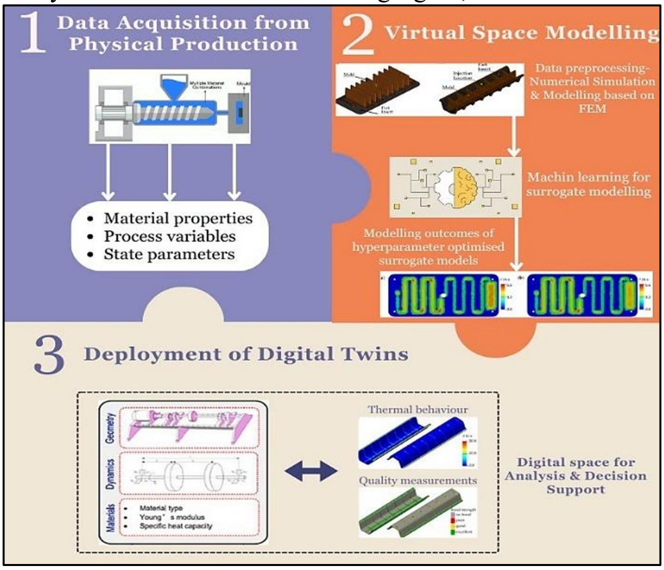

Fig. 1. A physical production-based DT based on the framework of cyber-physical production systems using FEM and machine learning, adapted from [32, 33]

The figure shows that the process began with a detailed parametric manufacturing process simulation. It created a wealth of data representing possible scenarios. The data from these FEM simulations formed a training set for machine learning algorithms. The study compared several machine learning approaches to identify the most effective predictive model (named as FEM surrogate). This surrogate could rapidly predict outcomes based on new process parameters in real-time to enable quality control and decision-making.

Findings suggested that Random Forest and Decision Tree methods were most promising in creating accurate and efficient FEM surrogate models. In addition, the experimental results underlined that the computationally predicted times at temperatures above melting cannot be measured directly in the manufacturing process. However, they can serve as reliable indicators to predict bond strength.

5.3 Recyclable Elium®-based composites

In this work [34], researchers carried out advanced resin reaction modelling using data-driven techniques and DT methods to study the polymerisation of Elium® resin-based composites for electric vehicle component manufacturing. This commercial resin is known for its reactive properties. The optimised simulation results were combined with a recurrent neural network. This neural network was able to model discrepancies between simulation and experimental data. In this way, a DT of high predictive ability was constructed.

The model was successfully validated on an experimental set not used during training. Post-processing of the DT results enabled the computation of the resin polymerisation degree through the part's thickness and processing time. The proposed active resin solutions provided advantages such as reduced processing time and energy gains. However, the challenges lay in mastering the complex manufacturing processes to achieve the desired mechanical properties in the final products. Through the DT approach, the study addressed the need for confidence in controlling the resin processing to avoid hot spots that could compromise material integrity and mechanical properties post-manufacturing.

6 Future challenges

The future of FRPs for efficiency and sustainability using DTs is promising and multifaceted. Manufacturers are using them to enhance manufacturing through cost savings and improved efficiency. As the DTs mature over time, the manufacturers could incorporate production and sustainability metrics into a single DT to obtain the full benefits of the model [35]. However, the implementation of DTs is not without challenges. Some of the key challenges that need to be addressed for developing promising DTs concerning advanced FRPs are summarised in Figure 2.

Fig. 2. An overview of different challenges in large-scale implementation of DTs for modern synthetic or green FRPs [2, 9-11, 17, 27, 36]

7 Conclusions

In recent decades, digital twins (DTs) have evolved from a nascent concept to a sophisticated tool that is reshaping the modern composite industry. They are enhancing the ability to predict, analyse, and optimise the characteristics of FRPs. This has enabled more sustainability and efficiency of the latest manufacturing practices. However, implementing DTs in modern production systems for FRPs is not without challenges. Despite these challenges, the benefits of DTs, like the ability to leverage gathered data for optimisation and continuous improvement, make them a worthwhile investment

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