Integration of NDT into the manufacturing process chain of functionalized UD-tape components

Aaditya Suratkar[1], Christian Schürger[1], Jannik Summa[2], Ralf Schlimper[3], Klaus Wolf[4], Philipp Rosenberg[1], Frank Henning[1]

[1]Structural composites, Polymer Engineering, Fraunhofer Institut für chemische Technologie (ICT), Joseph-von-Fraunhofer Straße 7, 76327 Pfinztal, Germany
[2]Sensorbasierte Lösungen und Applikation, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (IZFP), Campus E3 1, 66123 Saarbrücken, Germany
[3]Bewertung von Faserverbundsystemen, Fraunhofer-Institut für Mikrostruktur von Werkstoffen und Systemen (IMWS), Walter-Hülse-Straße 1, 06120 Halle (Saale), Germany
[4]Business Area Multiphysics, Fraunhofer-Institute for Algorithms and Scientific Computing (SCAI), Schloss Birlinghoven, 53757 Sankt Augustin, Germany

Abstract

Complex structures made of thermoplastic unidirectional tape (UD-tape) composites are often manufactured in a series of individual steps. Defects may be induced at each of the process steps, altering irreversibly the final product quality. One of the effective defect correction methods is by creating a digital representation of the manufacturing steps and quality characteristics by recording the steps through integration of suitable sensor technologies. In that regard, quality assessment during the production of complex thermoplastic UD-tape composites, using hybrid injection molding with process-integrated Non-Destructive Testing (NDT) formed the key focus of this study. Multiple locations in the process chain for quality assessment; two (post-consolidation and final demonstrator steps) of which will be discussed in this paper. The quality of the laminate was evaluated using integrated eddy-current sensors and that of the final part with ultrasonic testing in this investigation. The application and potential of these NDT to create a holistic digital quality footprint for manufacture of highly complex function-integrated parts using thermoplastic composites are discussed in this study.

1. Introduction

Thermoplastic unidirectional tape (UD-tape) materials have emerged as a frontrunning strong, sustainable yet lightweight solution in the recent years. Thermoplastic UD-tapes are not only cost-effective and recyclable but also offer a higher design flexibility. Complex structures consisting of structural elements like ribs, metal inserts, etc. combined with UD-tapes are increasingly becoming a norm across various structural applications for composite materials. The general manufacturing process for these structures comprises of multiple steps, namely manufacturing UD-tape strips from constituent fiber and matrix systems, manufacturing consolidated laminates from the UD-tapes and combining the laminates with structural elements to form the final structure through a suitable process. However, defects (Figure 1) may be introduced at any of these steps, proving detrimental to the quality of the structure, resulting in the manufactured part being identified as scrap. It is, hence, of utmost importance to monitor the quality of the part through all the process steps. Defective parts, if recognized at an earlier stage, can potentially be removed from the process, reducing the waste and enhancing overall production efficiency.

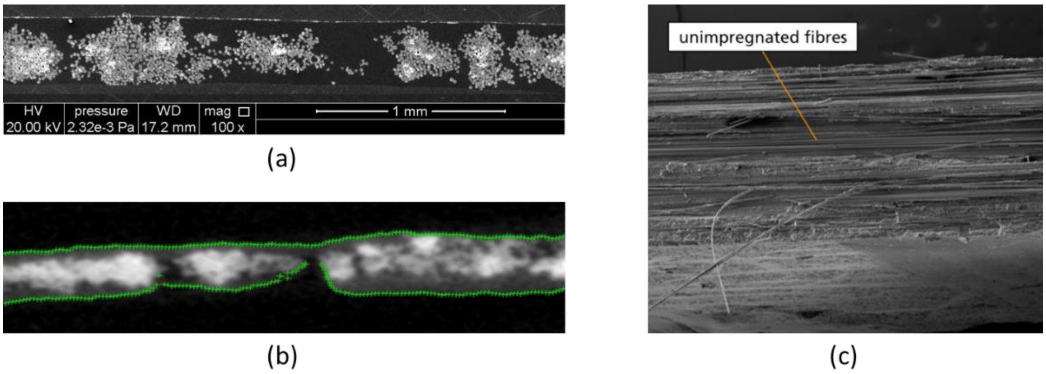


Figure 1: Defects in thermoplastic UD-tape based structures: (a) Inhomogenous fiber volume fraction distribution (b) Uneven laminate thickness (c) Poor impregnation (Fraunhofer Institute for Microstructure of Materials and Systems IMWS, 2023)

One of the strategies to assess the quality of the part at multiple steps in the process is by creating a digital representation of all the process steps, known as a 'digital twin' (DT). DTs are primarily based on real time operational data-feeds and reflects the actual corresponding physical asset (Gardiner, 2016). Effective application of DTs allows the manufacturer to react to any inaccuracies as soon as they are detected, hence, substantially improving production efficiency. DTs were effectively implemented in a recently concluded project ("DigiProp"), focused on mass-production of propellers using thermoplastic composites, by a consortium in The United Kingdom. The consortium succeeded in reducing the carbon fiber waste by 50% in this project by application of DTs (National Composites Centre, 2023) (Gardiner, 2021). Machine-learning based models were implemented to track and reduce defects in the wind turbine blade production in another project, which is a collaboration between America-based TPI Composites and WindSTAR Center (Renews.biz, 2023). High predictive accuracies were achieved in this project faster than the conventional physics-based simulations.

Development of DTs as a tool for improving manufacturing efficiency has been a subject of various recent academic studies. Reduced defects in the final structure, high predictive efficiencies and higher overall efficiencies were demonstrated upon application of DTs in all the studies, which were based on numerical simulations and Non-Destructive Testing (NDT) data (Zuo, et al., 2023) (Kalidindi, et al., 2022) (Wang, et al., 2021) (Polini & Corrado, 2020) (Burov & Burova, 2020). There are, however, numerous challenges yet in the implementation of DTs such as insufficient data, automated information collection and required infrastructure (Anderon, 2020).

Some of these challenges were addressed in the digitalTPC project (Fraunhofer Gesellschaft, 2021) completed by a consortium of Fraunhofer institutes in Germany, comprising of Fraunhofer Institut für Chemische Technologie (ICT), Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (IZFP), Fraunhofer-Institut für Algorithmen und Wissenschaftliches Rechnen (SCAI) und Fraunhofer-Institut für Mikrostruktur von Wekstoffen und Systemen (IMWS). DT representing complete manufacturing chain (explained in detail in Section 2.2) for thermoplastics composites structure based on UD-tapes was implemented in this project, entailing the use of non-destructive sensors and NDT at various steps in the chain to extract processing data. The application of NDT for quality-assessment and its connection to the DT, which forms a subset of digitalTPC project, is discussed in this paper.

2. Materials and Methods

2.1. Materials

The thermoplastic composites system in this study was based on polyamide-6 thermoplastic matrix and carbon fiber reinforcements. The polyamide-6 system was the Ultramid® B24 N-Polymer system, provided by BASF AG. This resin system is reported to have lower viscosity that facilitates impregnation of the fibers and suited for high-rate production requirements (BASF, 2023). The reinforcing T700S carbon fiber system (based on TORAYCA™) was supplied by Toray Composite Materials America, Inc. The fiber tows consisted of 12k fibers and 50C sizing type was used in this study. The fibers are standard polyacrylonitrile (PAN)-based fibers with a tensile modulus of 230 GPa (Toray Composite Materials America, Inc., 2018). These constituent materials were then processed into UD-tapes and further into the demonstrator component (discussed in detail in Section 2.2).

2.2. Manufacturing process

The process chain (Figure 2) for production of thermoplastic UD-tape composites consisted of several individual steps, starting from manufacturing of UD-tapes to final component using hybrid injection molding. UD-tapes were manufactured in the first step from fibers on a coil and polymer granules through a melt impregnation process (Fraunhofer Institute for Microstructure of Materials and Systems IMWS, 2023) at Fraunhofer IMWS. The rest of the steps were completed at Fraunhofer ICT. The UD-tape strips were then cut to desired lengths from the manufactured UD-tape spool and placed next to each other to form a single ply, geometrically closer to the shape of desired part, on a layup table using Dieffenbacher Fiberforge technology (Dieffenbacher, 2023) at Fraunhofer ICT. Several such plies were then arranged on top of each other at different angles and ultrasonically spot welded to form a stacked 'tailored blank'. (Figure 3.a.).

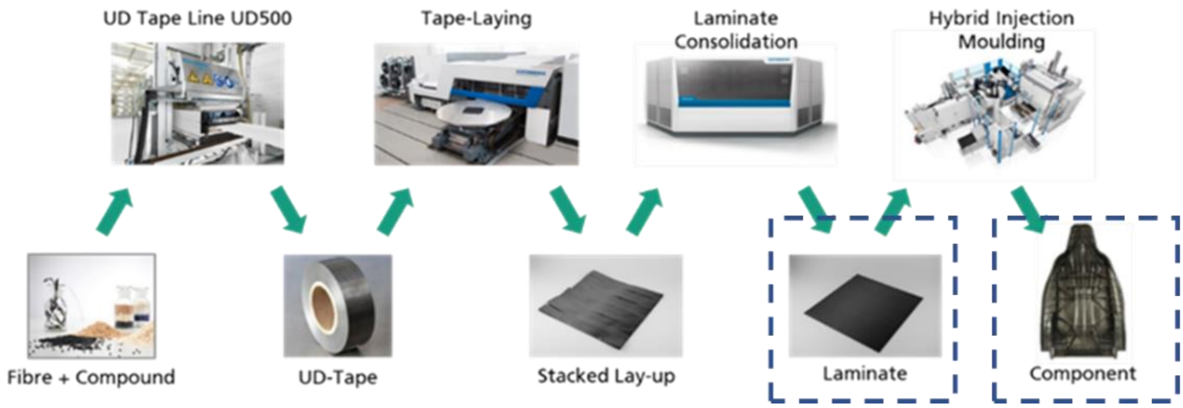


Figure 2: Process chain for thermoplastic unidirectional tape composites. Defect detection in boxed steps is discussed in this conference article.

The stacked layup was then consolidated under 1 bar vacuum and temperature of 245°C with Dieffenbacher Fibercon technology (Dieffenbacher, 2023) into a semi-finished laminate (Figure 3.b.). With infrared heating, the laminates are heated above melting temperature in 90 s and cooled to demolding temperature of approximately 100°C in 120 s by means of contact cooling. The product after consolidation is a laminate with very low void content and homogenous fiber volume distribution. The quality of the laminate was assessed using eddy current testing (Section 2.3.1) in this study.

The ‘hybrid’ process combines various steps into one to manufacture the final part with multiple semi-finished components. This concept presents itself as a very viable opportunity for mass-production of highly complex parts based on thermoplastic composites. The process in this study comprised of four distinct modules. The laminate is infrared heated (module 1) to 260 °C and then transferred onto the mold (module 2) by a robotic gripper system. The mold is mounted on to a hydraulic press (module 3), which opens and closes vertically, in this study. A bolt-on injection molding machine (module 4) was connected to the lower half of the mold. As the mold closes, the laminate is stamp-formed into the desired shape and the required clamping force of 10.000 kN is applied. The injection unit then injects 280 °C hot melt into the mold within 90 s. Once the laminate inlay is overmolded with ribs, the final demonstrator part is cooled and demolded (Figure 3.c.). The defects in the final demonstrator component are analyzed using ultrasonic scanning technology (Section 2.3.2).

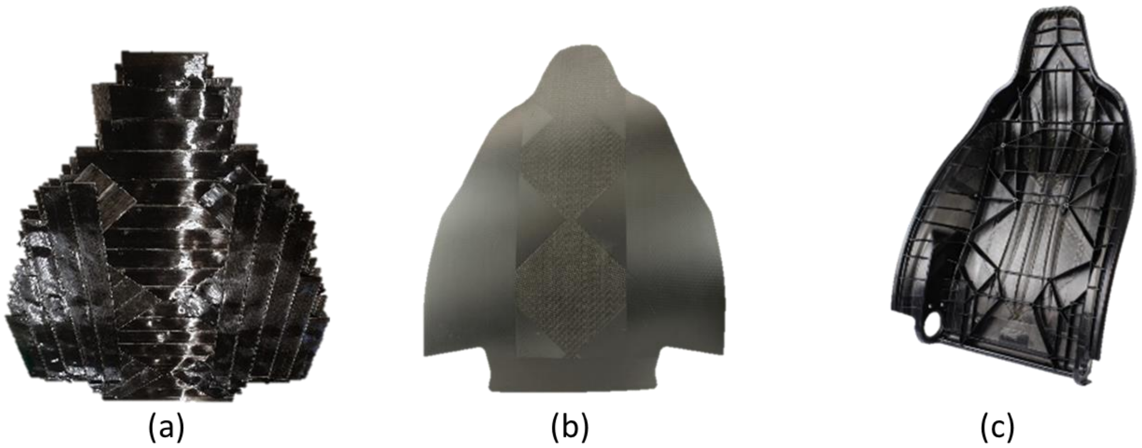


Figure 3:(a) UD-tapes stacked, spot welded and cut in desired shape (b) Consolidated laminate (c) Demonstrator part (Fraunhofer Gesellschaft, 2021)

2.3. Non-destructive testing methods

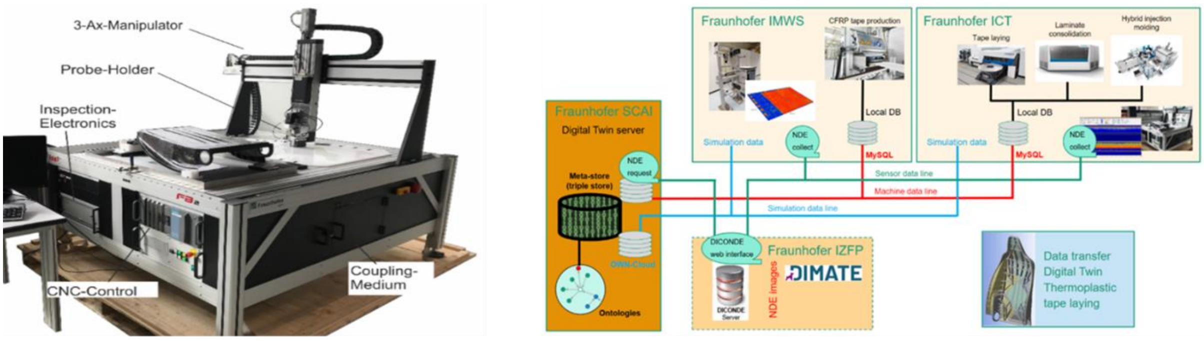
2.3.1. Eddy current testing

Eddy current testing is an electromagnetic testing method based on the working principle of a probe guided over the surface of a component to detect defects in the component by measuring the complex electric impedance of an inducted magnetic field. The testing system developed by Fraunhofer IZFP is integrated within the production process at Fraunhofer ICT (Figure 4) and communicates with the manufacturing-cycle through a robotic control. This enables the application of eddy current testing of the consolidated laminate before the key manufacturing steps of thermoforming and injection molding and the final quality control.

The testing system at Fraunhofer ICT comprises of an array of four coils, spring-loaded probe, inspection frequency at 8 MHz and 0.1 mm scan step-size in scan- and index-direction. The spring-loaded probe enables quick inspection with necessary resolution, while ensuring equidistance between the coils and consistent contact-pressure during inspection. The eddy current inspection starts as soon as the robotic control places the consolidated laminate onto the inspection table, where the manipulator-head guides the eddy current array over the laminate and retakes its rest position upon completion. The data-processing, relevant rescaling and filtering then occurs. The post-processed data is finally displayed and later saved in DICONDE-standard and automatically uploaded to the DICONDE-server, which is located at Fraunhofer IZFP. The laminate is then transferred to hybrid-injection molding, after which the robotic system places the final component for ultrasonic scanning.

2.3.2. Ultrasonic testing

The same manipulator-head (Figure 4) that holds the eddy current array carries a single ultrasonic transducer and the system has the capability to switch automatically into the ultrasonic mode. Hence, as in the case of eddy current testing (Section 2.3.1), the contact-mode between the component and the manipulator-head is through the spring-loaded mechanism. The testing system in this study is restricted to inspection of flat or semi-shell surfaces with low curvature. The ultrasonic scanning of the regions of interest starts as soon as the robotic control moves beyond the bounds of working area of the manipulator-head. The scans are carried out at 5 MHz inspection frequency, 80 MHz sampling rate and 0.5 mm and 2.0 mm step sizes in scan- and index-directions respectively. The data is stored in and uploaded to the DICONDE-standard and -server at Fraunhofer IZFP respectively. The management of twin assets then begins with the creation of metadata entries and their transfer to the metadata storage memory, which takes place at Fraunhofer SCAI. The metadata is stored and organized according to pre-defined ontologies in a central server at Fraunhofer SCAI, via which all the data is linked (Figure 4.b.).



(a) (b)

Figure 4: (a) Process-integrated setup for eddy current of consolidated laminates and ultrasonic testing of final component at Fraunhofer ICT (Fraunhofer Gesellschaft, 2021) (b) Data management between various Fraunhofer Institutes (Meyer, et al., 2021)

3. Results and discussion

Eddy-current testing and ultrasonic testing methods were employed in this study to detect and assess the quality critical defects such as gaps and poor impregnation in consolidated laminates and final demonstrator components respectively. The thickness of the constituent UD-tapes plays an important role in the resultant quality of the consolidated laminates and by extension, the final demonstrator part. Uneven thickness would result in non-uniform application of pressure on the tape surface area, leading to gaps, pores, and overall variations in laminate thickness. The thickness was, hence, used as a characterizing feature in the defect characterization tests.

The eddy current tests (Figure 5) could be effectively employed in visualizing the defects in the consolidated laminates. The blue areas in Figure 5.a. and Figure 5.b. represent the thinner areas in the ply and the yellow areas represent the thicker areas. It can be clearly concluded that the severe thickness gradient in second ply has a detrimental effect on the total laminate thickness. Furthermore, Gray-level contrasts in eddy current signal could also be used to determine other defects such as errors in cutting or draping of tapes (Figure 5.c.) and gaps in the laminates (Figure 5.d.). Eddy current test method, hence, provides a representation of actual state of the laminate.

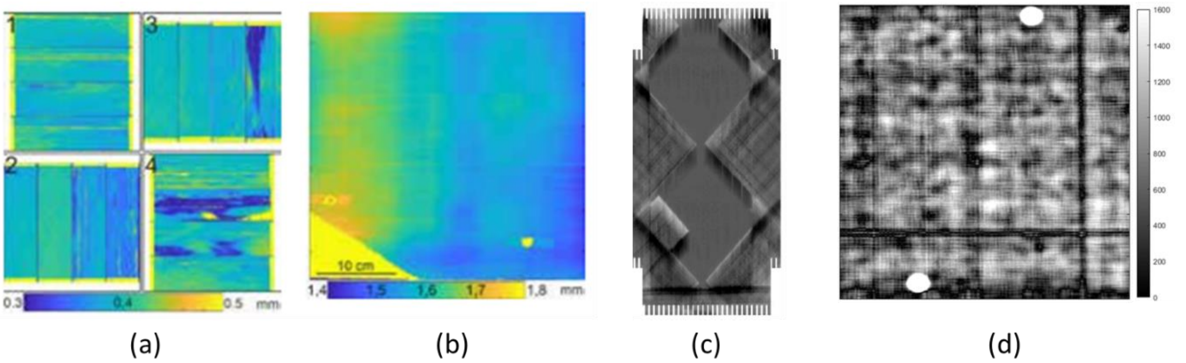


Figure 5: (a) Ply-level tape thickness variations (b) Thickness variations in consolidated laminate (Summa, et al., 2021) (c) Laminate with overlaid tapes (dark contrast) and tape cut longer than desired (d) Gaps in the laminate, indicated by dark lines (Oswald, et al., 2022)

The consolidated and defect-free laminate is then warmed to processing temperature, placed in the mold and overmolded with ribs to form the final demonstrator part. Ultrasonic scanning is then used to assess the quality of final part (Figure 6). Two flat strips, labelled as A and B in Figure 6, were scanned in pulse/echo technique to check for defects. The part was, however, found to be free of any major, observable defects with accurately overmolded ribs. It may hence be said that rejection of defective laminates is the previous steps through the application of DT proved to be an effective strategy in manufacturing of defect-free demonstrator parts.

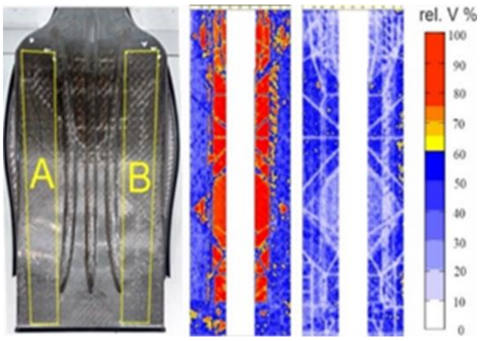


Figure 6: Ultrasound images of demonstrator component from sections A and B at 1 mm and 1.9 mm in middle and on the right respectively (Oswald, et al., 2022)

Thickness was used as a characterizing feature in this study, as aforementioned. It must be noted that the molds are designed for specific thicknesses in the process. It is, therefore, important to carefully track the thickness of the laminate, even beyond the defect data. If the laminate is defect-free but thicker than designed, the mold may close only partially, leading to incomplete or inappropriate overmolding in the final step. Similarly, there may be excessive overmolding along undefined local paths if the laminate is thinner than designed.

Corrective action to ensure the desired thicknesses at later stages can already be taken by measuring the thickness of constituent UD-strips, as was investigated within the realms of the digitalTPC project at Fraunhofer IMWS. The thickness information was employed to reject the tapes with higher levels of thickness variations than the set-tolerance with a set of pre-defined steps. The discrepancies were handled by either cutting the affected portion out or replacing the affected UD-tape strips. The equipment calculates the length of strips that must be cut-out to place on the affected area. If the next strip is found to have thickness variations or defects as well, it is rejected, and another piece is considered till the blank is eventually defect free and is then passed onto the next step.

A further outlook of this study is the defect-based and thickness-driven decision making. Once the defects in any of the sub-steps are communicated to the system, it may not be necessary to scrap, replace or patch the part. The defects or inaccuracies may be more conveniently eliminated by modifying the process parameters in subsequent steps, which can be achieved by a rigorous implementation of the DTs.

4. Conclusions

Digital twinning has emerged as a promising strategy to enhance production efficiency of complex structures based on thermoplastic unidirectional tape composites. Complex structures based on carbon fiber reinforced polyamide-6 were manufactured with hybrid injection molding within the realms of the digitalTPC project, with the output being assessed at every sub-step through sensor and non-destructive testing methods. The quality assessment of the consolidated laminates and demonstrator component using eddy current testing and ultrasonic testing methods respectively was discussed in this paper. Thickness was used as a quality characterizing parameter. Eddy current testing could successfully track variations in the thicknesses of the consolidated laminates, along with defects such as gaps between the tape strips and presence of longer (or shorter) strips. The setup was found to be capable of taking corrective action in either rejecting a defective laminate or rectifying the defect to yield a largely defect-free demonstrator component, as characterized by ultrasonic testing.

References

Anderon, C. B., 2020. *Challenges and Benefits of Implementing a Digital Twin in Composites Manufacturing.* [Online] Available at: https://www.cgtech.com/images/pdf/Challenges-and-Benefits-of-Implementing-a-Digital-Twin-in-Composites-Manufacturing.pdf
[Accessed 03 June 2023].

BASF, 2023. *Ultramid® B24 N (PA 6).* [Online] Available at: https://chemicals.basf.com/global/de/Monomers/polyamide_intermediates/polyamide_for_fibers/ultramid_b24_n_pa_6.html
[Accessed 01 June 2023].

Burov, A. E. & Burova, O. G., 2020. Development of digital twin for composite pressure vessel. *Journal of Physics: Conference Series ,* 1441(012133), pp. 1-15.

Dieffenbacher, 2023. *Fibercon.* [Online] Available at: https://dieffenbacher.com/en/forming/products/tape-laying/fibercon
[Accessed 01 June 2023].

Dieffenbacher, 2023. *Fiberforge.* [Online] Available at: https://dieffenbacher.com/de/forming/produkte/tapeverarbeitung/fiberforge
[Accessed 29 May 2023].

Fraunhofer Gesellschaft, 2021. *digitalTPC - Digital Twin for Thermoplastic Composites Technology,* Germany: Fraunhofer Gesellschaft.

Fraunhofer Institute for Microstructure of Materials and Systems IMWS, 2023. *Innovative high-performance thermoplastics for efficient use in the mass production of lightweight structural designs.* [Online]
Available at: https://www.imws.fraunhofer.de/en/kompetenzfelder/kunststoffe/highlights/paz-lightweight-thermoplastics-lightweight-construction.html
[Accessed 29 May 2023].

Gardiner, G., 2016. *Digital twin, digital thread and composites.* [Online]
Available at: https://www.compositesworld.com/articles/digital-twin-digital-thread-and-composites
[Accessed 02 June 2023].

Gardiner, G., 2021. *DigiProp positions Dowty Propellers and its customers for sustainable, next-generation platforms.* [Online]
Available at: https://www.compositesworld.com/news/digiprop-positions-dowty-propellers-and-its-customers-for-sustainable-next-generation-platforms

Kalidindi, S. R., Buzzy, M., Boyce, B. L. & Dingreville, R., 2022. Digital Twins for Materials. *Frontiers in Materials,* Volume 9, pp. 1-15.

Meyer, M. et al., 2021. *A digital twin for lightweight thermoplastic composite part production.* Berlin, Presented at the NAFEMS World Congress 2021, pp. 1-26.

National Composites Centre, 2023. *DigiProp: Developing the next generation of composite propeller blades for turboprop aircraft.* [Online]
Available at: https://www.nccuk.com/news/digiprop-developing-the-next-generation-of-composite-propeller-blades-for-turboprop-aircraft/

Oswald, J. et al., 2022. *Automatische Prüfung Von Carbonfaser-Tape-Gelegen Zur Überführung in Den Digitalen Zwilling.* Kassel: DGZfP-Jahrestagung 2022.

Polini, W. & Corrado, A., 2020. Digital twin of composite assembly manufacturing process. *International Journal of Production Research,* 58(17), pp. 5238-5252.

Renews.biz, 2023. *TPI creates digital twin to enhance blade production.* [Online]
Available at: https://renews.biz/83245/tpi-creates-digital-twin-to-enhance-blade-production/
[Accessed 02 June 2023].

Summa, J. et al., 2021. *Zerstörungsfreie Prüfmethoden zur Merkmalsextraktion für den digitalen Zwilling der Thermoplast-Composite Wertschöpfungskette.* Berlin: Deutsche Gesellschaft für Zerstörungsfreie Prüfung e.V. (DGZfP).

Toray Composite Materials America, Inc., 2018. *T700S Standard Modulus Carbon Fiber.* [Online]
Available at: https://www.toraycma.com/wp-content/uploads/T700S-Technical-Data-Sheet-1.pdf.pdf
[Accessed 01 June 2023].

Wang, Y. et al., 2021. Digital twin enhanced fault prediction for the autoclave with insufficient data. *Journal of Manufacturing Systems,* Volume 60, pp. 350-359.

Zuo, J. et al., 2023. A New General Framework for Response Prediction of Composite Structures Based on Digital Twin with Three Effective Error Correction Strategies. *Applied Composite Materials,* Volume 30, pp. 449-483.