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Overcoming Challenges in Manufacturing Complex Structures with Automated Dry Fibre Placement

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Introduction

The automated deposition of dry fibre materials using Automated Fibre Placement (AFP) followed by high temperature resin infusion has emerged as a promising alternative to the use of pre-impregnated materials for manufacturing high value composite structures [1]. In this additive manufacturing process, the machine deposits a course of multiple dry fibre tapes containing a binder, which is thermally activated by a heat source to adhere the incoming tapes to the substrate [2]. The deposition is followed by high temperature vacuum-assisted resin infusion as an out-of-autoclave manufacturing route [3].

The automated manufacturing process of complex geometries can be expensive and time consuming if a trial and error approach is utilised. This work aims to develop an understanding of the fundamental aspects of the process in a systematic manner, employing the principle of the pyramid of testing to manufacturing. This enables a better understanding of a highly complex process and a reduction of the development time. The required knowledge includes information about the material, process control of the deposition phase and impact of geometrical complexity on the infusion process. This work showcases the development and application of a number of process analysis and definition tools to eliminate the extensive test campaign typically required to manufacture new highly complex structures by automated means.

Experimental Work

The pyramid of testing approach was applied to the development of both the automated deposition and vacuum infusion manufacturing processes for a highly complex part (see Figure 1). A broad base of material characterisation leads to a gradually reducing trial matrix for coupons, features and a component as a combination of different features. The demonstrator component was designed to incorporate four challenging features common in aerospace structures: a ramp (1:5), a corner (10 mm corner radius) and a thick section (up to 24 mm), which results in double curvature on the chamfered radius and therefore in plane fibre steering, see Figure 2. The project is focused on the use of commercially available materials and machines.

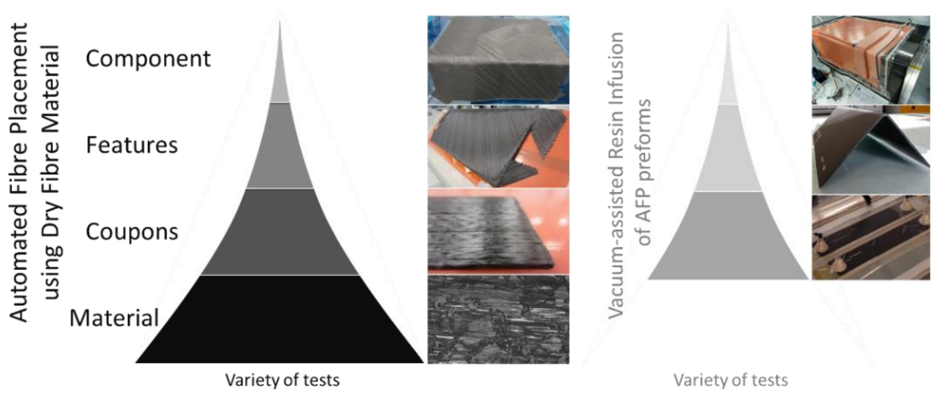

Figure 1: Pyramid of testing approach for dry fibre AFP deposition (left) and infusion of preforms (right)

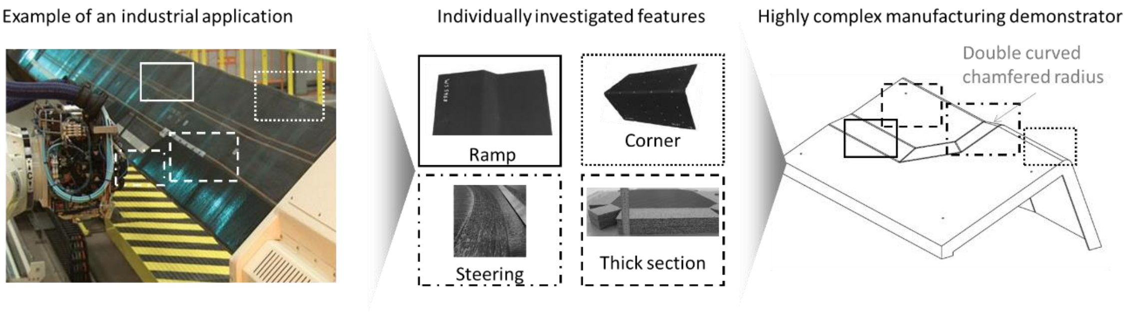

Figure 2: Example of industrial application, individual features and complex component manufactured as demonstrator

First, the commercially available dry fibre materials bindered with a thermoset (typically an epoxy) or a thermoplastic binder were characterised. Two material formats are available on the market (slit broad good or spread tow) offered in various areal weights (126 -262 g/m^2). With the support of a decision making tool (Analytical Hierarchy Process, AHP), five different dry fibre materials from four different suppliers were compared in terms of their performance in the manufacturing process. Criteria for each material were procurement, raw material, AFP manufacturing, infusion and laminate quality [4]. An AHP based selection tool was developed which supports a manufacturing quality driven material choice and a database of material characteristics was built. Material TX1100 (Cytec Solvay) was identified to be the most suitable dry fibre material for the highly complex part used in this project.

Coupon trials were used to derive the process parameters for the AFP machine. A series of tests determined a material specific relationship between set laser power and delivered temperature for a given speed [5]. A state-of-the-art industrial AFP machine (Coriolis Composites SAS, France) was used in this work. Up to eight 6.35 mm wide tapes can be deposited simultaneously at a speed of up to 1000 mm/s. The binder (5-10 wt. %) is activated with a 3 kW fibre-coupled diode laser using two diode stacks at λ = 1025±10 nm (Laserline GmbH, Germany). Process control has been gained by determining the relationship between heater power, deposition speed and processing temperature. A predictive semi-empirical model was developed to reduce the number of teste required to generate input to the machine controller rapidly.

In order to predict quasi-isotropic corner preform quality, deposition trials with single courses (eight tape wide strips), deposited in different configurations (0°/90°/±45°, corner radius: 5, 10 and 25 mm) were conducted. The surfaces of the manufactured samples were measured using an articulated arm with an integrated laser line scanner (ModelMaker MMDx 100 digital laser scanner and MCAx35+ Manual Coordinate measuring Arm, Nikon, Japan). The preform surface is compared to the tool surface to determine the thickness, which is converted into preform fibre volume fraction. The effects of ply direction and different corner radii were quantified and used to predict resulting preform fibre volume fraction of quasi-isotropic panels. These results formed the basis of a design tool that predicts the minimum acceptable corner radius [6], and enabled parameter optimisation and quality prediction of corner manufacturing derived from a small and controlled number of trials. The quantitative assessment of steered ply quality required a novel measurement method to capture out-of-plane dimensions to create a more robust quality criterion than the current visual inspection approach. The previously described surface measurement method was used to gather data that was subsequently used to generate metrics of surface topology based on established surface roughness metrics [7]. A quantitative method for the evaluation of in-plane steered tapes was developed to link the manufacturing program simulation with physical deposition.

In parallel, the infusion of dry fibre AFP preforms was investigated using a well characterised aerospace grade resin for high temperature vacuum infusion. Small scale, quasi-isotropic coupons provided an insight into flow behaviour of dry fibre preforms by quantifying flow front progression and permeability. Each preform had a laminate design with different gap widths with all plies having a gap with of 1, 2 or 4 mm as well as gap frequency of one gap every 25.4 or 50.8 mm. These preforms were infused to gain insight into the importance of gap size and gap spacing in two infusion set-ups: pure in-plane and a combination of in-plane and through thickness flow [8]. It was found that, within the limits of the tested configurations, the impact of the infusion set-up is of far greater influence on the infusion time than the preform design. These tests allowed an infusion strategy for simple feature geometries to be developed and was later applied successfully to the complex demonstrator.

Discussion and Conclusion

Manufacturing a complex part by Automated Dry Fibre Placement and high temperature vacuum infusion requires an in-depth understanding of the entire process. Each step in the process presents its own challenges. A structured pyramid of testing approach was shown to enable effective manufacturing process development and has developed a valuable knowledge-base to enable efficient industrial implementation. The proposed design tools, measurement methods and test campaigns were shown to reduce the development cost by reducing the use of costly material, machine and engineering hours.

While the first objective of the development activity was the efficient delivery of a specific project, it is an investment into future projects. The developed tools capture the gained knowledge so that it can be applied easily to new material and machine combinations. The methods were codified as transferrable tools that are not specific to the tested material and geometry combination, thus allowing a quick turnaround for new configurations in the future.

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