PREFORMING LARGE COMPOSITE AEROSTRUCTURES: A UNIQUE UK CAPABILITY

Mattia Di Francesco, Chris Hopcraft, Laura Veldenz, Peter Giddings
National Composites Centre
Feynman Way Central, Bristol & Bath Science Park, Emersons Green,
Bristol, BS16 7FS

The National Composites Centre (Bristol, UK) is making significant investments in automated preforming by acquiring hybrid machines combining Automated Fibre Placement with Filament Winding, Automated Fibre Placement with Automated Tape Laying and Automated Fibre Placement of wide tapes with wide fabric layup in three standalone machines. These machines will be able to process thermoset prepregs, thermoplastic prepregs, and dry fibre materials in widths ranging from 6.35 to 5000 mm. The equipment will support a range of commercial and collaborative R&D projects aiming to reduce the cost and the risk involved in the automated preforming of new components by reducing the knowledge barrier to entry. This paper presents the equipment and shows through a case study how the NCC is meeting the challenge of developing in-depth understanding of a novel automated process and material combination to provide value to its member companies.

1. INTRODUCTION

Lukaszewicz *et al.* have shown a drastic and steady increase of publications on Automated Tape Laying (ATL) and Automated Fibre Placement (AFP) since the 1990s [1].The adoption of automated manufacturing processes is in fact widely recognized as a key enabler for the widespread, scalable industrial application of composite materials. ATL, AFP and related automated preforming technologies are being developed continuously to:

- **Improve capabilities** by extending the range of parts that can be manufactured using automated preforming equipment. Increasing the range of materials and material formats that the equipment can handle and increasing the quality of the products that can be manufactured would enable the introduction of automation in the manufacturing process of more products.

- **Increase productivity** by increasing the Overall Equipment Effectiveness through, among others, lean manufacturing and smart manufacturing [2]. Increasing the OEE would enable industry to meet the production demands with a lower number of machines, therefore reducing the manufacturing cost of each part.

- **Reduce barriers to entry** by reducing the investment needed to develop the process knowledge and understanding required to benefit from the implementation of automated preforming technology. This would enable risk averse companies, including smaller ones, to invest in automation.

A significant degree of overlap exists between the three development goals and the activities required to reach each of them (Figure 1). A key stakeholder group which tends to lead development in each area can be identified for each of the three goals. The development of improved machine capabilities is the focus of the machine manufacturers (e.g. MTorres, ElectroImpact, Coriolis Composites, etc.). These companies invest heavily in upgrading their product offering to meet the current and future demands of their customers. Increasing the machine productivity through improved operations is driven by the effort of the composites manufacturer (e.g. GKN Aerospace, Premium Aerotech, Safran, etc.) to reap the benefits of automation and gain competitive advantage over their competitors through, among others, increased deposition speed and optimised ancillary operations (e.g. spool change, etc.). The barriers to entry are often linked to a lack of knowledge and information. The NCC, in line with its vision to "*enable design and manufacturing enterprises to deliver winning solutions in the application of composites*", aims to reduce the technology knowledge barrier to entry for automated preforming technologies.

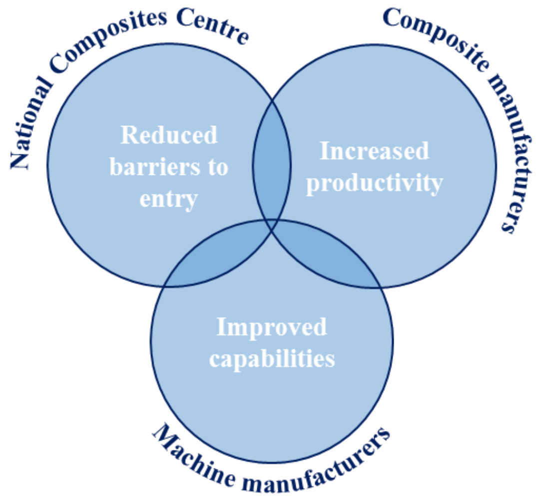

Figure 1. Development goals for the automated preforming technologies and key stakeholder groups

This paper presents the automated preforming capabilities available at the NCC (section 2.1) with a focus on large scale preforming (section 2.2). It then showcases how the NCC is reducing the knowledge barrier to the adoption of automated preforming technologies (section 3). A small scale example of how process knowledge and understanding was codified to enable rapid, transferable process definition is presented as a case study of how the development of the large scale preforming processes presented will be addressed.

2. AUTOMATED PREFORMING CAPABILITIES

2.1 NCC capabilities overview

The NCC is expanding the range of automated preforming capabilities it offers to tackle a wide range of customer R&D requirements. This expansion is enabled by funding from the UK Aerospace Technology Institute (ATi) through three funded programs (AutoProStruct, HiStruct and NTProStruct), the South West Local Enterprise Partnership and the High Value Manufacturing Catapult. On completion of this ambitious expansion in 2019, the NCC will host a world-leading automated deposition offering that combines established and emerging technologies with disruptive Non-Crimp Fabric (NCF) deposition technology (Table 1).

This portfolio of equipment enables development of technologies including Filament Winding (FW), Automated Tape Laying (ATL), Automated Fibre Placement (AFP) and pick-and-form spanning three classes of materials (thermoset prepregs (TS), thermoplastic prepregs (TP), and bindered dry fibres (DF)). By combining deposition technologies, NCC customers can assess applicability and exploit strengths of material formats with widths ranging from 6.35 to 5000 mm over geometries starting at sub-metre complex features and extending to full-scale aerostructures.

Table 1. Automated preforming capabilities at the NCC

	Coriolis Composites	Electro Impact	LCG
Preforming technology	FW, AFP	ATL, AFP	ATL, AFP, Pick and form
Material class	TS, TP, DF	TS, DF	DF
Material format	Eight 6.35 mm tapes	Eight 12.7 mm tapes, or 75/200/300 mm tape	Six 38 mm tapes, or up to 5 m wide fabrics
Maximum part size	10 m long x 3.6 m diameter rotating barrel, or 1.5 x 2.5 m	7 m long x 4.6 m diameter rotating barrel, or 1.5 x 2.5 m	20 x 5 m
Machine availability*	July 2018	April 2019	September 2019

However, successful process development requires more than capital equipment [3]. The complexity of program generation and optimisation tasks creates a high barrier to entry for businesses adopting automated deposition technologies. Sophisticated equipment requires sophisticated machine programming and program optimisation using a range of software tools, practical knowledge and know-how. On the shop floor, the preforming process needs to be monitored, e.g. via in-line thermal monitoring, and the preform has to be evaluated by, for example, non-contact metrology. The underlying relationships between the process settings and the output quality can then be characterised and understood to define transferable process definition tools that are relevant to a variety of parts and machine/material combinations.

2.2 Automated large scale preforming

The machine aims to provide a capability to manufacture large-scale aerospace structures, up to 20 x 5 x 1.5 m (Figure 2). The system is currently being designed and built around a flexible automation platform utilising a twin bridge precision gantry to deploy a number of deposition, trimming and inspection systems (Figure 2). There are four deposition end effectors, and the expected deposition speed for all of them is up to 1000 mm/s.

The cell is being designed and manufactured by a consortium of three companies, *LCG. Loop Technology Ltd.* provides the FibreROLL and FibreFORM end effectors that enable the layup of pre-cut NCF, as well as the system integration, *Coriolis Composites S.A.S.* provides the automated dry fibre placement end effector that enables the layup of unidirectional tapes, and *Güdel Lineartec (U.K.) Ltd.* delivers the six Degrees of Freedom (DoF) and the five DoF high precision positioning systems (bridges).

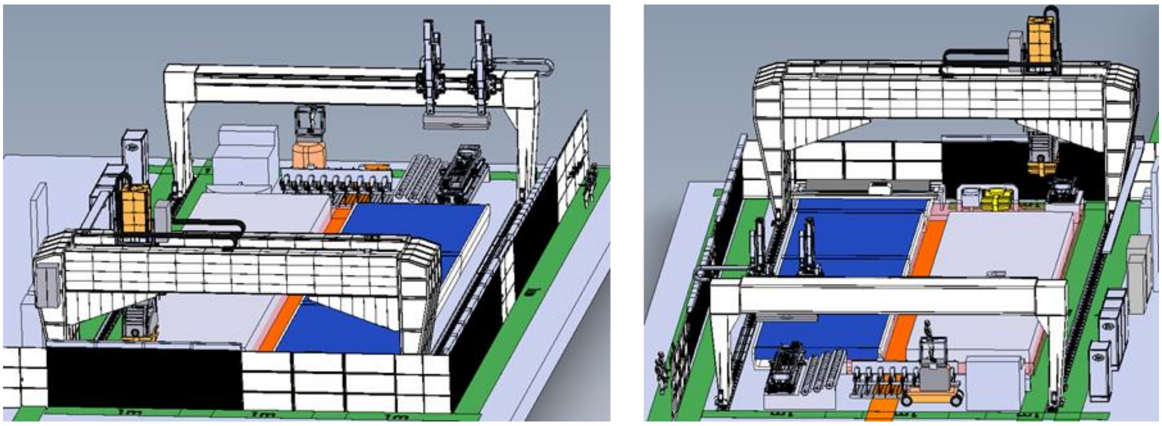

Figure 2. NCC's hybrid wide fabric and wide tapes deposition system (LCG)

The NCC's hybrid wide fabric and wide tapes deposition system has four end effectors that can be used in isolation or in combination to manufacture a preform:

- **FibreROLL end effectors** (Figure 3a & b): A 1.3 m wide and a 5 m wide roller system that address the need to lay down plies up to 1.3 m wide over moderately complex double curvature geometries and up to 5 m wide over flat, or low curvature, surfaces. These two end effectors include precision drive and nip rollers to allow handling of a wide range of ply shapes. High flow vacuum grippers embedded within the rollers can be individually actuated to initiate ply pickup. The drive rollers in this configuration have distinct functionality. One roller is used for pick up and deposition while the other acts as a core onto which the material is wound. The system will also include forward and backward looking 3D imaging systems used for path compensation and deposition verification.

- **Dry Fibre Placement** (Figure 3c): an eight tapes, each 38.1 mm wide, AFP head that enables high rate deposition (up to 1000 mm/s) onto double curvature geometries of intermediate complexity. Each tape is individually fed, cut and restarted by an individual cassette with a compliant compaction roller and heating system for binder activation. Each cassette can hold up to 8 kg of material.

- **FibreFORM** (Figure 3d): a large scale (4 x 1.5 m) pick and place system that can lift pre-cut plies from a ply cutter bed and forms them using 270 end-effector mounted suction cups to follow a three dimensional shape that can be approximated by a 5^{th} order polynomial function.

Overall, the system will bring together three of the current methods of dry fabric deposition in one machine, enabling the manufacturer to take advantage of the benefits that each process offers in the manufacturing process of the same part. However, this comes with significant challenges. Each manufacturing process needs to be characterised, its limitations understood, and in some cases, the capability enhanced to meet the requirements. For example, complex ply shapes may be difficult to process over specific geometries and the edge tracking of the material could be difficult if stitching is loose or thread direction causes fraying. Above all, programming and operating such a complex machine to manufacture a variety of bespoke parts will require specialist skills that need to be developed.

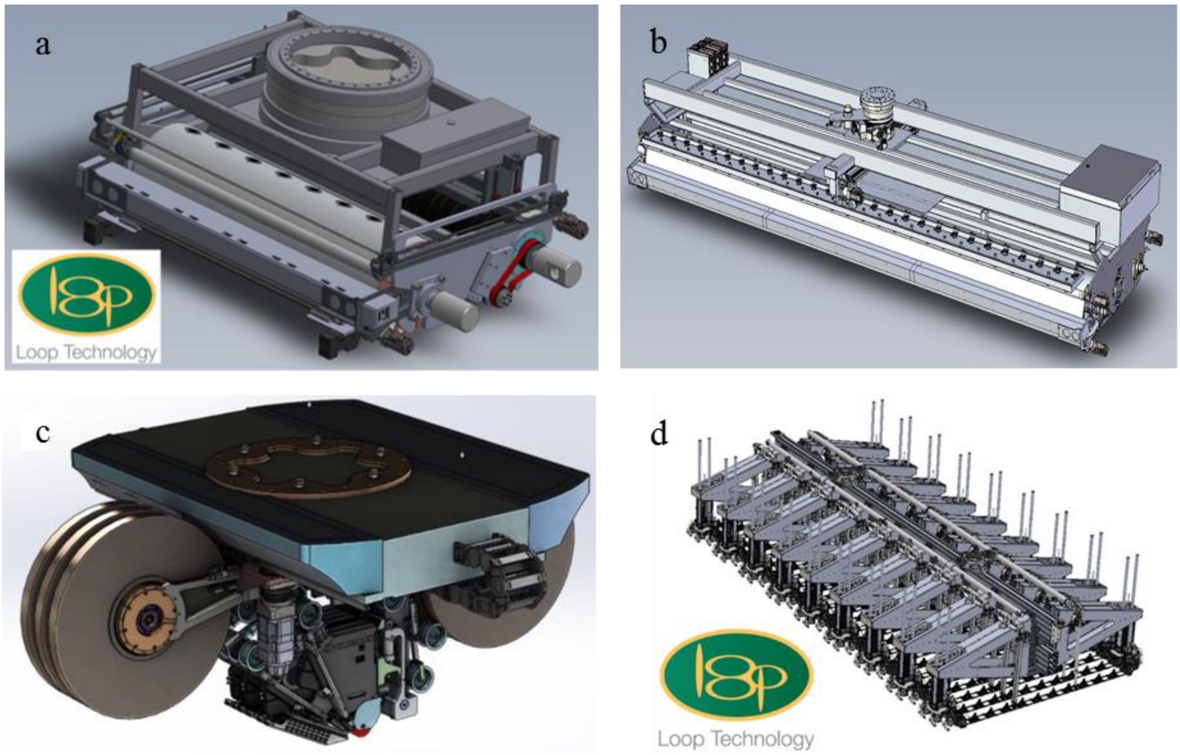

Figure 3. NCC's hybrid wide fabric and wide tapes deposition end effectors: (a) 1.3 m fibreROLL (Loop Technology Ltd.); (b) 5 m fibreROLL (Loop Technology Ltd.); (c) Dry Fibre AFP (Coriolis Composites S.A.S.); (d) fibreFORM (Loop Technology Ltd.)

3. PREFORMING PROCESS DEVELOPMENT

3.1 Process development approach

A pyramid of testing approach (Figure 4) was applied to the development of the automated preforming process with dry fibre tapes (AFP) for a complex part. The development of a broad knowledge base on different materials and their processability requires a relatively low budget and effort, but enables an objective selection process for materials and process parameters. When the complexity increases, only a selected set of materials and processing parameters need to be tested. The complex demonstrator component can then be manufactured right first time based on the knowledge accumulated. The knowledge is captured at each step and applied to guide the following one, thus showing how rapid process definition can be approached in a cost effective way. This can then be scaled up to be used to guide the cost effective development of the large scale preforming processes enabled by the NCC's hybrid wide fabric and wide tapes deposition machine.

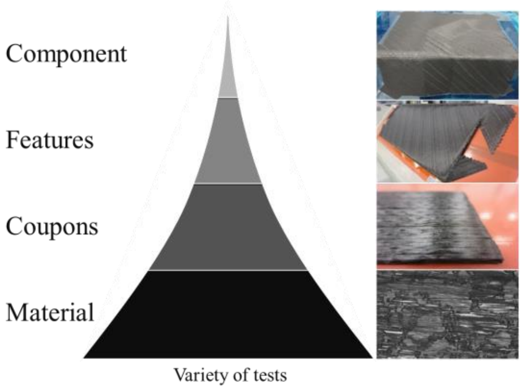

Figure 4. Pyramid of testing approach for dry fibre AFP deposition

3.2 Material level

Commercially available dry fibre materials bindered with a thermoset 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. The TX1100 (*Solvay*) material was identified to be the most suitable dry fibre material for the highly complex part used in this project.

3.3 Coupon level

Coupon trials were used to determine the control parameters for the AFP machine. 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 $\lambda = 1025 \pm 10$ nm (Laserline GmbH, Germany). Temperature control during the process was achieved by determining the relationship between heater power, deposition speed and processing temperature [5]. A predictive semi-empirical model was also developed to reduce the number of tests required to generate the control function.

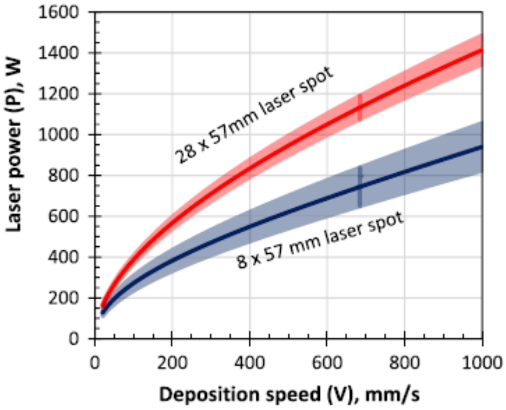

Figure 5. Isothermal (200 °C) laser power versus deposition speed curves for dry fibre – 8 x 57 mm and dry fibre – 28 x 57 mm (95 % confidence interval shown). [5].

3.4 Feature level

Feature trials were used to verify the parameters determined at the coupon level. Four challenging features, which are common in aerospace structures were selected: a ramp (1:5), a corner (10 mm corner radius) and a thick section (up to24 mm). As an example, the results of the investigation of the corner feature are presented.

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 scanned 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 used to calculate the preform fibre volume fraction. The effects of ply orientation and different corner radii were quantified and used to predict the resulting preform fibre volume fraction of a quasi-isotropic corner preform. The outcomes from these trials were used as the basis of a design tool that predicts the minimum acceptable corner radius [6], and enabled parameter optimisation and quality prediction of corner from a small and controlled number of trials.

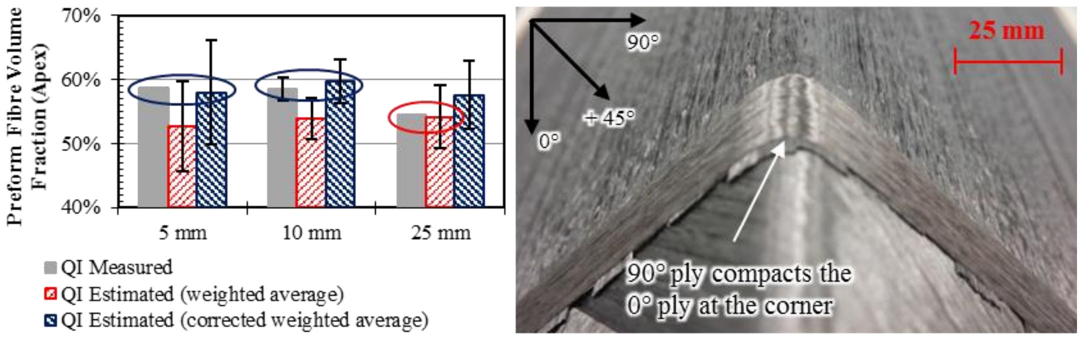

Figure 6. Results of prediction of preform fibre volume fraction as a manufacturing guide [6]

3.5 Component level

The gained process knowledge and understanding enabled the manufacture of a demonstrator right first time. The results of previous trials enabled objective material selection based on manufacturability and performance. Then a transferable semi-empirical model was developed for rapid process parameter selection to enable a fast turnaround of feature manufacturing with suitable processing parameters. The predictability of feature quality enables informed design of a demonstrator component that is representative of industrial applications.

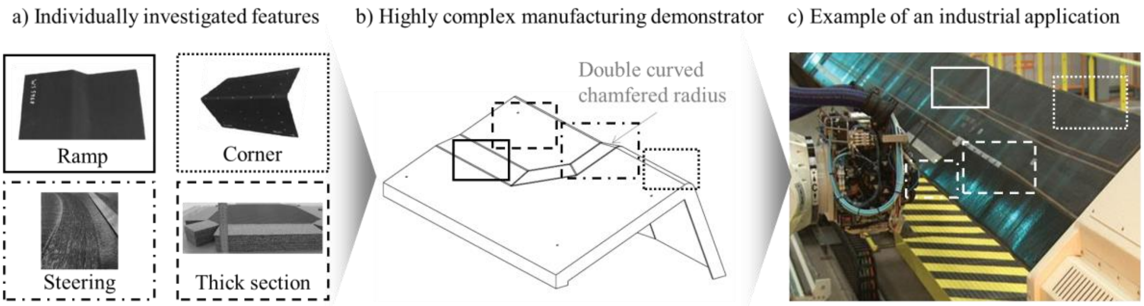

Figure 7.Individual features manufactured (a); the resulting complex component designed for manufacture (b) and an example of industrial application (c)

4. FINAL REMARKS

The case study shows that a structured pyramid of testing approach enables effective development of a manufacturing process and has generated 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.

This framework forms the basis of the capability development activities that will enable the successful deployment of the automated preforming capabilities the NCC is acquiring.

5. ACKNOWLEDGEMENTS

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