Benchtop-AFP: an Exploration of Democratised Automated Fibre Placement

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Abstract. This paper outlines the creation and evaluation of Benchtop-AFP, an innovative approach to producing composite materials akin to Automated Fibre Placement (AFP) but without the high capital expenses typical of traditional AFP methods. This unique technique, with further refinement, could serve as a valuable tool for research and development in automated fibre placement. As a world first, it aims to democratise AFP research, particularly for institutions where access to full-scale AFP facilities is unavailable and limited due to financial, skills, or safety constraints. This article presents the new method and provides examples of samples generated using this technique.

1 Introduction

Automated Fibre Placement (AFP) has been developed as a highly effective manufacturing technique for large composite parts, marrying the benefits of Automated Tape Laying (ATL) and Filament Winding (FW) to enable the manufacturing of large, bespoke, variable stiffness laminates at speed [1]. Human intervention is still involved in the current state-of-the-art, in particular in the activity of defect rework [2]. Despite the successes of AFP, the development of automated systems is made exclusive due to the very high capital costs associated with the system infrastructure including the end-effectors themselves, and the gantry or 6-axis industrial robots upon which they are typically mounted [3]. The exclusivity of this research environment precludes smaller institutions or researchers from successfully innovating within the field of AFP research, either through lack of access to existing systems, or through lack of capital funds required to support such research activities. Innovation in automating the remaining manually performed tasks is thus restricted to those institutions with access to full AFP systems, despite this problem being one at the layup and not the machine level.

We seek in this paper to democratise this research field through the development of a lower cost, lower scale, flexible, accessible research environment which retains the core aspects of AFP systems using more readily accessible technology. In this article, we refer to democratisation, in a narrower technical sense, as a transition that encompasses institutional reforms, expansion of access to critical technical infrastructure, knowledge, and skills, for greater citizen participation in research and decision-making.

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Section 2 details the composites manufacturing techniques commonly used including AFP and explore the benefits and disadvantages of each, before describing AFP in more detail.

In section 3, the Benchtop-AFP is described along with comparison to other techniques and a demonstration of samples created using the technique, showing their internal structure as analysed using Ultrasonic-NDT imaging.

2 Automated Composites Manufacturing

Automated Tape Laying (ATL) and Fibre Winding were early attempts at automating composite manufacturing processes. ATL involves laying down pre-impregnated (prepreg) tapes onto a tool surface, while Fibre Winding involves winding continuous reinforcing fibres over a rotating mandrel. These techniques paved the way for the development of Automated Fibre Placement (AFP) [1].

AFP emerged as an advanced composite manufacturing technique, combining elements of ATL and Fibre Winding. It involves the automated layup of individual reinforcing fibres or tows (bundles of fibres) onto a tool surface, offering greater flexibility and control compared to earlier methods [4]. Traditional AFP systems typically consist of a robotic arm or gantry system equipped with a fibre placement head [3] (see Figure 1). The head houses mechanisms for fibre delivery, cutting, clamping, and layup onto a tool surface. These systems often incorporate advanced sensors and control systems for precise fibre placement and path optimisation [5].

Analysis of labour demand of early tape-based automated composite manufacturing techniques, including both ATL and AFP, against manual layup shows a 70-85% reduction in person hours [6]. For AFP specifically, manual labour savings of 50% were found for complex contoured parts, while a figure of 10% was found for simpler, flatter parts. [7].

The ability of AFP to produce composite parts at a rate of 8.6kg/hr, compared with approximately 1kg/hr for manual lay-up techniques, has contributed to its growing popularity. AFP has been shown to have a much higher throughput rate for composite parts compared to manual layup manufacturing of 8.6kg/hr [8] compared to 1kg/hr [9], respectively.

Typical parts manufactured using AFP are wing spars and sections of fuselage in the aerospace industry [10]. AFP has also been utilised in the wind-energy sector, where the technique has been used to manufacture bespoke variable-stiffness turbine blades [11].

A major constraint for the adoption of AFP to more complex parts is the design of the AFP head. In order deliver manufacture larger parts more effectively, larger heads have been developed, the size of which is a direct barrier to the navigation of the head over complex curvatures without contacting any other section of the part surface [12] [13]. Current research in the direction of deploying AFP on more complex curvatures has focused on modular AFP heads [14].

The high capital cost associated with traditional AFP systems remains one of the primary barriers to their widespread adoption, especially for smaller organisations, research institutions, and educational facilities with limited budgets [7]. Stated costs for acquisition of AFP machinery from literature range from £1.0-1.2M [15], [16], [17] .

This financial barrier has motivated the exploration of alternative approaches, such as the Benchtop-AFP technique proposed in this paper, which aims to provide a more cost-effective solution for research and development in automated fibre placement.

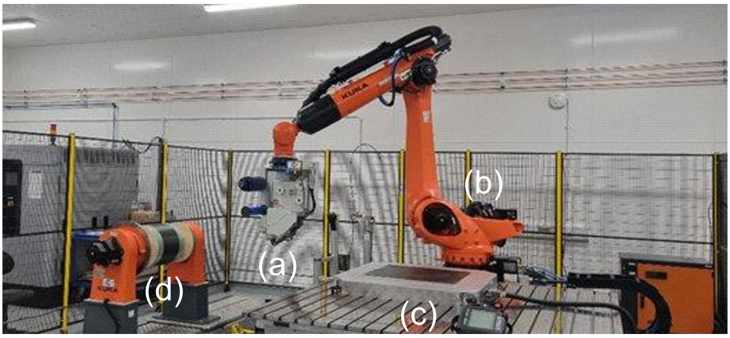

Fig. 1. Typical AFP system featuring (a) AFP end-effector, (b) 6-axis industrial robot, (c) Heated tooling place, and (d) Rotating mandrel

3 Benchtop-AFP

The motivation for the development of Benchtop-AFP arose initially from system availability of a traditional AFP system. To generate samples for analysis for other research, the core features of an AFP system were mimicked through readily available technology. What followed was an exploration of a new model for AFP manufacturing, utilising the benefits of cobotics for small-scale, flexible automated composites manufacturing. Figure 2 shows a non-scaled diagram of Benchtop-AFP. Tows are placed on the Polytetrafluoroethylene (PTFE) film covered 3D-print bed by the human operator, considering alignment and ply orientation. The cobot is then programmed to pass over the tow and apply the consolidation force along the length of the newly placed tow.

Using a 3D-print bed, tool temperature can be mimicked to a repeatable and accurate level. The temperature of the print bed was tested with a heat sensor gun and found to agree with the stated temperature in the control hardware. The chosen print bed was a disassembled Creality Ender-3 Pro 3D-printer, capable of rapidly heating between 0-110°C. A new printer can be purchased directly from the manufacturer for £236 or a broken printer repurposed thus saving money and the environment.

The use of a collaborative robot for the application of consolidation force was used as the deployed force could be controlled with similar repeatability as in the heated tooling aspect. In the developed Benchtop-AFP system, a universal robots UR10e robot was used. The UR10e can deploy a consistent downward force along a tool path of up to 100N. The UR10e is available in the range of £30,000 from retailers or direct from the manufacturer. In recent years, cobots have become increasingly ubiquitous in many manufacturing research settings.

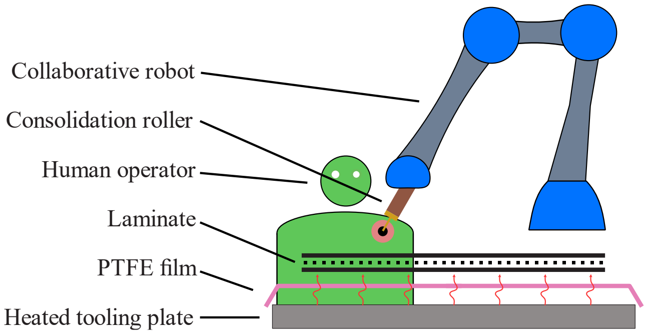

Fig. 2. Diagram of Benchtop-AFP

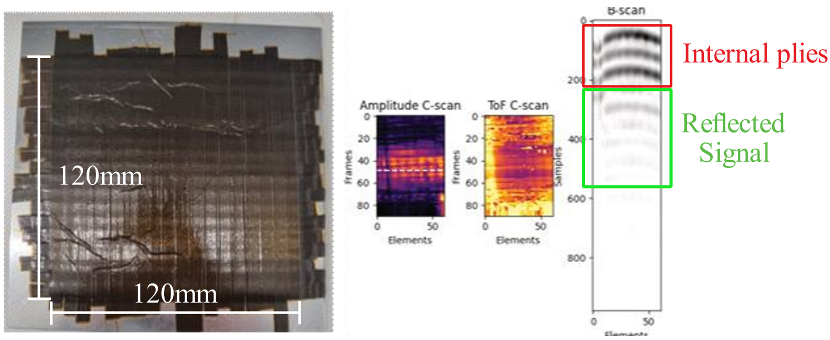

Fig. 3. Sample after curing (left), internal structure at scan line (white dashed on C-scan) showing three clear inner 0° plies (right)

Benchtop-AFP occupies a new space between traditional AFP and hand layup. This is illustrated in Table 1 with reference to key process descriptors.

The benchtop-AFP system was tested in generating 120x120mm [90,0,0,0,90] test laminates mounted on aluminium plates. Figure 3 shows this sample cosmetically post-curing and a depth wise sectional image (B-scan) of its internal structure, revealed using an ultrasonic phased array NDT method, as in [18]. The method records the amplitude of echo responses from inside the samples, the relative amplitude of these signals is converted into a grayscale image representing the internal structure of the scanned component. Due to the relative thinness of the samples, weaker reflected signals can be seen below the three stronger ply signals.

The B-scans across the samples showed similar results as for the section shown in Figure 3, where the three internal 0° plies can be clearly seen as continuous plies with limited undulation or fibre breakage. The curvature of the signal can be attributed to the warping of the aluminium plate during curing. Additionally, the deviation in the linear trend in each of the three plies at the left most side of the B-scans is a result of the scanning method, where the probes were lifted from the sample.

Benchtop-AFP as a proof of concept, retains the core features from typical AFP systems of controllable compaction pressure, and a heated tooling bed for a far reduced price than that of the typical AFP systems. While it does not include an AFP end-effector as in typical AFP systems, the positional accuracy of layup is human led, hence derived from operator proficiency. Moreover, with the human "in-cell" with the Benchtop-AFP system, novel methods in human-robot collaborative composites layup can be developed.

The lowered system price when compared to typical AFP is the cornerstone of the democratisation of this system. Here, smaller institutions or researchers can feasibly acquire or use existing technology to perform research on aspects of AFP at a small scale. It is important to note here, that in the current configuration of Benchtop-AFP, there is a large

Table 1: Comparison between manufacturing techniques

	AFP	**Benchtop-AFP**	**Manual Layup**
Scale	High	Low	Low
Cost	High	Medium	Low
Flexibility	Low	High	High
Collaboration	Low	High	Medium
Throughput/Efficiency	High	Low	Medium
Variability	Low	Medium	High

constraint on the scale of the parts which may be produced, governed in the first instance by the size of the 3D-print bed used, and secondarily by the reach of the collaborative robot used.

A particularly useful use case for Benchtop-AFP is in the study of defects and reworking in AFP, areas with existing significant, and growing research interest respectively. Given the state-of-the-art for defect rework is currently manually performed [2], Benchtop-AFP is uniquely placed as a collaborative technique for producing small scale laminates with defects upon which rework research may be performed.

4 Conclusion

While Benchtop-AFP may have limitations in terms of part size, layup rate, and overall complexity compared to industrial AFP systems, it could provide a valuable platform for researchers, educators, and small-scale manufacturers to explore and develop AFP techniques, optimise fibre placement strategies, and test new materials or configurations without the need for multi-million-dollar investments.

The use of a collaborative robot opens the space for a human-centred approach to AFP research and development. Benchtop-AFP sits in a unique space between typical AFP and hand-layup or other traditional composites manufacturing methods. It benefits from the reduced variability of an automated method, while not suffering from the prohibitive costs associated with typical AFP configurations. This comes with a reduction in scale when compared to AFP and to a certain extent efficiency, where traditional measures such as part throughput are concerned, however, the removing the industrial robots or gantries from the configuration leaves a more flexible and collaborative workspace. Here the benefits of automation can be married with the intuition and skill of human operators.

By thinking beyond the constraints of existing AFP configurations, Benchtop-AFP could democratise access to AFP technology, fostering innovation and enabling a broader range of organisations to engage in automated composite manufacturing research and development.

5 Further Work

Further development of the concept of Benchtop-AFP is needed. Through this, the potential of the method for the manufacturing of complex parts using the benefits of AFP without the capital costs may be explored. To validate the method, testing and analysis of the parts manufactured through Benchtop-AFP is necessary. These parts should be compared in terms of performance and quality against similar parts manufactured using traditional AFP and hand layup. Additionally, the process of generating these parts should be examined in terms of time efficiency and compared across techniques.

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