Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 232 (2024) 2167–2180

Procedia Computer Science

www.elsevier.com/locate/procedia

5th International Conference on Industry 4.0 and Smart Manufacturing

An overview of current research in automated fibre placement defect rework

Stig McArthur[a,b]*, Jörn Mehnen[a], Catherine Yokan[b], Iain Bomphray[b]

[a] The University of Strathclyde, Glasgow, UK, G1 1XQ
[b] Lightweight Manufacturing Centre, NMIS, Renfrew, UK. PA4 8DJ

Abstract

Automated Fibre Placement (AFP) is receiving increasing attention from academia and industry. This is due to its widespread application in major sectors such as the automotive, marine, aerospace, renewables, and rail industry. AFP defects pose a significant barrier to efficient part throughput due to their lengthy processing time in inspection and rework. While there is a plethora of research on the causes and effects of various defect types, the subsequent reworking of these defects has not been thoroughly investigated. Although some papers have examined manual rework, their scope is limited. Insights from manual hand layup and similar methods can be applied to this context. This article presents the first comprehensive review of the academic literature in the field of defect rework, alongside an analysis of rework process experiments conducted by the authors to provide insight into current industry best practices. Following this, the article focuses on analysing the rework process in AFP and proposes guidelines and best practices. It emphasises the need for further research in this area, along with the findings of other researchers, to demystify the rework activity and inspire new investigations. Such research can offer valuable insights into enhancing reworking techniques and exploring automation possibilities. Automation can assist in manual reworking or even eliminate the need for it entirely, thereby reducing manufacturing time. The suggested directions for future work include developing automated rework processes to achieve near-full automation of AFP.

Keywords: Automted Fibre Placement (AFP); defects; rework; composites; automation

* Corresponding author. Tel.: 01415482091.
E-mail address: Stig.McArthur@strath.ac.uk

1877-0509
10.1016/j.procs.2024.02.036

1. Introduction

Automated Fibre Placement (AFP) usage has been steadily increasing over the decades since its development. Figure 1 shows a comparison of the usage compared with other methods, from Red C. [1]. The ability of AFP to produce composite parts at a rate of 8.6kg/hr [2], compared with approximately 1kg/hr for manual lay-up techniques [3], has contributed to its growing popularity.

Early adoption of tape-based automated composite manufacturing techniques in aerospace companies is reported to have a 70-85% reduction in person hours compared with a manual layup of the same parts [4]. However, despite this improvement, analysis of the manufacturing time associated with AFP found that large periods are spent inspecting for and reworking defects [5, 6]. This process greatly reduced machine utilisation at a cost to the manufacturer [7].

While extensive research has focused on defect detection, little attention has been given to the rework of defects, which continues to be performed manually, requiring machine shutdown [8]. Addressing this gap, this research paper aims to present an investigation into the rework activity associated with AFP. Examining the literature and conducting an experimental setup will introduce a set of best practices for defect reworking. These guidelines will provide researchers with a valuable foundation to demystify the reworking process and explore avenues for introducing automation, thereby enhancing the efficiency and effectiveness of the AFP process.

By shedding light on the underexplored area of defect reworking and proposing strategies for its automation, this article offers novel insights into improving the AFP process.

Section 2 of this article provides a comprehensive overview of composites manufacturing, highlighting the significance of automated processes. In this context, Automated Tape Laying (ATL), which involves the placement of composite tape, and Filament Winding, a method that involves winding continuous filaments onto a mandrel, are explored. The main focus, however, is on Automated Fibre Placement, which is discussed in greater detail.

Section 3 shifts the focus towards AFP defects, which pose challenges in achieving optimal quality and efficiency. Understanding the types of defects encountered during the AFP process is crucial for addressing and mitigating their impact on the final product.

In Section 4, defect detection and inspection techniques applicable to AFP are examined. Thermography, and profilometry are among the methods explored, providing valuable insights into how these techniques can aid in identifying and evaluating defects.

Section 5 explores the critical aspect of defect reworking in the AFP process. This section emphasises the need for developing efficient and automated solutions for defect reworking in AFP.

To address this need, Section 6 presents a study on best practices for defect reworking in an experimental setup. The methodology employed in this study, including the selection of samples and reworking techniques, is described. The outcomes of this study serve as a foundation for proposing improved methods and introducing automation to the defect reworking process.

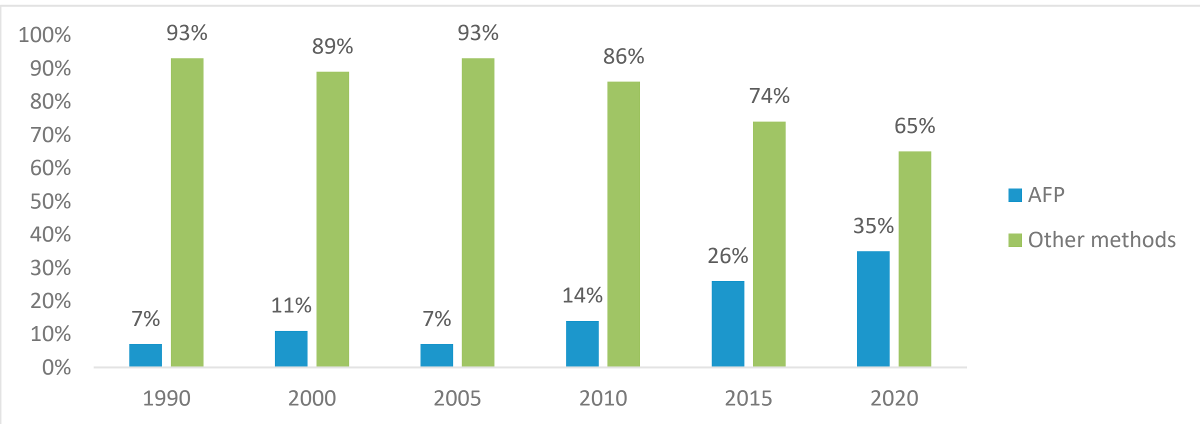

Figure 1 - Comparative usage of AFP vs other composites manufacturing methods over time, redrawn after [1]

2. Composites Manufacturing

Composite materials are a class of materials defined as materials consisting of two different constituent parts which, when combined, result in a material with superior mechanical properties than either of the constituent parts alone [9]. The two constituent parts are defined as (1) the matrix, and (2) the reinforcement. The role of the matrix is to hold the reinforcement in place and to transfer load between reinforcement [10]. Typically, matrices come in the form of polymer matrices, which may be thermoset or thermoplastics polymers, metal matrices, or ceramic matrices [11]. The role of the reinforcement is to improve the mechanical properties of the composite materials and be the principal load carrying medium. Typical forms are flakes, fibres, or particles, with fibres being the dominant form used across research and industry [12].

Composite materials are used widely across the aerospace, automotive, renewables, transportation, and marine industries [13]. Composite products are manufactured using a wide range of techniques depending on the part geometry, cost, desired manufacturing rate, availability of equipment and expertise. Traditionally, hand and spray layup are used. These techniques involve the manual application of the matrix and reinforcement to a mould in a predefined sequence. The final form created by this method is a laminate consisting of multiple layers or plies of composite material. Each layer can have a specific fibre angle, or all layers may be arranged with parallel fibre angles. The sequencing of stacking of these plies and their respective ply angle is of great importance to the final mechanical properties of the composite part and is a key stage in the design of composite products [14]. As a consequence, composite materials can be highly orthotropic in nature, meaning that they have different material qualities in different directions. Because of this quality, composite parts can be optimised in terms of mechanical properties, to the structural needs involved in the performance of the part in question.

Once the laminate is created, curing is performed. Curing is a high-temperature and/or pressure process during which the following effects are induced in the composite:

- Resin viscosity is reduced, which in turn,
  - ensures full adhesion to the reinforcement, though wetting out of the reinforcement
  - allows voids to exit,
  - allows the resin to flow out and through the part and increase the fibre volume fraction.
- Crosslinking occurs between polymers in the matrix material. This effect can be accelerated by the elevated temperatures reached in curing.
- The glass transition temperature of the material is raised [15].

Hand and spray layup are traditionally used methods for composite manufacturing. These are typically fully manually performed methods where technicians lay or spray sections of the composite material onto a mould of the desired part shape, before consolidating the part to the desired geometry [16]. Hand and spray layup have been found to be best suited to manufacturing smaller parts with complex geometries [12]. Crowley et al. [17] note that features that allow a part to be defined as complex are typically double curvature, intersecting planes and sharp corners, and that the magnitude of this complexity can be roughly approximated by the severity of the geometry involved in these features. As part size increases, the time taken for manual layup increases and the cost-effectiveness versus automated methods of composite manufacture decreases [18]. Modelling of costs for five aerospace companies based in China by Weitao Ma [19], found that labour costs accounted for 42% of total manufacturing costs.

2.1. Automated Tape Laying

As such, various automated methods have been developed. These include Automated Tape Laying, Filament Winding, and Automated Fibre Placement.

Automated Tape Laying (ATL) is an automated approach that mimics manual manufacturing the closest. In this method, larger sections of composite material are deposited sequentially onto a mould by an industrial robot until a complete laminate is formed and is ready for curing [20].C. Red [1] found that for placing parts with wide tapes of more than 304.8mm in width on relatively flat or minimally curved surfaces, ATL is an optimal method for automated composites manufacturing. Due to the larger tapes used by ATL, this technique is not suitable for small parts with complex geometries.

2.2. Filament Winding

Filament Winding (FW) is the process of winding fibres around a mandrel-mounted mould. The fibres pass through a bath of the matrix resin before being wound around the mould. A carriage containing the fibres and matrix bath is typically used and translates along an axis parallel to the main axis of the mandrel. The speed of translation of this carriage controls the fibre angle of the deposited material. Typically, FW is used for cylindrical parts such as storage tanks, for which it is highly repeatable and cost-effective [21]. A limitation of FW is its inability to produce parts where material follows a non-geodesic path [22].

2.3. Automated Fibre Placement

Automated Fibre Placement (AFP) is a combination of the FW and ATL methods. In this method, small tapes of materials, called tows, are fed through an AFP head, and deposited onto a mould in strips [23]. The AFP head is typically mounted on a gantry system or 6-axis industrial robot [24].

AFP has been utilised extensively in the aerospace industry for the manufacturing of wing spars and sections of fuselage [25] [26]. The ability of AFP to manufacture bespoke, variable stiffness composite components has led to an increase in the adoption of composite materials in new markets, such as energy, where wind-turbine blades have been manufactured using the technique [27] [28].

The utilisation of AFP with intricate parts is limited by the design of the AFP head. In such cases, the configuration of the feeding and cutting units, as well as the dimensions of the heat source and compaction roller, become excessively large for the head to navigate complex curvatures without making contact with the surface of the part [29] [30]. Current research is being explored in modular AFP heads to enable the use of the method on parts with more complex geometries [31].

A review of AFP commissioned by the United States Department of Defence found that manual labour savings through AFP could be as high as 50% in the case of a complex contoured part, while for simpler and flat parts savings were estimated to be greater than 10% [32].

The main issues for AFP are its high capital cost for equipment and tooling, high operating costs, and the still relatively high cycle time when compared with other techniques [33]. A major reason for the high cycle time is the presence of defects and the processes used for their inspection and rework.

Analysis of the typical cycle times for AFP by Electroimpact [5] and Boeing [6] found that inspection and rework accounted for 63% and 32% respectively. Further analysis by Rudberg et al. [7] found that AFP cells are typically only used to layup material 42% of the cycle time, with the rest of the cycle divided between inspection (28%), tool moves (11%), reliability recovery (10%), and operator breaks (9%).

3. AFP Defects

Despite its many advantages, AFP suffers from a high defect rate as a result primarily of head movement, improperly steered fibres, and variations in material [2] [34]. The inspection, detection, removal, and rework of these defects present a significant challenge.

Defects are imperfections in the layup that cause the final part to fail structurally or cosmetically. In the literature, defects are broadly categorised into those induced through improper management of process parameters, and those induced through improper placement of material [21].

Process-induced defects are caused by improper management of the key parameters of tow feed rate, curing/melting temperature, consolidation force, layup speed, and environmental conditions. Incorrect management and programming of these parameters leads to defects such as poor tow adhesion, wrinkles, gaps and overlaps, and increased presence of voids [21]. The presence of process-induced defects in a laminate leads to improperly managed stresses within the final part [35] and therefore parts with lower load capacity [36] and fundamental frequency [37].

Defects induced through improper placement of material are categorised into various types by [38]. The defects defined include:

- *Gaps*: where the space between tows is larger than a specified maximum allowable value.

- *Overlaps*: where the edge of a tow is placed over the top of an adjacent tow. Typically overlaps occur where gaps do.
- *Twists*: where the face of the tow facing away from the mould surface changes along a length of the tow. This is typically caused by slippage and twisting inside the AFP head.
- *Wrinkles*: where a fold is formed across the width of a tow and excess material is consolidated on top of the same tow. This is typically caused by the wrong settings of the feed rate of the tow causing bunching of material before the point of consolidation.
- *Fold*: where material becomes caught and is consolidated folded over along the length of the tow.
- *Pucker*: where a section of the tow does not adhere to the layup surface despite the lengths before and after adhering properly.
- *Bridging*: where a tow is stretched across a radius in the mould surface and lifts off the mould surface. This is typically caused by improper feeding of material during the laying up around the radius.

Figure 2 shows an example of a Gap and Overlap defect caused by the misalignment of a tow.

If left untreated between the layup of sequential plies, defects can become embedded within the layers of the laminate. Defects can in some cases become aligned through many plies in the thickness direction, this phenomenon is described as Defect Stack-up [39]. The effect of defects on the structural properties of the laminate compound when stacked, typically manifesting in larger strength knockdowns in the case of aligned gaps [39]. Defect stack-up has also been cited as a primary cause for out-of-plane waviness in the laminate [40]. Waviness has been found to reduce the flexural strength of a laminate by 12-15% [41]. Woigk et al. [42], note that the severity of the effect of a given defect on the mechanical properties of a laminate correlates with the degree of ply waviness caused by the defect.

4. Defect detection and inspection

Currently, inspection of parts for quality control in AFP is either done manually through vision by a skilled operator or by one of the following described automated methods [24] [43].

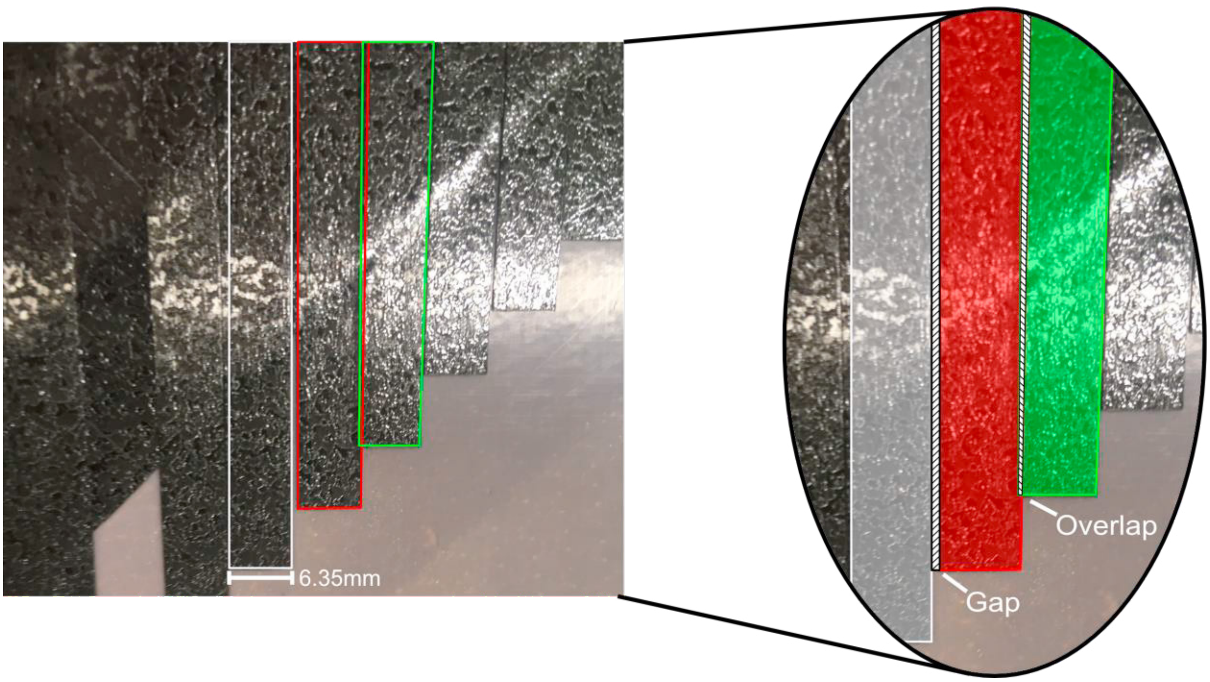

Figure 2 – Examples of gap and overlap defects in AFP tows. (left) showing misaligned tow (red) with respect to adjacent tows (white, green); (right) Zoomed and illustrated view of gap and overlap regions (hatched) as a result of misaligned tow (red).

A major issue with the visual inspection method is the low contrast between the substrate and tows, making defects difficult to see with the naked eye. Additionally, the process of manual inspection is very time intensive and relies on expert-level knowledge [24]. The time delay caused by manual inspection is very costly in terms of efficiency for manufacturers using AFP [7].

Various types of detection techniques have been reported in the literature to be able to detect gap and overlap defects. Fibre-Bragg sensors are thin fibre gratings inserted within a composite part at the point of manufacture. These have been used by [44] to measure the strain and temperature of a part manufactured using AFP and have been shown to successfully detect gap and overlap defects.

Zambal et al. [45] used a convolutional neural network combined with RGB images to detect gap and overlap defects through intelligent image segmentation.

An important definition to note is in-situ inspection and ply-by-ply inspection. In ply-by-ply inspection, the inspection system is dormant until all or part of the layup process is completed, whereupon the AFP deposition is halted while the whole part is inspected for defects. In-situ inspection methods, by contrast, are capable of inspecting the surface of the substrate as tows are deposited. This maximises machine usage during the entire process, hence improving process throughput [24].

Thermography and profilometry are the two most promising techniques for the detection of surface-ply defects and shall be examined in more detail in the following sections.

4.1. Thermography

Thermographic inspection refers to the use of thermal imaging cameras, usually combined with imaging processing software. The thermal camera is used to analyse the difference in temperature between the tow and substrate. The difference in temperatures recorded are caused by differences between the heat transferred through the laminate and hence are indicative of differences in the tows. Through this data, information on tow position and the existence of defects can be derived.

Research by [46] describes the process of detecting gaps and overlaps through thermography. In cases of a gap, the decrease in substrate thickness causes less heat to be absorbed, thus a higher temperature is read. Conversely, in cases of an overlap, more heat is absorbed by a thicker substrate, hence a lower temperature is recorded [47].

Experimental research by [48] demonstrated the ability of thermography to successfully inspect for and identify all defect types. Other researchers, [49], used thermography and an edge detection algorithm to localise tows and detect temperature discrepancies. In [50], Brasington et al. combined thermographic detection methods with a Convolutional Neural Network (CNN) to further improve thermographic defect detection.

4.2. Profilometry

Profilometry functions using a laser which is projected onto the surface of the layup. The reflected patterns can be used to infer the surface geometry of the layup and hence, any deviations in the pattern are indicative of defects and other layup discrepancies [24] [51].

A benefit of this method is that it can overcome the colour contrast issues cited for the inspection of AFP-produced parts [52].

Experiments were performed by [53] and found that profilometry was successful in detecting gaps and overlaps with sizes between 0.004” (0.1016mm) and 0.200” (5.0800mm). Foreign object debris (FOD), bridging, puckering, delamination, and tow twist were also successfully identified, providing these defects were large enough in their deviation from the expected surface topology than the minimum resolution of the profilometer used.

Research by [24] notes that profilometry requires the use of complex data processing algorithms to produce the detection results from the raw data collected. This entails a high demand for processing power, especially where high feed-rate AFP processes are considered. The authors also note that with proper optimisation of data processing, profilometry offers superior surface detail and, thus, eases analysis and identification of defects compared to other inspection methods currently in use.

5. Rework

The process of reworking defects in AFP layups is not yet thoroughly studied in the literature. However, reworking is practiced extensively in industry. The following section serves as a presentation of the available literature in this area, where the authors' analysis and inferences are included. Additionally, results from interviews with expert practitioners from industry are included in this section.

A definition of rework in the context of composite manufacturing is given by D. Hughes [54]: "Rework is the finishing step that can mitigate the source of scrap waste. Rework refers to the manual inspection and modification of defect plies or tows."

It is the contention of the authors of this article, that this definition need not be restrictive to manual inspection and modification, and research in future should expand this to include automation. In [8] Sacco et al. examine the effect of manually reworking defects on a composite part containing two curves. Technicians used their hands on a range of tools to rework defects. Figure 3 displays some of the typical tools used by technicians for the rework activity. The techniques used by the technicians to rework defects include shifting tows, reapplications of tows and replacing tows.

While some techniques are discussed in literature, no standards exist on either processes or tolerances involved in defect reworking. This view was supported by interviews conducted by the authors of this paper with industrial stakeholders with extensive experience in developing and implementing AFP. Further, D. Hughes [54] presents a similar view in his analysis of rework literature.

In their conclusion to the paper, Sacco et al. [8] propose a set of best practices recommendation for repair of defects for a part of this type. These include:

- In areas of large curvature or where high degrees of steering are used, only those defects resulting from improper adhesion between the tow and substrate should be repaired. Other defects are likely design driven.
- Replacement of tows for wrinkles is proposed over reconsolidation to avoid the creation of transverse wrinkles.
- Only large wrinkles should be repaired through reconsolidation together with the application of additional heat.

Since the process of manually reworking defects is similar in nature to the manual laying up of composite parts, the examination of this method is prudent. Elkington et al. [16] examined and categorised the different techniques used by technicians in performing this task. They defined eight techniques used by technicians and characterised these different techniques by the operation required to perform them. Table 1 outlines these methods. The operations are defined as:

- *Grasping*: where a section of the material is held in place by the hand of a technician.
- *Pulling*: where a section of the material is held by the technician and pulled in a direction.

Figure *3* - Reworking tools, left to right: hard compaction roller, soft compaction roller, straight pick, L-shaped pick, tweezers.

Table 1. Characterizations of hand layup techniques (after [16])

Technique	Grasping	Pulling	Pressing	Both hands necessary	Motion Necessary
One-handed guiding	✓	✗	✓	✓	✗
Two-handed guiding	✓	✗	✓	✓	✗
Manual folding	✓	✓	✗	✓	✗
Hoop shearing	✗	✗	✓	✓	✓
Double-tension shear	✓	✓	✗	✓	✗
Tension and sticking	✓	✓	✓	✓	✓
Mould interaction shearing	✗	✗	✓	✗	✗

✓= is required, ✗ = is not required

- *Pressing*: where the technician pushes their hand across the surface of the material, typically against the surface of the mould.

  The techniques are further characterised in Table 2 by the requirement for two hands or only one hand.

6. Study on best practice

The authors of this paper conducted their own observational study on the practice of reworking gap and overlap type defects produced during AFP manufacturing. Experiments were carried out in order to examine the rework process and draw some observational conclusions for a set of best practices.

6.1. Experimental Setup

The AFP system used comprised of a KUKA KR120 R3100 6-axis industrial robot, a bespoke single tow AFP head, and a bespoke heated tooling plate upon which the tows were deposited. Figure 4 shows this AFP cell.

Standard material as used in many industries was Hexcel M91/34%/ UD194/T700GC ¼ inch prepreg tows. The programming software Verticut Composites Programmer (VCP) from GTech was used to create a laminate and tool paths. The laminate was created with a [0/45/90/-45] laminate structure.

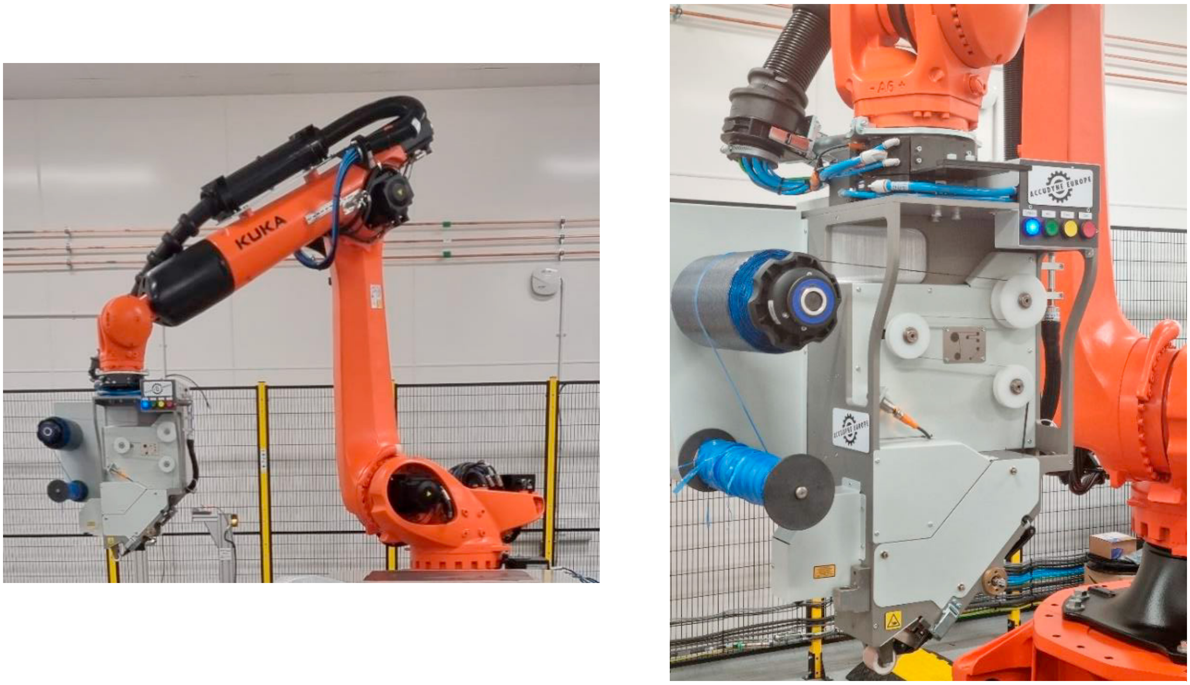

Figure 4 - AFP cell used in the experiment. (left) Kuka KR120 6-axis industrial robot; (right) bespoke AFP head from Accudyne.

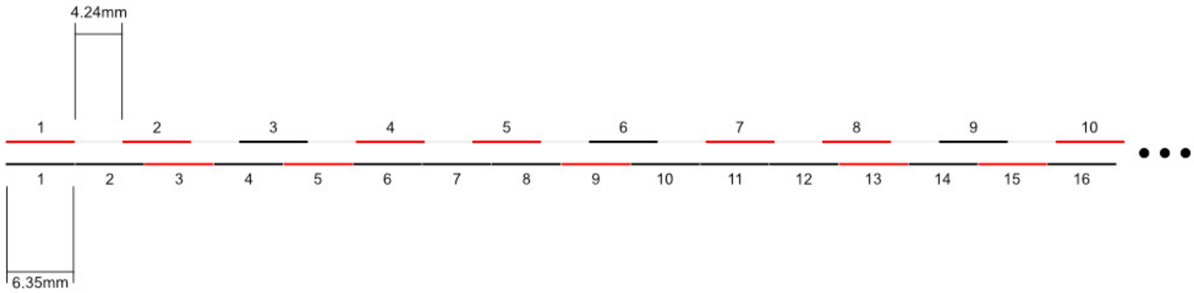

Figure 5 - Artificial gap and overlap inducing pattern. (Top) 'Dummy ply' showing programmed gap width with intentionally unlaid plies 1,2, 4, 5, etc. (red) and laid plies 3,6,9, etc. (black); (bottom) 'Actual' ply with intentionally unlaid plies 3,5,9,13, etc. (red) and laid plies 1,2,4,6,7, etc.

The temperature of the heated tooling and placement rate are key processing parameters determining the degree of bonding between tows. In [55] tooling temperature is examined between 30-120°C with regards to the void content and crystallinity of the parts. They suggest that a median temperature of 60°C is the optimal temperature for the lowest void content. Yassin et al. [56] in their review of process parameter optimisation attempts for AFP high temperature and low speed lead to the highest bonding rate. In this experiment, a medium bonding rate was sought in order for the reworking activity to be examined. The values of 55°C and 15m/min were chosen as median values seen across the examined literature.

Artificial gap and overlap defects were inserted using a novel method described below. These artificial defects are introduced using a second dummy ply for each ply containing the defects. The dummy ply is programmed to have a gap between tows with a width of 4.24mm or 2/3 of the width of the 1/4" tows. By systematically missing tows in a repeatable pattern on both the underlying ply and dummy ply, a repeated pattern of gap and overlap defects was created across the width of the test sample. In the underlying ply, every third, fifth and ninth tow in ten is not laid. Then only every third tow in the dummy-ply is laid down. Figure 5 shows this pattern.

Next, the misaligned tows were reworked. The process followed the description given in [8]. Picking tools were used at the thin edge of the tow to lift it from the underlying tow with as little disturbance as possible. Industrial heat guns, capable of producing heat up to 660°C were used to provide a localised source of heat to the defective tow, this helped to begin the delamination process. The authors also found the use of thin flat blades of a Steel Feeler Gauge (Figure 6) very useful for sliding under the tow once lifted from the underlying tow and progressing the delamination along its length. A pulling force was used to affect the delamination process.

The authors made use of scalpels to splice tows at arbitrary points along the length of the tow. This was done to emulate the splicing of a defective but not misaligned tow, i.e., in the case of a twist-type defect where only the defective is to be removed and not the entire tow.

Once removed, the tows were 're-laid' by running the AFP machine for the specific tow number that was removed. This was done entirely manually by counting the tows laid in sequence. It should be noted that for instances where partial splicing was performed, relaying of the tow was not done as this would have required the generation of a new AFP program which limits the deposited tow to the length of the removed area not the entire length of the tow.

Figure 6 - Steel Feeler Gauge

The observations made during this exercise are highlighted below:

- The longer the time since material deposition, the larger the degree of adherence between adjacent tows, and hence the greater the challenge in removing a single tow without damage.
- Peeling off one tow from the top of another without additional application of heat greatly increases the chance of negatively affecting the underlying tow.
- Tows peeled unevenly, i.e., at an angle different from their fibre angle. These tows tend to break into separate fibres. This, in turn, increases the change of disturbing adjacent tows.
- Splicing tows around a defect area is possible but extreme care must be taken not to damage underlying tows by cutting deeper than the depth of one tow.
- Tows removed from a ply at 90° to the underlying ply tended to induce delamination in the underlying tows as seen in Figure 7.

The following guidelines are given for the reworking of defects following this study:

- Minimise the time between material deposition and reworking to prevent increased difficulty in maintaining separation between adjacent tows.
- When peeling one tow from the top of another, apply additional heat to minimise the negative impact on the underlying tow.
- Peel tows evenly and in alignment with their fibre angle to avoid breaking into separate fibres and disturbing adjacent tows.
- If splicing tows around a defect area, exercise extreme caution to avoid damaging underlying tows by cutting deeper than the depth of one tow.

A more comprehensive body of research concerning the rework process can be developed as we integrate the guidelines presented by Sacco et al. [8] for addressing wrinkle-type defects.

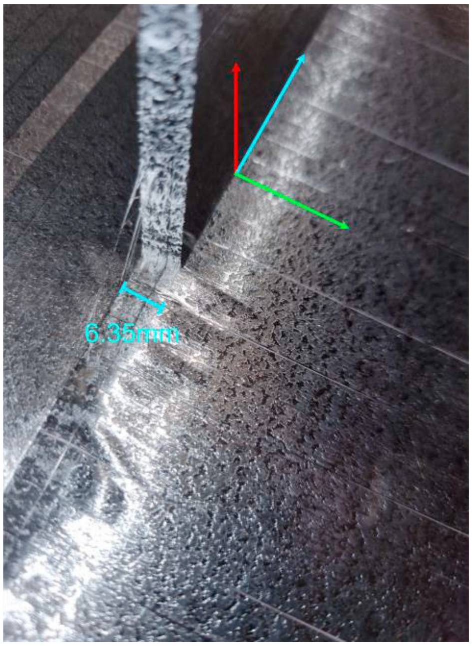

Figure 7 - example of delamination caused by perpendicular peeling. Axes shows directions of surface ply (blue), underlying ply (green), peel perpendicular to ply surface (red)

7. Conclusions

Defects occurring in AFP are a well-studied area in terms of classification, detection and identification. An in-depth analysis of the causes and effects of a wide range of types of defects have been presented in the literature.

Identification of defects is an emerging field at an intersection of hardware and technology challenges and challenges with data analysis methods such as machine learning. Despite the large body of valuable research in these areas, the subsequent operation of reworking defects is not well studied.

Some papers analyse the effect of manual rework, but these are limited in scope and application. Parallels can be drawn from manual hand layup and other related methods.

This article examines the rework activity and suggests a set of guidelines and best practices. Further developments in this study, alongside conclusions drawn by other researchers, provide valuable demystification of this activity and can lead to further novel research. Such research would yield valuable insight into 1) improvement in reworking techniques, 2) opportunities for automation, both in part to aid manual reworking, and in full to eliminate this task and reduce the manufacturing time required.

In conclusion, the findings from this study shed light on the reworking of defects in Automated Fibre Placement (AFP) and provide valuable guidelines for practitioners in the field. The experimental results highlighted the challenges associated with removing individual tows and the impact of various factors on the rework process. These insights contribute to a deeper understanding of the complexities involved in defect reworking and pave the way for further research and development.

The observed correlation between the time since material deposition and the degree of adherence between adjacent tows emphasises the importance of timely reworking to prevent difficulties in separating tows without causing damage. The need for additional heat during the peeling process to minimise negative effects on underlying tows underscores the significance of temperature control in achieving successful rework outcomes.

Furthermore, the recognition that uneven peeling of tows at angles different from their fibre angle can lead to breakage and disruption of adjacent tows highlights the necessity for precision and alignment during the rework process. Careful splicing around defect areas, while avoiding damage to underlying tows, emerges as a crucial consideration when addressing defects in AFP.

These guidelines, derived from experimental observations, provide practical recommendations for technicians and engineers involved in defect reworking. Implementing these guidelines can lead to improved efficiency, reduced damage, and enhanced overall quality in the AFP manufacturing process.

To further advance the understanding and application of defect reworking, it is recommended to incorporate the guidelines put forth by Sacco et al. [8], which address wrinkle-type defects. This integration of research efforts can contribute to the development of a comprehensive body of knowledge surrounding the rework process in AFP.

In conclusion, this research serves as a significant contribution to the field of defect reworking in AFP, offering valuable insights and practical recommendations for industry professionals, and contributing to the demystification of the rework activity in academia. The guidelines presented offer a significant step towards a full set of best practices and standardisation of the rework activity.

8. Suggestions for further work

The process of reworking defects in AFP is costly in terms of machine downtime and remains one of the few tasks to be conducted manually by technicians. Further work in this field should aim at developing automated rework processes. Doing so would allow for near-full automation of the AFP process. To achieve this end, further work is required in analysing the current rework process.

No recognised industrial standard has been found for assessing the success of the process, emphasising the necessity to develop a robust framework for evaluating automated solutions. The establishment of such a standard practice would prove highly advantageous to both academia and industry, as it would provide a shared benchmark for assessing and comparing various methodologies, promoting innovation, ensuring quality control, and facilitating meaningful research and development within the field.

Further, the use of tooling across manual rework must be accounted for in any attempts at automated rework. As such end-effectors must be developed and evaluated for their success at performing the rework task.

9. Acknowledgements

This research has been kindly supported by the Doctoral Training Centre with the National Manufacturing Institute Scotland (NMIS), UK.

10. References

[1] C. Red, "The outlook for thermoplastics in aerospace composites, 2014-2023," *High-Performance Composites,* vol. 22, no. 5, pp. 54-63, 2014.

[2] D. Lukaszewicz, C. Ward and K. D. Potter, "The engineering aspects of automated prepreg layup: History, present and future," *Composites: Part B,* vol. 43, pp. 997-1009, 2012.

[3] S. Krowlewski and T. Gutowski, "Effect of the Automation of Advanced Composite Fabrication Process on Part Cost," *18th International SAMPE Technical Conference,* 7-9 October 1986.

[4] M. N. Grimshaw, C. G. Grant and J. M. L. Diaz, "Advanced technology tape laying for affordable manufacturing of large composite structures," *International SAMPE symposium and exhibition,* pp. 2484-2494, 1999.

[5] T. Rudberg, J. Nielson, M. Henscheid and J. Cemenska, "Improving AFP cell performance," *SAE International Journal of Aerospace,* vol. 7, no. 2, pp. 317-321, 2014.

[6] A. Halbritter and R. Harper, "Big parts demand big changes to fibre placement status quo," Meza Arizona USA, 2012.

[7] T. Rudberg, J. Cemenska and E. Sherrard, "A process for delivering extreme AFP head reliability," *SAE Int. J. Adv. & Curr. Prac. in Mobility,* vol. 1, no. 2, pp. 333-342, 2019.

[8] C. Sacco, A. Brasington, C. Saidy, M. Kirkpatrick, J. Halbritter, R. Wehbe and R. Harik, "On the effect of manual rework in AFP quality control for a doubly curved part," *Composites Part B: Engineering,* vol. 227, p. p. 109432, 2021.

[9] T. G. Gutowski, Advanced Composites Manufacturing, New York: John Wiley & Sons, 1997.

[10] N. Saba, M. Jawaid and M. Sultan, "6 - Thermal Properties of oil Palm biomass-based composites," in *Lignocellulosic Fibre and Biomass-Based Composite Materials*, Serdang, Malaysia, Woodhead Publishing, 2017, pp. 95-122.

[11] F. Matthews and R. Rawlings, Composite Materials: Engineering and Science, 3 ed., Cambridge: Woodhead Publishing, 1994.

[12] T.-D. Ngo, Introduction to Composite Materials, Composite and Nanocomposite Materials, IntechOpen, 2020.

[13] Mordor Intelligence, "Advanced Composite Materials Market -Growth, Trends, and Forecast (2020-2025)," Mordor Intelligence, 2020.

[14] M. Albazzan, R. Harik, B. Tatting, Z. Gurdal and , "Efficiet design optimisation of nonconventional laminated composites using lamination parameters: a state of the art," *Composites Structures,* vol. 209, pp. 362-374, 2019.

[15] C. Hull and T. W. Clyne, An Introduction to Composite Materials, 2nd Edition ed., Cambridge: Cambridge University Press, 1996.

[16] M. Elkington, D. Bloom, C. Ward, A. Chatzimichali and K. Potter, "Hand Layup: understanding the manual process," *Advanced Manufacturing: Polymer and Composites Science,* vol. 1, no. 3, pp. 138-151, 2015.

[17] D. M. Crowley, M. P. Elkington, C. Ward and K. D. Potter, "Hand lay-up of complex geometries-prediction, capture and feedback," *International SAMPE Technical Conference,* January 2016.

[18] P. K. Mallick, Composites Engineering Handbook, 1st ed., New York: Dekker, 1997.

[19] M. Weitao, *Cost Modelling for Manufacturing of Aerospace Composites,* Cranfield University: MSc Research Thesis, 2011.

[20] H. D. Do, "End-Effectors for ply placement and consolidation in low-cost automated composites

manufacturing," RMIT Univesity Press, 2001.

[21] C. Red, "The outlook for thermoplastics in Aerospace Composites," Composite World, Gardner Business Media Inc, United States of America, 2014.

[22] E. Oromiehie, B. Prusty, P. Compston and G. Rajan, "Automated fibre placement based composite structures: Review on the defects, impacts and inspection techniques," *Composite Structures,* vol. 224, 2019.

[23] ASM International, ASM Handbook: Volume 21, Composites, Materials Park, OH: ASM International, 2001.

[24] R. Harik., "Automated Fiber Placement: Statues, Challenges and Evolutions (Submitted)," *SAE,* 2021.

[25] A. Brasington, C. Sacco, J. Halbritter, R. Wehbe and R. Harik, "Automated Fiber placement: A review of history, current technologies, and future paths foward," *Composites Part C: Open Access,* vol. 6, 2021.

[26] M. Jonsson, D. Eklund, A. Jarneteg, M. Akermo and J. Sjolander, "Automated manufacturing of an integrated pre-preg structure," *The second international symposium on autaomted composites manufacturing,* 23-24 April 2014.

[27] T. S. Angell and T. Rudberg, "Manufacture of substructure by automated fibre placement," in *Society for the Advancement of Material and Process Engineering (SAMPE)*, Wichita, Kansas2013, 2013.

[28] W. Elmar and J. Bernhard, "Composites Market Report," 2014.

[29] M. Barile, L. Lecce, M. Esposito, G. M. D'Amato and A. Sportelli, "Advanced AFP Applications on Multifunctional Composites," *The second international symposium on Automated Composites Manufacturing,* 23-24 April 2015.

[30] M. R. Setvati, Z. Mustaffa, N. Shafiq and Z. I. Syed, "A review on composite materials for offshore structures," in *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, volume 5, Materials Technology; Petroleum Technology*, San Fransisco, California, USA, 2014.

[31] J. W. Hao, "Devevlopment of composites manufacturing automation technology," *Aeronautical Manufacturing technology,* vol. 17, pp. 26-29, 2010.

[32] B. Denkena, C. Schmidt and P. Weber, "Automated Fibre Placement Head for Manufacturing of Innovative Aerospace Stiffening Structures," *Procedia Manufacturing,* vol. 6, pp. 96-104, 2016.

[33] US Department of Defence, "CMH17: PMC's material usage design and analysis," SAE International CMH-17, Wichita, KS, 2014.

[34] A. Bjornson, J. E. Lindback and K. Johansen, "Automated Removal of prepreg backing paper - a sticky problem Technical Report," SAE Technical Paper, 2013.

[35] D. Lukaszewicz, *Considerations for Automated Layup of Carbon-Fibre Thermoset Preimpregnates (PhD Thesis),* 2011.

[36] K. Croft, L. Lessard, D. Pasini, M. Hojjati, J. Chen and A. Yousefpour, "Experimental study on the effect of automated fibre placement induced defects on performance of composite laminates," *Composites Part A Applied Science Manufacturing,* vol. 42, no. 5, pp. 484-91, 2011.

[37] D. Evans, "Fibre Placement," in *Handbook of Composites*, Boston, MA, USA, Springer, 1998, pp. 476-87.

[38] R. Grone and M. Grimshaw, "Composite Tape Laying Machine with pivoting presser member". US Patent Patent US4627886, 1971.

[39] R. Harik, C. Saidy, S. Williams, Z. Gurdal and B. Grimsley, "Automated Fibre Placement Defect Identification Cards: Cause, Anticipation, Existence, Significance, and Progression," in *SAMPE Conference and Exhibition*, Long Beach, CA, 2018.

[40] X. Li, S. Hallett and M. R. Wisnom, "Modelling the effect of gaps and overlaps in automated fibre placement (AFP)-manufactured laminates," *Science and Engineering of Composite Materials,* vol. 22, no. 2, pp. 115-129, 2015.

[41] N. Bakhshi and M. Hojjati, "An experimental and simulative study on the defects appeared during tow steering in automated fibre placement," *Composites Part A: Applied Science and Manufacturing,* vol. 113, pp. 122-131, 2081.

[42] Y. Tang, W. Wang, H. Wang, J. Li and Y. Ke, "Influences of wrinkles induced by tows' offset in automated

fibre placement on the bending propertise of composites," *Composite Structures,* vol. 297, no. 2, 2022.

[43] W. Woigk, S. Hallett, M. I. Jones, M. Kuhtz, A. Hornig and M. Gude, "Experimental investigation of the effect of defects in Automated Fibre Placement produced composite laminates," *Composite Structures,* vol. 201, pp. 1004-1017, 2018.

[44] J. Bruning, B. Denkena, M. Dittrich and T. Hocke, "Machine Learning approch for optimisation of automated fibre placement processes," *Procedia CIRP,* vol. 66, pp. 74-78, 2017.

[45] E. Oromiehie, B. Gangadhara, P. Compston and G. Rajan, "In-situ simultaneous measurement of strain and temperature in automated fibre placement (AFP) using optical fibre Bragg grating (FBG) sensors," *Advanced Manufacturing Polymer Composites Science,* vol. 3, no. 2, pp. 52-61, 2017.

[46] S. Zambal, C. Heindl, C. Eitzinger and J. Scharinger, "End-to-end defect detection in automated fiber placement based on artificail data," in *Proceedings of the Fourteenth International Conference on Quality*, Mulhouse, France, 15 May 2019.

[47] P. Juarez and E. Gregory, "In Situ Thermal Inspection of Automated Fiber Placement for manufacturing induced defects," *Composites Part B: Engineering,* vol. 220, p. 109002, 2021.

[48] B. Denkena, C. Schmidt, K. Voltzer and T. Hocke, "Thermographic online monitoring system for automated fibre placement processes," *Composites Part B Engineering,* vol. 97, pp. 239-243, 2016.

[49] E. Gregory and P. Juarez, "In-situ thermography of automated fibre placement parts," in *44th Annual Review of Progress in Quantitative Nondestructive Evaluation, Volume 37*, Provo, Utah, USA, 16–21 July 2017.

[50] C. Schmidt, B. Denkena, K. Voltzer and T. Hocke, "Thermal image-based monitoring for the automated fibre placement process," *Proceedings of the 1st CIRP Conference on Composite materials parts manufacturing,* vol. 62, pp. 27-32, 2017.

[51] C. Schmidt, E. Hocke and B. Denkena, "Artificial intelligence for non-destructive testing of CFRP prepreg materials," *Prod. Eng.,* vol. 13, p. 617–626. , 2019.

[52] E. Hu and F. Haifeng, "Surface profile inspection of a moving object using dual frequency Fourier transform profilometry," *Optik,* vol. 122, no. 14, pp. 1245-1248, 2011.

[53] C. Sacco, "'Machine Learning methods for Rapid Inspection of Automated Fibre Placement Manufactured Composite Structures' PhD Thesis," University of South Carolina, Columbia, South Carolina, USA, 2019.

[54] J. Cemenska, T. Rudberg and M. Henscheid, "Automated in-process inspection system for AFP machines," *SAE International Journal on Aerospace,* vol. 8, no. 2, 2015.

[55] A. Chadwick and M. Willmeroth, "Use of in-process monitoring and ultrasonic to detect defects in thermoplastic AFP-produced parts," in *22nd International Conference on Composite Materials (ICM22)*, Melbourne, Australia, 2019.

[56] D. Hughes, "19 - Materials waste reduction," in *Design and Manufacture of Structural Composites*, L. C. M. Harper, Ed., Woodhead Publishing, 2023, pp. 475-497.

[57] J. Chen, K. Fu and Y. Li, "Understanding processing parameter effets for carbon fibre reinforced thermplastic composites manufactured by laser-assisted autoamted fibre placement," *Composites Part A: Applied Science and Manufacturing,* vol. 140, p. 106160, 2021.

[58] K. Yassin and M. Hojjati, "Processing of thermplastic matrix composites through automated fibre placement and tape laying methods," *Journal of Thermplastic Composite Materials,* vol. 31, no. 12, pp. 1563-1725, 2018.