USE OF IN-PROCESS MONITORING AND ULTRASOUND TO DETECT DEFECTS IN THERMOPLASTIC AFP-PRODUCED PARTS

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ABSTRACT

Automated manufacturing methods such as automated fibre placement (AFP) have led to a significantly increased production rate of fibre-reinforced composite components. However, this increased production is accompanied on an increased reliance on autonomous quality control or post-manufacturing inspection methods. The rising popularity of thermoplastic-matrix composite materials and out-of-autoclave manufacturing pushes this reliance even further, with the primary objective of many manufacturers being a single-step manufacturing process. To achieve this goal, defects or deviations during the manufacturing process must be identified as soon as possible, preferably without the need for additional destructive or non-destructive testing steps. In this work, a unidirectional carbon fibre-reinforced PPS laminate was manufactured containing a series of AFP-inherent defects; charring from excessive heating, poor consolidation from insufficient heating, foreign material inclusions, and missing tow material. The visibility of these defects was then assessed using in-process monitoring, via temperature readings from a thermal camera, and subsequent ultrasonic scanning of the laminate. The in-process monitoring displayed sound detection of the missing material and poorly consolidated tow, as well as a variation in the substrate surface caused by charring during deposition of the previous ply. However, the camera was unable detect temperature variations caused by the foreign aluminium inclusions. This shortcoming is attributable to the current (coarse) averaging used when outputting temperature values. Future work will aim to quantify the current minimum detectable length and reduce it through modifications to the collection software. The ultrasound scanning method was able to detect all defects within the laminate, with a combination of amplitude-based and time-delay-based read-outs producing the greatest visibility. The results from this work will be further developed in order to increase the detectability of defects during manufacturing and hence deliver more robust automated quality control capabilities.

1 INTRODUCTION

The very nature of Automated Fibre Placement (AFP) manufacturing aims to limit the number of personnel directly involved in the production process of a given part; in turn decreasing associated costs and increasing the total achievable production rate. However, a high level of automation demands robust systems and protocols through which any disturbance or defect in the production line can be identified at the earliest possible stage. The ability to minimise this Time-to-Detection (T2D) phase is critical, with prolongation being directly transmutable to increased costs.

At present several investigation approaches exist to identify potential defects stemming from production. The first and most comprehensive is destructive (or intrusive) part testing. Costs associated with this method are high owing to additional preparation and testing steps as well as the consumption of the component itself. Second to this step is Non-Destructive Testing (NDT), which also involves subsequent post-manufacturing activities but does not result in component destruction. The final approach is in-process monitoring, where defects are identified during manufacturing. This approach results in the fastest T2D but places a high demand on automated systems and hence produces the lowest assurance confidence of the three.

2 THE AFP PROCESS AND ASSOCIATED DEFECTS

Automated Fibre Placement involves the deposition and consolidation of fibre-reinforced thermoset or thermoplastic material to produce parts through additive manufacturing. By using polymer material containing continuous, unidirectional (UD) fibres, components produced using this method are able to further capitalise on the high strength-to-weight ratio of composite materials by aligning the load-bearing fibres with intent rather than distributing them uniformly within the part volume. This allows increased directional strength and hence a lower material demand. A diagram of this manufacturing method is shown in Figure 1.
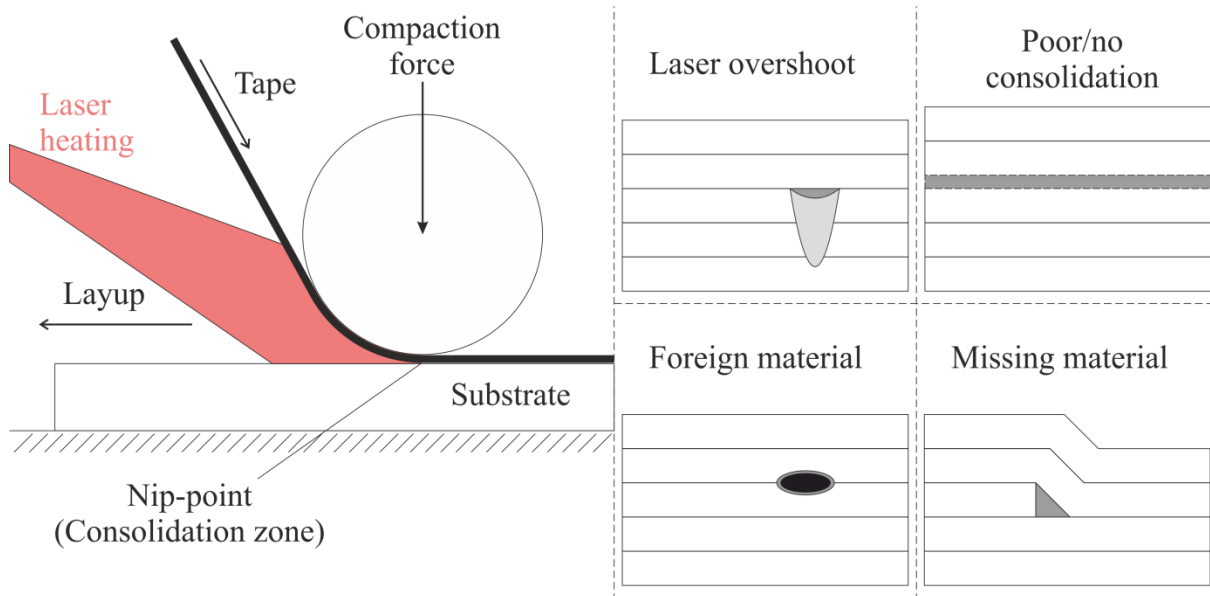

Figure 1: Automated fibre placement principle (left) and common manufacturing defects (right)

While AFP technology has existed in some form or another (be it research-based or commercially available) for more than 30 years [1], the majority of its application has focused on thermoset rather than thermoplastic applications. However, due to the increasing popularity of fibre-reinforced thermoplastic composites (CFRP), owing to their improved toughness, welding, and recyclability properties, the implementation of large-scale, AFP-manufactured thermoplastic components for aerospace applications is currently in motion [2-4].

As both thermoset and thermoplastic AFP methods utilise the same manufacturing principle, the differences between the two are directly attributable to the processing requirements of the material, being post-layup curing and the deposition temperature.

AFP-produced parts utilising thermoset material operate in a two-step process, with tape deposition followed by a curing process in an oven or autoclave. While a similar method has been used in thermoplastic AFP manufacturing as a means of compensating for low levels of ply consolidation or high porosity [3,5], the nature of thermoplastic material makes a single-step process preferential as it removes costly bagging procedures and the procurement of large curing facilities. However, this in turn places a higher demand on process quality assurance, with minor defects able to be compensated by the consolidation step existing in the final part instead.

The most common thermoplastic matrix materials used to produce aerospace parts (PPS, PEEK, PEKK) require processing temperatures several times higher than their thermoset counterparts. These high temperatures, combined with the desire to rapidly deposit material to minimise production time, have led to the use of hot gas torches and eventually high-power laser heat sources [1] to facilitate material deposition. Modern thermoplastic AFP facilities utilise near-infrared lasers with output powers of several kW, meaning that sudden malfunctions in heat regulation can cause severe and often irreparable damage to the material during manufacturing. By a similar merit, the high temperatures required can result in poorly consolidated material following a sudden loss or reduction of laser power

during manufacturing. Considering these heat source-associated defects, as well as others stemming from incorrectly applied UD tape or the accidental inclusion of foreign material, a list of AFP-inherent defects and their impacts on the laminate structure can be developed. Such a list is given in Table 1, with diagrammatic examples of the defects shown in Figure 1.

Defect	Effect
Laser power overshoot	Material degradation
Insufficient laser power	Poor/no consolidation
Foreign material	Poor/no consolidation
Missing tow material	Disruption to adhesion and contour of subsequent plies; cavity generation

Table 1: Typical AFP defects and their effects on the deposited material

This list of defects correlates well to previous investigations concerning thermoset materials [6,7], with the addition of the heat source-specific defects being novel to the authors' knowledge. These defects are hence used as the basis for this work, with the overarching objective being their detection using in-process monitoring and, where necessary, subsequent NDT methods.

3 EXPERIMENTAL SETUP

The thermoplastic AFP facility of the German Aerospace Center (DLR) is located at the Institute of Structures and Design in Stuttgart, Germany. The facility combines a 6 Degree-of-Freedom (DoF) robotic arm with a 2 DoF planar tooling surface and rotational axis system to facilitate the production of a range of different part geometries and complexities. An image of this facility is shown in Figure 2.
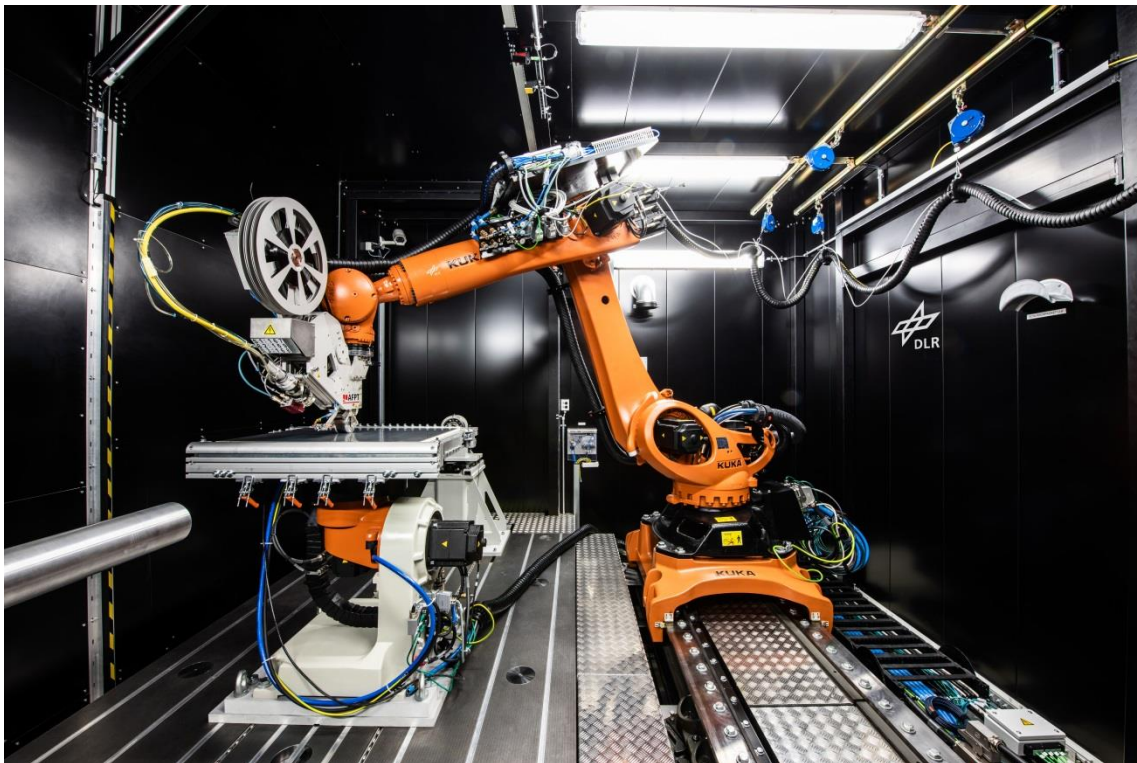

Figure 2: DLR thermoplastic AFP facility in Stuttgart, Germany

For the purpose of this study, the Multi Tape Deposition Head (MTLH) developed by AFPT GmbH was used to deposit tape on the planar tooling. The MTLH utilises a 6 kW diode laser and water-cooled roller to consolidate single UD tapes with widths between 12.7 and 50.8 mm or three 12.7 mm tapes simultaneously.

The tape used within this work comprises Fortron PPS and AS7 carbon fibres in a 12.7 mm wide prepreg with a 55% fibre content by volume. The thickness of the unconsolidated tape was 0.19 mm.

3.1 IN-PROCESS MONITORING

During manufacturing, information on the Cartesian position of the consolidation point, as well as the nip-point, substrate, and incoming tape temperatures are recorded using the facility control centre. Temperature values are captured using an Automated Technology IRS128-I thermal camera and used in a feedback loop to regulate laser power and maintain the user-defined process temperature. The detector resolution of this camera is 168 x 128 pixels, with the total capture area being divided in three and each third determining an averaged value for the three temperatures. Values of the laser power incident on the consolidation zone are also recorded. A diagram of this data capturing system is shown in Figure 3.

As the process temperatures are used to define the output of the laser, temperature, not laser power, is used as the preferred reference parameter when assessing the effectiveness of material deposition. The occurrence of defects listed in Table 1 can hence be correlated with a change in recorded temperature as listed in Table 2.
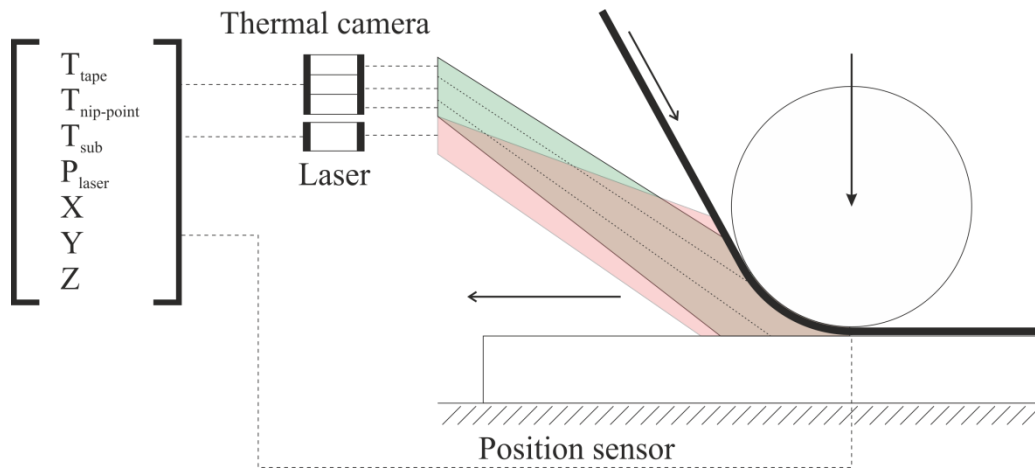

Figure 3: In-process monitoring during AFP manufacturing

Defect	Effect on recorded temperature
Laser power overshoot	Sharp increase
Insufficient laser power	Sharp decrease
Foreign material	Sudden increase/decrease owing to differing emissivity of foreign material compared to tape
Missing tow material	Ambient value (zero gain) owing to facility safety feature

Table 2: Typical AFP defects and their effects on recorded temperature values

Excess or insufficient laser heating conditions are logically recorded as a sharp increase or decrease, respectively, while foreign material may result in either an increase or decrease in recorded temperature owing to a change in emissivity compared to the UD tape. Finally, a facility safety feature prevents laser power being applied in the absence of material to be deposited, allowing tape run-out to be associated with a zero gain value compared to the ambient or tool surface temperature. Recording positional data allows process information to be plotted over the course of single tows, whole plies, or

whole parts using a dedicated script developed at DLR [8]. The ability to plot the precise location of suspected defects hence allows a good comparison with spatially resolved NDT methods.

3.2 ULTRASOUND SCANNING UNIT

For the purpose of this work, ultrasound (US) scanning has been selected as the post-manufacturing NDT method due to its proven ability to detect defects in composite bodies with high accuracy [9,10]. This investigation utilised an Olympus OmniScan MX2 US scanning unit with a phased array probe to detect defects in the final laminate. The scanning head specifications and scan settings are listed in Table 3.

Parameter	Value
Number of elements	64
Scanning frequency	5 MHz
Bandwidth	1.0 – 17.8 MHz
Pulse width	100 ns
Pulse voltage	40 V
Amplifier gain	2.4 dB

Table 3: Ultrasound scan settings

4 LAMINATE MANUFACTURING AND DEFECT IMPLEMENTATION

In order to compare the visibility of defects listed in Table 2, a unidirectional laminate ($[0°]_{11}$) was produced with the following defects:

- Foreign material, aluminium foil, 0.10 mm, 5 x 30 mm
- Foreign material, aluminium tape, 0.05 mm
  - 5 x 5 mm
  - 10 x 10 mm
  - 20 x 20 mm
- Foreign material, release agent
- Missing tow
- Simulated laser dropout, $P_{laser} = 0$ W
- Simulated laser overshoot, moderate and severe substrate charring below and above the polymer flash point, respectively

The final dimensions of the laminate (x,y,z) were 300, 300, and 2.2 mm, with the positions of various defects visible in Figure 4. Foreign material was placed at different through-thickness (z-direction) locations to assess the quality of visibility as a result of the available scanning surface for a real-world part. Due to spatial constraints of the final laminate, the same variation could not be repeated for the other defects.
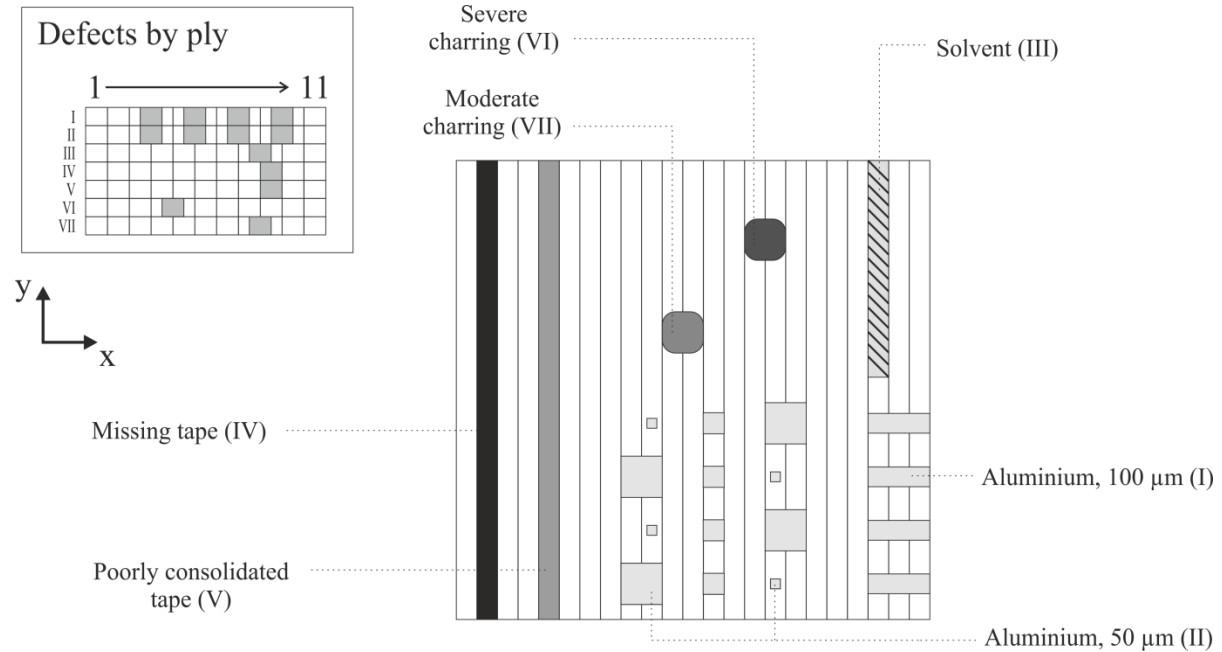
Figure 4: Defect locations within the laminate

5 RESULTS

Figure 5 shows plies 9 and 10 of the laminate reconstructed using the monitoring software, with a mesh size of 12.7 x 5.0 mm (x,y) . These plies contained missing and poorly consolidated tows and the foreign aluminium material, respectively. As can be seen from the figure, the missing and low-power defects are clearly visible as areas of reduced temperature in ply 9. Recorded temperatures in these areas are dependent on the tooling temperature and substrate thickness, though since the tooling temperature is held considerably lower than the polymer melt temperature (in order to ensure substrate stability), such defects can be clearly distinguished from the surrounding standard deposition. It should be noted that the additional low-temperature zone on the right side of the image was also intentional. This was used to apply the release agent to ply 8 without contaminating the roller.
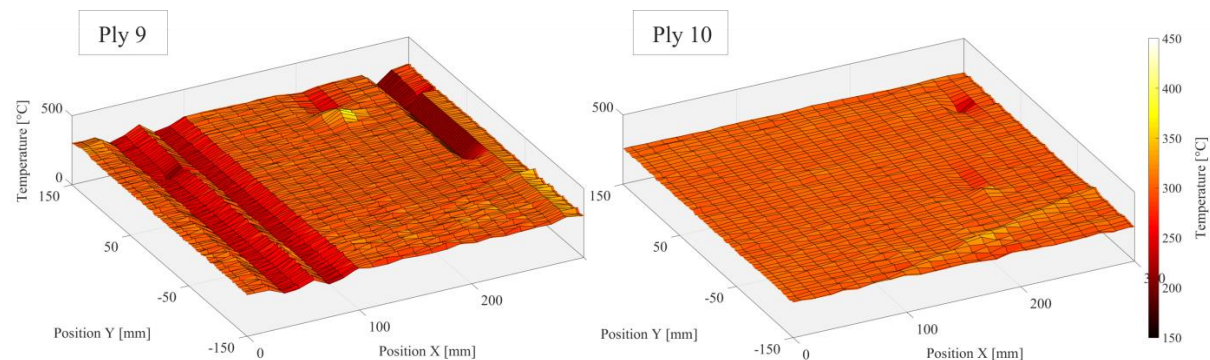

Figure 5: Reconstruction of plies 9 and 10 using in-process monitoring values

Despite the difference in emissivity and reflectivity from the UD tape, none of the four aluminium material segments produced a significant deviation in the recorded temperature when applying ply 10 to the form. In the reconstruction shown, certain minor deviations from the mean surface temperature are seen, though their magnitude is not sufficient to correlate them with any confidence. Interestingly, the only surface defect registered by the thermal camera was that resulting from the severe charring (simulated power overshoot) from the previous ply (8). This charring, shown in Figure 6, was significantly more aggressive than that applied to ply 4, with the substrate heated to above the polymer

flashpoint (500°C [11]). While the homogeneity of the charring is difficult to estimate, it is visible to the naked eye over an area of approximately 40 x 40 mm^2. The characteristic length of this defect (in the direction of deposition) is hence twice that of the largest aluminium addition. As recorded values for the nip-point temperature are averaged over a reasonably larger number of pixels, it is possible that foreign body inclusions must be larger than those used in this study in order to be registered by the camera in its current configuration. Future investigations will look to quantify the minimum detectable length and improve it through alterations to the temperature averaging function.
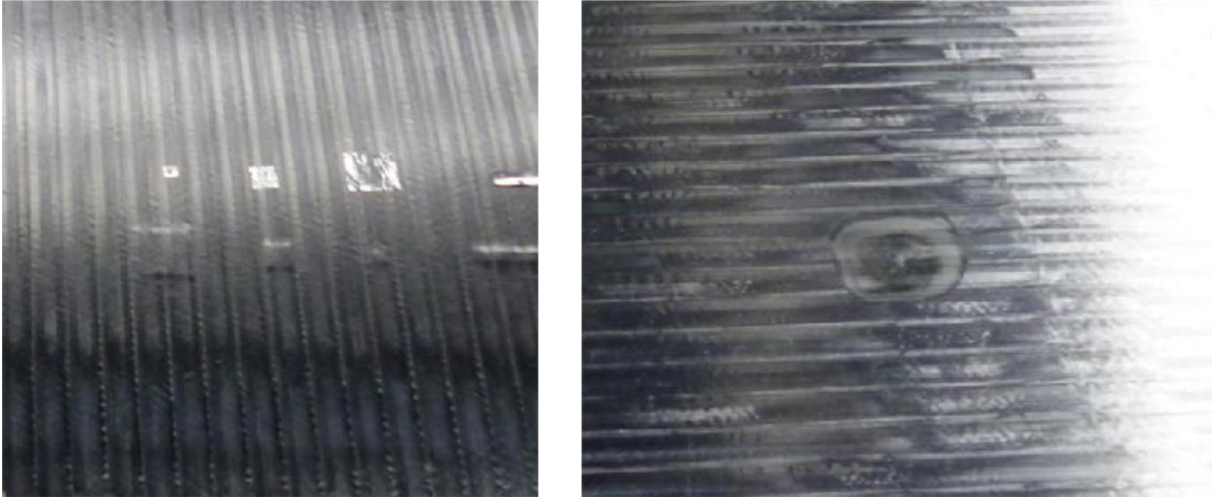

Figure 6: Aluminium foreign material before and after tape deposition (left) and severe substrate charring (right)
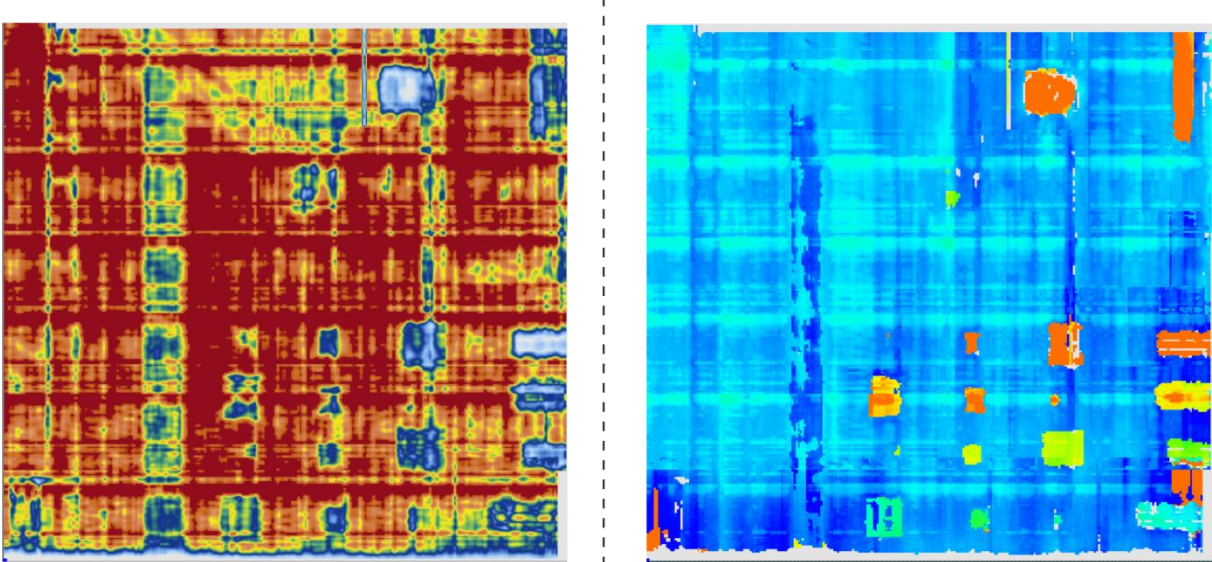

Figure 7: Ultrasound scanning results using the return signal amplitude (left) and time-dely (right)

Figure 7 shows US scans of the laminate using both the amplitude and time-delay of the return signal to identify defects. As can be seen, both methods were able to detect the full list of defects, though with differing degrees of clarity. Aluminium inserts were clearly visible using both methods, though the time-delay scan, with the settings utilised, was not as effective at identifying the smallest inserts (5 x 5 mm). This setback is somewhat compensated by the ability to display the different relative depths at which defects are located. The release agent between plies 8 and 9 was much more visible using the time-delay method, with the unconsolidated area being easily distinguishable against

the laminate background. In contrast, the missing and poorly consolidated tapes were more visible using the amplitude method. Finally, while both methods were able to clearly identify the severely charred area, the time-delay method was able to highlight the moderate charring much more effectively. As for the foreign material inclusions, variations of laser overshoot are of interest for future investigations, including their impact on the mechanical properties of the final part.

Table 4 lists the various defect visibilities using the three methods. Each method displayed an affinity for a particular defect type, with the resulting overlap between ultrasound and in-process monitoring providing a comprehensive analysis tool, albeit at the cost of an additional process step following part manufacturing. As previously identified, improvements to the in-process monitoring method could be made by increasing the resolution of exported temperature values to allow the detection of smaller foreign inclusions. However, this improvement will not likely make any change to the detection of transparent inclusions such as the release agent, and so a minor degree of NDT may be ultimately unavoidable. Future works will address these issues in order to minimise the T2D of AFP defects.

Defect	Process monitoring	US, amplitude	US, time-delay
Aluminium, 100 μm	-	●●●	●●●
Aluminium, 50 μm	-	●●●	●●
Release agent	-	●	●●●
Missing tape	●●●	●●	●
Laser dropout	●●●	●●●	●
Laser overshoot	●●●	●●	●●●

Table 4: Defect detection success/quality

6 CONCLUSIONS

Within this work, a variety of defects were intentionally added to an AFP-produced UD laminate in order to assess their detectability using in-process monitoring and post-manufacturing ultrasound scanning. While variations in the recorded processing temperature (owing to drop-outs or overshoots) were clearly identifiable using the monitoring method, the inclusion of foreign aluminium material went undetected. The only variation to the substrate surface identified using this method was in the form of a severely charred area where the local temperature was above the flash point of the material. In contrast, all defects were reasonably well identified using ultrasound scanning, with amplitude and time-delay methods displaying affinities for different defect types. Overall the combination of these two methods was able to identify all defects with high confidence. The results of this work can be used as a basis with which to identify shortcomings in the in-process monitoring, particularly the minimum size of detectable inclusions, in order to minimise the time-to-detection of manufacturing defects for AFP-produced thermoplastic parts.

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