Data Acquisition and Monitoring for Thermoplastic Components Produced using AFP

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Abstract:
Standard thermoplastic manufacturing methods, such as autoclave and hot-press production, provide minimal spatially-resolved information on process parameters incident on the workpiece. In contrast, the localised, additive nature of automated fibre placement can provide a much higher resolution database for temperature values by utilising an appropriate acquisition and analysis tool. Such a tool has been developed at the German Aerospace Center (DLR), allowing researchers to optimise laser-heating control parameters, predict and reduce the total waste material volume, and provide 3D spatially-resolved information for comparison with non-destructive testing analysis in the post manufacturing stage.

Keywords: In-situ Manufacturing, Automated Fibre Placement, Monitoring

Introduction

Thermoplastic composite components have been increasingly incorporated in the aerospace, automotive, and energy industries in recent years, replacing classical metallic structures and parts. This increased utilisation has hence generated a requirement for more time and cost-effective manufacturing processes to meet production demand. One of the most popular of these new processes is Automated Fibre Placement (AFP). Components manufactured through AFP do not require the time-consuming manual layup and vacuum-bagging procedures associated with autoclave or vacuum-heating processes, instead adding material locally in a continuous manner. Figure 1 shows the AFP process and DLR facility.
However, this local addition of material is not only useful when considering cost but the monitoring of part quality as well. Standard thermoplastic composite manufacturing methods such as autoclave and hot-press processes gather data at limited number of points, resulting in a coarse understanding of process parameters (temperature, pressure) during the production cycle. Furthermore, non-intrusive measurements are limited to the part surface, with information from within the internal part volume requiring intrusive techniques. This lack of overall information places greater emphasis on Non-Destructive Testing (NDT) in the post-manufacturing phase to ensure part quality, adding further costs in addition to the labour-related costs mentioned previously. In contrast, the nature of AFP adding material to discreet locations means process parameter data at each of these locations is available, allowing a significantly higher resolution overview of the manufacturing process, and subsequent part quality, to be obtained.

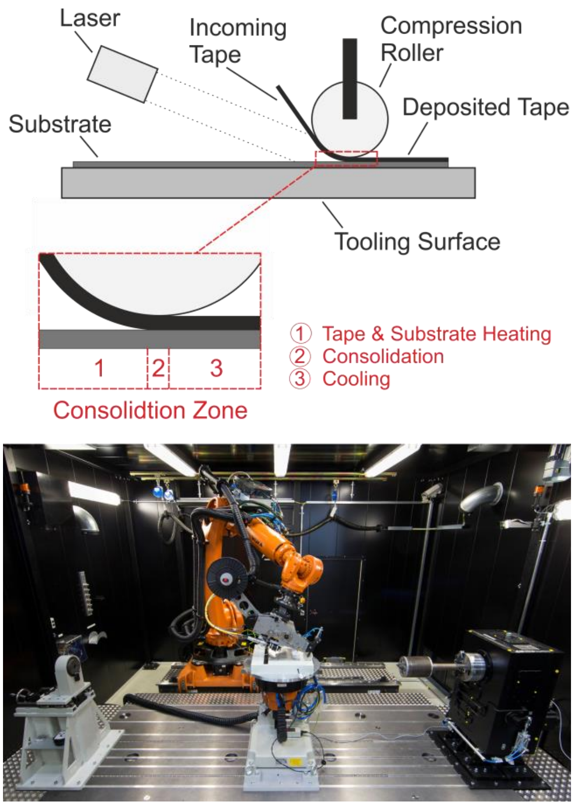

Fig. 1 - AFP process (top) and facility at DLR Stuttgart (bottom)

This paper reports on a data acquisition and analysis programme developed at the German Aerospace Centre (DLR). This programme allows locally-collected process parameter data to be assessed on a 1D, 2D, or 3D basis over the complete part geometry, enabling the optimisation of input parameters, minimisation of inherent waste material, and a more detailed comparison with NDT methods.

AFP Facility at DLR

Data presented in this paper was obtained using the AFP facility at the DLR Institute of Structures and Design in Stuttgart, Germany. This facility, developed by Automated Fibre Placement Technology (AFPT) and shown in Figure 1, is comprised of a six degree-of-freedom robotic arm, two degree-of-freedom heated planar tooling surface, and rotational axis tooling mounts. The combination of these components allows a wide variety of part geometries to be realised, including axisymmetric, planar, and single and double-curved. Attached to the end of the robotic arm, the Single Tape Winding Head (STHW) uses a 6 kW diode laser ($\lambda \approx 1000$ nm) to heat 5.0 - 25.4 mm wide unidirectional (UD) prepreg tapes to the required process temperature. This laser power range allows the use of a variety of thermoplastic matrix tapes (PEEK, PEKK, PPS) as well as deposition speeds in excess of 15 m/min.
CFR-PPS prepreg tape purchased from Suprem was used as the working material for the purpose of this investigation. Physical and thermal properties of the tape are listed in Table 1.

Table 1 - CFR-PPS physical and thermal properties

Property	**CFR-PPS**
Matrix material	Fortron PPS
Fibre material	Carbon, AS7
Tape width [mm]	12.7
Tape thickness [mm]	0.2
Fibre volume (v_f) [%]	55
Melt temperature (T_m) [°C]	281
Glass transition temperature (T_g) [°C]	90

Data Acquisition and Processing

During the manufacturing process, information on the input parameters and conditions in the consolidation zone are displayed in real-time in the AFPT control centre. It is this information which forms the basis of the improved analysis software developed at DLR. Information collected in the control centre tool is temporally resolved, intended as an active display rather than a means of post-manufacturing analysis. However, by identifying critical process parameters or conditions and translating values to a spatially-resolved basis, a much more powerful investigative tool is realised.
Figure 2 shows the most important parameters when assessing the material deposition zone. These are the incident laser power (P_{laser}), applied roller pressure (p_{roll}), consolidation point tool-specific location (X,Y,Z), nip-point temperature (T_{np}), incoming tape temperature (T_{tape}), and substrate/preceding ply temperature (T_{ply}). Values for the laser power and critical temperatures are obtained through the laser control unit and head-mounted thermal camera, respectively. The control centre uses measured values from the camera to regulate laser power in pursuit of the defined working temperature, T_{set}. The applied roller pressure is defined by the operator through the APFT control centre. The location of the consolidation point in Cartesian coordinates is recorded by the KUKA robot control software.

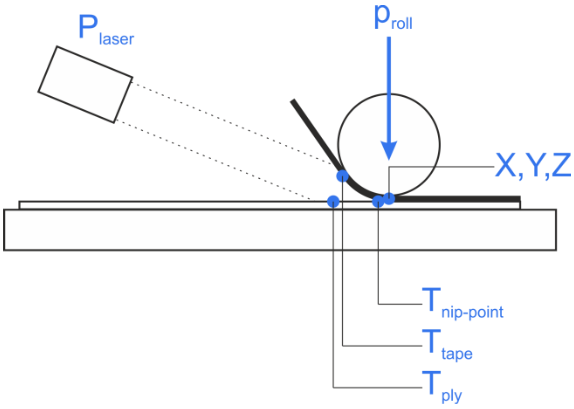

Fig. 2 - Location of critical AFP parameters during operation

Values for these parameters and other process parameters collected in the control centre are imported into a special software tool (C#) for post-processing. Linear interpolation is used between adjacent data-points as well as filtering algorithms to refine the area of interest to zones of tape deposition. The process parameters can then be visualised over a single tow (1D), entire ply (2D), or entire part (3D). Using an area average in the X-Y-plane, a visualisation of the process parameters on the manufacturing surface is achieved, allowing the fast comparison of the surface or part quality owing to the input parameters.

Results

The first use for recorded data is in the assessment of individual tows deposited by the tape head. As previously discussed, the control centre uses measured temperature data from the process thermal camera to adjust laser power and maintain the defined process (set) temperature. It should be noted that the tape head is in motion during this adjustment, with acceleration from standstill to the constant layup speed (v_{layup}) adding further complexity. The AFPT control centre uses two primary adjustment parameters, L_a and L_b, to enable the operator to finetune the adjustment in order to reach the set temperature as quickly as possible. Areas where the set temperature is not met risk resulting in so-called waste zones, where sub-melt temperatures lead to poor tape consolidation. These waste zones must be removed from the final part, increasing associated process costs through both material consumption and an increased tooling area. Areas of poor consolidation also prohibit the deposition of subsequent layers, unless the entire part undergoes further treatment in a post-manufacturing oven or autoclave process.

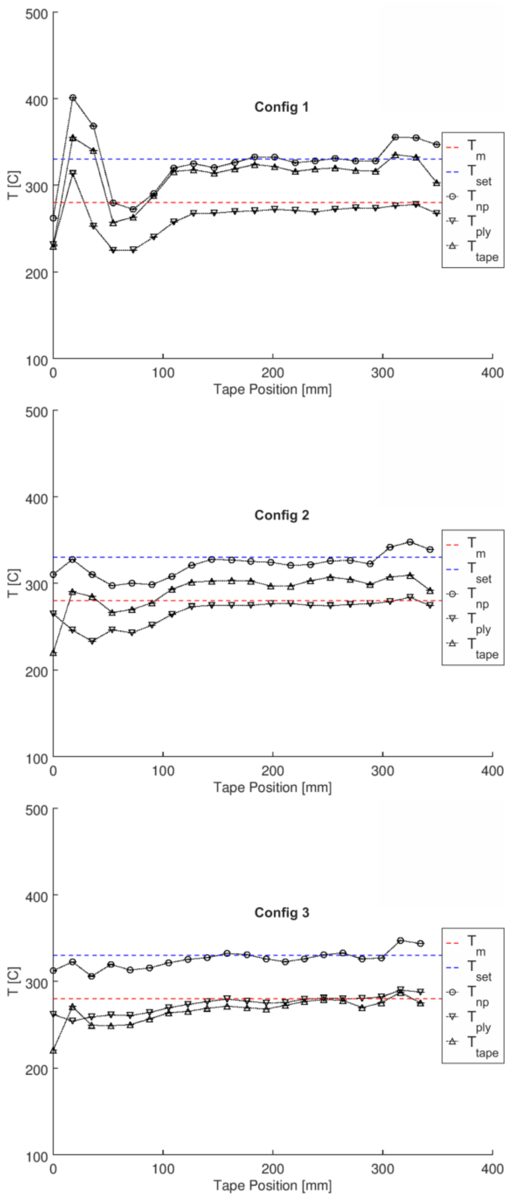

Fig. 3 - Impact of laser modulation factors on heating profile and associated waste material zone

Figure 3 shows variations of L_a and L_b for a fixed layup speed and set temperature. Mean values for T_{np}, T_{tape}, and T_{ply} (with standard deviation) are listed in Table 2.

The impact of these two parameters on the resultant tow temperature profile is significant. The first configuration displays the highest maximum value for all three temperatures and highest mean value for all but the ply temperature. However, the initial 80 mm of deposited tape exhibits temperature fluctuations in excess of 100°C, with short durations below the polymer matrix melting temperature. This can result in significant material wastage in the final product.

The second configuration is able to reach the set temperature in the nip-point zone without the same strong fluctuation as the previous setting, though with a significant reduction in incoming tape temperature. Configuration three exhibits the most stable temperature profile, with the least variation in the nip point zone following tape deposition. However, this setting results in an even further reduced tape temperature, decreasing the time incoming matrix material spends being significantly heated before the consolidation step. Previous investigations have shown the drop in temperature of laser AFP systems to be significant immediately preceding contact with the substrate [1,2] and hence this trade-off between stability and energy distribution is significant.

A more in-depth investigation into the optimal laser parameter settings for manufacturing using this tape is presently underway, though with the focus of this paper being the analysis tool itself, these results serve as a sufficient example of its applicability to improving the quality of single tows

Table 2 - Temperature values resulting from laser parameter variation

Variable			
v_{layup} [mm/s]	120	120	120
T_{set} [°C]	330	330	330
L_a & L_b	Config 1	Config 2	Config 3
T_{np} [°C]	326 ± 33	321 ± 14	325 ± 10
T_{tape} [°C]	310 ± 30	291 ± 21	266 ± 15
T_{ply} [°C]	264 ± 21	267 ± 15	273 ± 10

By combining the spatially-resolved data in Figure 1 for multiple parallel tows, the temperature distribution of the entire ply can be assessed, as shown in Figure 4. This mesh plot displays the temperature distribution of a [0°] ply consisting of 22 tows. Each tow is approximately 400 mm in length. For this plot, the mesh characteristic length is equal to the tape width.

Building upon the second laser parameter configuration from the 1D analysis, the 2D ply yields a mean nip point temperature of 327°C and standard deviation of 17°C. These results vary from the 1D analysis as a result of the 2D analysis being performed on a laminate ply, where sustained tape deposition from previous plies is seen to influence the registered thermal camera temperatures and hence laser power regulation. This makes the determination of desired laser input parameters somewhat dependent on the part geometry, with values obtained from the 1D analysis acting as an initial estimate to be further refined. Regardless of this discrepancy, values of the 2D analysis indicate a ply where 95% of the total deposited material is within 11% of the set temperature and above the material melt temperature.

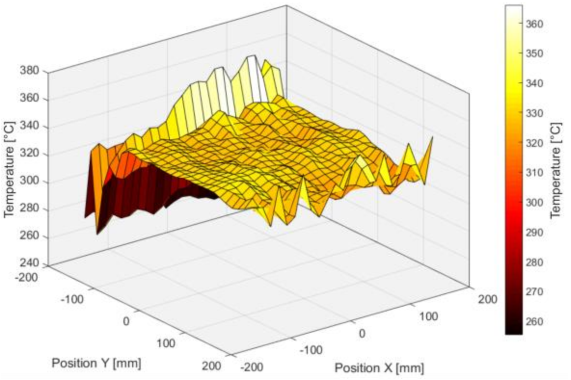

Fig. 4 - 2D mesh of ply surface area

An additional benefit of recording temperatures using this method is the ability to recreate the part surface with a high level of detail. Standard autoclave and hot-press manufacturing processes rely on thermocouple or thermometer devices to measure temperatures in fixed locations, with the measurement resolution dependent on the number and placement of elements. As a comparison, more than 700 thermocouples would have been required to produce the same level of detail as that in Figure 4. Furthermore, tape material is always deposited normal to the tool surface, allowing the contour of the part geometry to be followed. To achieve a similar result in an autoclave setup, numerous cameras would need to be coordinated, all with different angles and distances to the part surface.

Finally, the recorded data of multiple plies can be combined to assess the uniformity of the part in 3D. An example of four bonded plies ([0°/45°/90°/-45°]) is shown in Figure 5, with the desired final part area indicated by the shaded zone. As laminates produced through AFP typically consist of ten or more plies, a graphical inspection of all layers serves primarily to confirm the desired part has been achieved and identify critical defects; numerical values from the tool are used to assess part parameter uniformity as in the 2D analysis. Critical defects in deposited plies can be caused by a sudden loss of laser power, indicated as an abrupt drop in laser power and nip point temperature, or damage/contamination of the incoming tape surface, indicated by a sudden deviation in the laser power profile owing to an altered emissivity registered by the thermal camera. Regardless of the nature of the defect, the high spatial resolution of this analysis tool allows detailed comparisons with NDT methods to be performed.

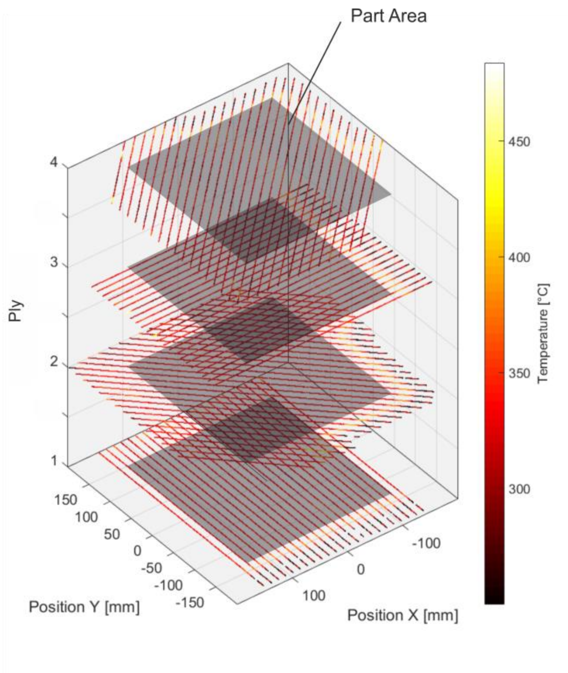

Fig. 5 - Final part area for a quasi-isotropic layup

Conclusion

By converting temporally-resolved process-monitoring data during the AFP process to a spatial domain, information on critical manufacturing parameters over a part surface area and volume can be determined with far greater resolution than that achievable in autoclave or hot-press facilities. This localised information can subsequently be used to optimise heating method parameters, predict and reduce total waste material, and allow a 3D reconstruction of the part volume for comparison with NDT.

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