Thermal imaging as a solution for reliable monitoring of
AFP processes

CARSTEN SCHMIDT$^a$, BEREND DENKENA$^b$, TRISTAN HOCKE$^a$ *, KLAAS VÖLTZER$^a$

a) Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, Ottenbecker Damm 12, 21684 Stade, Germany
b) Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany

*Corresponding author. E-Mail: hocke@ifw.uni-hannover.de
Summary

Nondestructive testing methods for prepreg materials and in-process monitoring of the Automated Fiber Placement (AFP) process are current and challenging topics. The thermography is a solution for both, to ensure the material quality of carbon fiber reinforced plastics (CRFP) tapes and to detect certain defects during the lay-up process. Moreover, many defects during the AFP process are related to a low material quality. A sensor-based system to monitor the winding process of CFRP tape as an analogous model to the manufacturing process of prepreg materials is presented. Provoke defects, such as variating fiber volume ratio or different tow geometries, are detected during the winding process as well as during the AFP process with the help of a thermal in-process monitoring system.

Introduction

Laminate defects during the Automated Fiber Placement (AFP) process cause long machine downtimes from 32% [1] up to 65% [2] of the production time. Due to the fact that there is no fully automated monitoring system available, the machine operator performs a time consuming visual inspection of each ply. Furthermore, due to the low contrast between the single tapes the inspection is prone to errors and not detected defects can cause rejects or high repair costs. Current research and development projects that consider to monitor the AFP process are using laser triangulation sensors, mounted behind the compaction roller, to determine the height profile of the placed course [3]. Defects such as spliced tows or overlaps can be
detected and documented [4]. A monitoring system based on this principle is already tested by Airbus [5]. This concept is neither able to monitor the tack quality of the tows nor to consider the fiber orientation [6]. This paper presents a thermal in-process monitoring system that determines the course edges and inspects the surface of the surrounding subsurface as well as the surface of the placed tows right behind the nip point.

Moreover, many defects occurring during the AFP process, such as connection faults or tow defects, result from a low prepreg material quality. Effects of storage aging decrease the material properties [7] and the degree of impregnation affects the tack of the prepreg [8]. Furthermore, a varying prepreg geometry lead to gaps or overlaps. The nondestructive quality assurance of prepreg materials is demanding for the operator due to the material properties and its small tolerances. The principle of the thermal in-process monitoring for the AFP process can also be used to ensure a good material quality to prevent defects during the AFP process.

Description

In the research project Therm-O-Plan, a thermal monitoring system in combination with an automated path planning is developed [9]. The monitoring system consists of a thermal camera, which is located just behind the compaction roller, and an evaluation module. The camera analyses the temperature contrast between the just-placed tows and the surface as well as the temperature in the Regions of Interest (ROI) (fig. 1). The edge detection on the one hand, detects the position of the tows in the camera coordinate system and stores them online. Comparing the actual tow position and the planned position identifies tow positioning faults and tow width defects. The thresholds for the edge detection are calculated on basis of a process parameter field including the lay-up velocity, the compaction force, the temperature difference to the subsurface and the laminate thickness. On the other hand the surface inspection detects temperature anomalies in the defined ROIs (fig. 1). Therefore, the temperature distribution in each single ROI is compared with a tolerance band that is calculated on the basis of the former IR frames. Temperature anomalies occur due to several different reasons, like foreign bodies, connection defects, tow splices or changing material properties. To define the thresholds for the monitoring system a parameter study is carried out using the in-house developed AFP head [10].

Figure 1: Thermal image during the AFP process including the Regions of Interest (ROI).
As mentioned before, many defects occurring during the AFP process result from a low material quality. Moreover, the cold storage of prepreg materials cause high costs and the storage aging decrease the material properties [7]. Hence, the research project Multi-Matrix-Prepreg (MMP) provides an online impregnation of carbon continuous filament during the AFP process to manufacture prepreg material online. The degree of impregnation and the prepreg consolidation need to be monitored to ensure a good material quality. Fig. 2 gives an overview of the monitoring concept for the online impregnation. The eddy current fork sensor determines the grammage of the prepreg that leads to the resin content depending on the filament tolerances. In addition, the IR camera detects air inclusions and local areas with a non-homogeneous impregnation. The prepreg width can be determined as well by the camera, but due to the camera resolution, the tow geometry is determined by the laser triangulation sensor in a higher resolution. Therefore, the warm prepreg is deflected on a pulley so that the lower prepreg surface deforms on the pulley surface. Now, the laser triangulation sensor measures the height profile and the cross section of the prepreg can be determined. The cross section includes information about the consolidation and the resin content depending on the filament tolerances. Hereafter, only the IR camera is considered and the technical possibilities are compared to the thermal in-process monitoring of the AFP process.

![Sensor concept of the quality assurance for online impregnation.](image)

**Experimental set-up**

The winding test facility (fig. 3a) was constructed to unwind a certain amount of tape from a large roll of material on smaller rolls that fit in the AFP head. The sensor concept to monitor the winding process is similar to a system that would be able to monitor the manufacturing process of the prepreg material. Therefore, the online impregnation will be integrated into the winding test facility for first experiments. Due to the fact that the impregnation chamber is still under development, tow defects that can occur during the impregnation process are produced manual. The winding process is monitored by an IRS640 infrared camera. The winding velocity is $0.2 \, \text{m/s}$ and the camera takes one frame every 10 mm. Analog to active thermography the monitoring system also includes a thermal stimulation. In contrast to a conventional thermal impulse, which temporary heats up the measuring object here a cooled pulley
stimulates the tape for a period of time with a defined temperature difference of $3 \, ^\circ C$, because the prepreg temperature might be to warm coming out of the impregnation chamber and needs to be cooled down anyway. This active thermography makes defects visible. The future online impregnation will lead to higher process and tape temperatures which allow a bigger temperature stimulation due to the pulley leading to higher temperature differences inside the material. To simulate tow defects the tow geometry is manipulated (cut outs and extra pieces) and the fiber volume ratio is varied, by adding and removing of resin. All in all twenty defects are provoked on 70 m tape. This roll of material is also part of the lay-up process of a three-ply $[0^\circ, 90^\circ, 0^\circ]$ laminate. The robotic AFP system (fig. 3b) can place four tows in each course. An IR camera is mounted behind the compaction roller to monitor the lay-up process. In this experiment three 700 mm x 700 mm plies are laid-up on a CFRP tooling whereby tow 3 is manipulated. The lay-up velocity is $0.15 \, \frac{m}{s}$ and the compaction pressure is 1.67 MPa.

![Figure 3: Experimental set-up of the winding test facility (a) and the robotic AFP system (b).](image)

**Thermal quality assurance for the production of thermoset tape**

Based on the winding test facility, the thermal quality assurance for the manufacturing of prepreg materials is shown. Fig. 4 gives an overview of the occurring defects during the winding process and the related thermal picture from the monitoring system. The IR pictures shows the temperature differences between the tape and the respective defect. Two different kinds of defects are presented: varying fiber volume ratio and varying geometry of the tape. In fig. 4a resin was removed by dropping some acetone on the laminate and carefully removing these drops with a cloth. Therefore, there is a local higher fiber volume ratio (HFVR) and the tape cools down faster, because of less tape volume which can be seen in the thermal image. On the other hand, additional applied EP2400 resin decrease the fiber volume ratio (LFVR) and the tape cools down slower at this point (fig. 4b). In fig. 4c a part of the tape is cut out to get a smaller tow width. This defect can easily be monitored if the tow temperature differs to the environmental temperature. To increase the tow thickness considering to a constant fiber volume ratio, a small piece of tape (AoM) is added on top of the tow. Hence, the tow cools down slower due to the higher local mass of material (fig 4d).
The small thermal pulse from the pulley is sufficient to detect the different provoked tow defects. The tolerance range to detect faults within the infrared picture must be set within a minimum signal-to-noise ratio (SNR) that is defined as the ratio between the signal amplitude and the standard deviation of the noise signal for good materials. Due to a high temperature contrast within the tape or to the background, large deviation of the fiber volume ratio are easily detectable as well as the varying tow width. Small deviation and the material thickness are more challenging especially for small material tolerances. The higher process temperature of the in future to be investigated online impregnation might cause a better thermal contrast. However, there is the possibility to increase to thermal pulse for example by further decreasing the pulley temperature as well.

Figure 4: Thermal quality assurance for thermoset prepreg.

Thermal in-process monitoring for the AFP process

The manipulated tow is placed during the AFP process of a three-ply laminate on a CFRP tooling. Fig. 5 shows the results of the thermal monitoring system for the described set-up. The outer course positions are marked with green dots if they are within the tolerance, edge position faults are marked with red circles and temperature anomalies with red crosses. Doing so the regions where a defect is detected are clearly visible and can be checked by the operator.

Fig. 6 shows examples of the in-process monitoring for varying fiber volume ratio and tow geometry in the second layer during the AFP process. Due to the low contrast to the subsurface, a visual inspection is very demanding. The edge detection localizes occurring gaps due to the smaller tow width (fig. 7c). The surface inspection is also able to detect the provoked defects. In contrast to the winding process, a higher fiber volume ratio (HFVR) is hard to detect (fig. 7a). The temperature profile is within the
tolerance band so that no faults are detected by the edge detection. Nevertheless, additional resin for a lower fiber volume ration (LFVR) (fig. 7b), a smaller tow width (cut-out) (fig. 7c) and an accumulation of material (AoM) (fig. 7d) are identified by the surface inspection. Even though the defects can be seen in the temperature profiles, the determined edges are mostly within the tolerance.

Beside the prepared defects in tow 3 some random faults occurring during the AFP process are detected. In the second layer three tow twists occur in the second. Fig. 7 pictures the second twist overlaid with the detected tow edges. The edge detection algorithm recognizes wrong edge positions of tow 3 and the increasing gap between tow 3 and tow 4. Therefore a tow width, a gap, and an edge position fault of the two edges of tow 3 are detected. The frames a, b and c are example frames taken while placing the twist. They are overlaid with the results of the surface inspection. During the tow twist the material is faulted so the double amount of material is placed in one spot. The higher material concentration results in a higher thermal capacity and
therefor in lower surface temperatures, which can be detected as a cold spot. In frame c the gap region is also within the ROI of tow 3, which exhibit the surface temperature and can be detected as a hot spot.

**Figure 7:** A picture of the tow twist 2 in layer 2 overlaid with the monitoring results.

**Results**

Material defects, such as changing fiber volume ratio and varying tow geometry, are detectable in both systems, the thermal quality assurance for prepreg materials and the thermal in-process monitoring for AFP processes. The results of both experiments are summarized in Table 1. The reliability of the quality assurance is measured in a signal-to-noise ratio. The range of the SNR is from 3.8 to 12.6 so that all defects are effectively detectable considering to the cooling pulse. During the lay-up process it is more difficult to detect higher fiber volume ratios due to a constant tow width and a good connection to the subsurface. Moreover, the lower fiber volume ratio is detected in the surface inspection as connection fault. The edge detection detects all varying tow width and also the surface detection detects the hot subsurface in the area of the resulting gap. An accumulation of material does not change the fiber volume ratio but there is a local thicker prepreg placed on the tooling. Subsequently this area heats up slower and cold spots are detected by the surface inspection. If the boundary of this area is inside the ROI of the edge detection, this defects also produce wrong edges.

**Table 1:** Results of the thermal quality assurance and monitoring system.

<table>
<thead>
<tr>
<th>Defect</th>
<th>Winding</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SNR$_{\text{min}}$</td>
<td>SNR$_{\text{max}}$</td>
<td>Edge detection</td>
<td>Surface inspection</td>
</tr>
<tr>
<td>HFVR</td>
<td>4.4</td>
<td>11.0</td>
<td>0/6</td>
<td>1/6</td>
</tr>
<tr>
<td>LFVR</td>
<td>4.6</td>
<td>12.6</td>
<td>0/6</td>
<td>4/6</td>
</tr>
<tr>
<td>Cut-out</td>
<td>4.2</td>
<td>7.0</td>
<td>4/4</td>
<td>3/4</td>
</tr>
<tr>
<td>AoM</td>
<td>3.8</td>
<td>10.8</td>
<td>2/4</td>
<td>3/4</td>
</tr>
</tbody>
</table>
Conclusion and Outlook

The evaluation of the experiments show that certain defects occurring during the AFP process are caused by a low material quality. A thermal quality assurance for the manufacturing process can increase the reliability of the process. Nevertheless, the thermal in-process monitoring system determines the course position and detects occurring defects during the lay-up process of the experimental set-up except for the higher fiber volume ratio. After this preliminary studies it is necessary to perform further tests in which the varying fiber volume ratio and the tow geometry are determined to define the system boundaries more exact. Additionally, detectable defects and its tolerances need to be investigated relating to structural-mechanical effects.

Acknowledgement

The authors would like to thank the Central Innovation Program for SMEs (ZIM) for funding the research work “Therm-O-Plan” and the Niedersächsisches Vorab, Volkswagen Foundation for funding the research work “Multi-Matrix-Prepregs”. They also thank the federal state of Lower Saxony and the European Regional Development Fund (ERDF) for funding the preceding project HP CFK.

References

5. Airbus Group. 2016. “Airbus Group’s InFactory Solutions is delivering for the future with products and services for connected manufacturing”.
7. Airbus Group. 2016. “Airbus Group’s InFactory Solutions is delivering for the future with products and services for connected manufacturing”.