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Thermal image-based monitoring for the automated fiber placement process

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Abstract

Due to increasing consumption of fiber-reinforced plastics (CFRP) especially in aerospace applications also production processes such as Automated Fiber Placement (AFP) gain in importance. However, manual visual inspection in the AFP quality assurance is time consuming and insufficient, not least through the low contrast of CFRP materials. The presented process monitoring for AFP bases on occurring temperature differences during the lay-up process. Therefore, a newly developed monitoring system containing an infrared camera integrated in the Fiber Placement head is presented. Its algorithm can localize tows as well as certain temperature anomalies. Combined with the process knowledge provided by the path planning defects can be detected online.

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Keywords: Automated Fiber Placement; Process Monitoring; Thermography;

1. Introduction

The Automated Fiber Placement (AFP) process evolves into one of the most important manufacturing processes in lightweight industries. During the process, the CFRP components are build up additive. Tows* are placed course after course on a tooling through a fiber placement machine. Certainly different kinds of defects can occur during the process and need to be detected. Not detected faults lead to high repair cost of the cured part at a later point of time. Therefore, the process monitoring and quality assurance are of high importance.

The quality control is predominantly carried out as a visual inspection by the operator after the lay-up of each ply. This operation is not only time consuming but also very difficult due to the low visual contrast of the CFRP material and huge toolings whereon the lay-up takes place. The time for inspection and repair during the AFP process sums up to 32 % [1]. At this time there is no commercial online monitoring system available for integration in to Automated Fiber Placement processes. Shadmehri et al. [2] link a laser projector with a vision system to assist the operator by projecting the characteristic properties on the target surface. This approach is able to identify the ply location and fiber orientation as well as it can detect gaps. Another approach is to monitor the system with a laser scanner mounted on the AFP head, to scan the placed surface geometry [1], [3].

The idea for a new developed thermographic monitoring system is to use the thermal contrast between the tows and the tooling surface that occurs during the lay-up process. Ideally, the material is kept cool to prevent fouling and to secure good material properties. However, to ensure a good tack, the tooling will be heated up just in front of the compaction roller. Hence, behind the roller the placed tows have a cooler temperature compared to the surrounding surface and a temperature gradient occurs.

The US patent 7513964 B2 [4] already pictures a thermal AFP monitoring system wherein an infrared (IR) camera is

* Tows are pre-impregnated thermoset carbon-fiber slit tapes storaged on a carrier foil.

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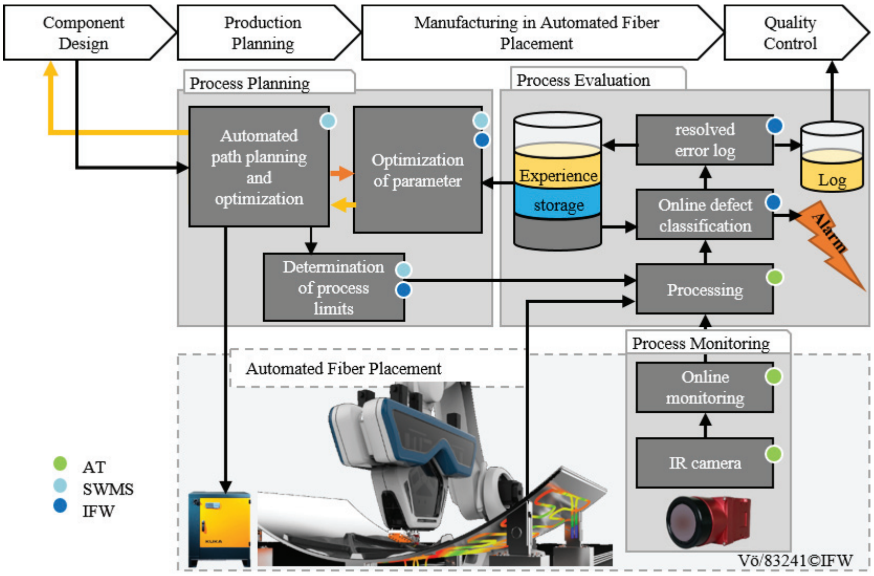

Fig. 1. Therm-O-Plan diagram

integrated. A heat or a cold flow is used to induce a thermal contrast. The composition of all frames shows a whole ply and can be analyzed. However, there is no known implementation of this patent so fare.

2. Thermographic Process Monitoring

The newly online monitoring system is part of the research project Therm-O-Plan that connects path planning, process monitoring and process evaluation as shown in the diagram of the superordinate solution (Fig. 1).

This project is a cooperation of the Institute of Production Engineering and Machine Tools (IFW) at the Leibniz Universität Hannover, Automation Technology GmbH (AT) and SWMS Systemtechnik Ingenieurgesellschaft mbH (SWMS). The aim is to develop an automated optimization module for path planning and process monitoring that is capable to be integrated into standard AFP systems. Therefore, the results of the monitoring module combined with the information of the path planning will be saved in an experience storage to generate process knowledge, that can be used to optimize the path planning and parameter adjustment of the AFP machine.

In the following, the focus will be on the thermographic process monitoring system and the data exchange between the path planning and the process monitoring to classify detected defects within prescribed tolerance ranges. The goal of the online monitoring system is to localize the tows and detect occurring defects during the lay-up process. Therefore, the algorithms are divided into two detection principles, the edge detection to determine the tow position and geometry and the surface inspection to detect defects and foreign bodies.

Looking via a thermal camera at the compaction point there is a temperature contrast between the relative cool tows placed on the heated surface (Fig. 2, 3). The thermal contrast is at its maximum right behind the compaction roller and the temperature profile at this line shows a good contrast between the surrounding surfaces and the cool tows (Fig. 4). If there is a gap of a certain size, the surface radiation is visible through the gap and will result in a local temperature maximum. If an overlap accurse the double amount of material placed results in a local temperature minimum. Using an edge detection algorithm, it is possible to detect the tow edge position. The positions of the tows are saved in the coordinate system of the robotic AFP system. Therefore, the actual position can be compared to the planned position and the algorithm can estimate the tow and gap widths. Planed gaps are not

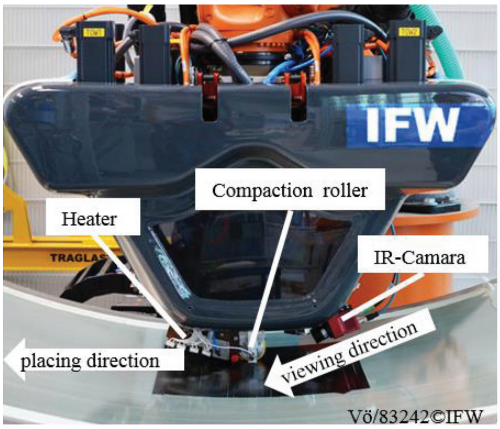

Fig. 2. IFW fiber placement head with thermal camera

avoidable but do not have any negative influence on the target properties, if they are within the planed tolerances. However, small overlaps are size-independent defects and need to be detected.

The other detection principle is the surface inspection. Many defects accompany with a low tack between the tows and the tooling surface. Hence, the heat transfer from the hot surface into the cold tows decrease. In addition, foreign bodies have different thermal properties and may heat up faster. These effects are detectable by the IR camera. To do so regions of interests (ROI) are defined for each tow and the surfaces next to the lay-up course, as shown in Fig. 3. To detect temperature anomalies like hot or cold spots the temperature values inside these ROI's are compared to a dynamic threshold that is generated for each ROI.

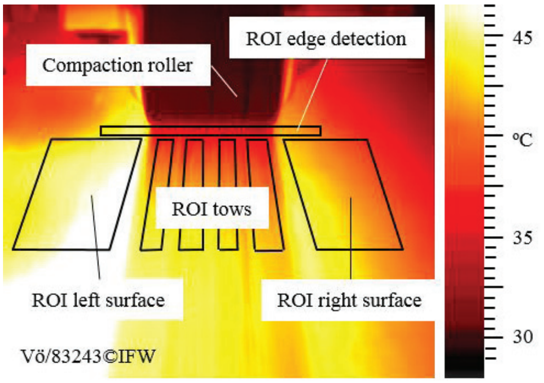

Fig. 3. Thermal image with regions of interest

3. Experimental set-up

AFP System and tooling

To investigate the thermal monitoring system an experiment was defined and carried out. A thermal camera was integrated into the AFP System that was developed in a former project called HP CFK†. The system consists of a KUKA KR300 and an in-house developed AFP head. It is able to place up to four ¼" tows per course and is designed for placing speeds up to 3 m/s.

The thermal camera integrated is an IRS-640 from Automation Technology GmbH. The camera has a resolution of 640*480 Pixel and can capture up to 100 frames per second in windowing mode. The optic setup captures approximate 150 mm in tow width with a resolution of 0.23 mm/pixel.

For this experiment, a 5-millimeter strong aluminum tooling was selected which is isolated to the tooling carrier by a 20 mm isolation plate (Fig. 5). On the tooling, a vacuum foil is placed and sealed with tacky tape and drawn by vacuum. The placing speed is set to 0.23 m/s and will be reached in the middle of the placing course. The AFP System needs to stop for tow cutting and for start and stop of the tow feeding process in the used configuration.

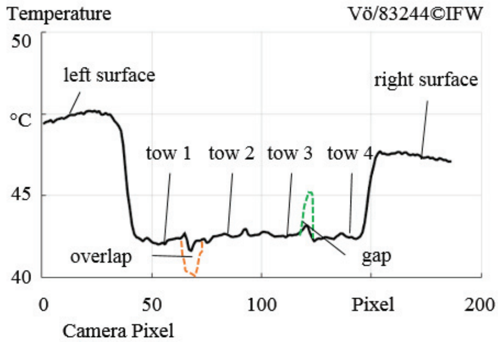

Fig. 4. Temperature profile of pixel line behind the compaction roller

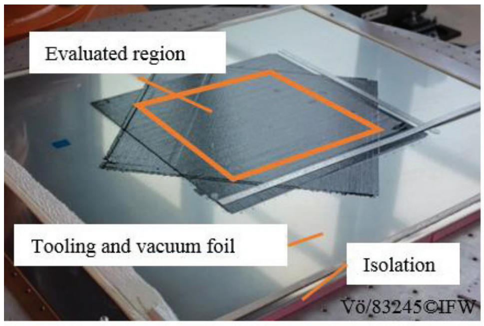

Fig. 5. Experimental setup and evaluated region

Laminate and included defects

For this experiment, an 8 ply symmetrical laminate was placed. The ply orientation is 0°, 90°, 45°, -45°, -45°, 45°, 90° and 0° and a single course is set to a fixed length of 520 mm (Fig. 6).

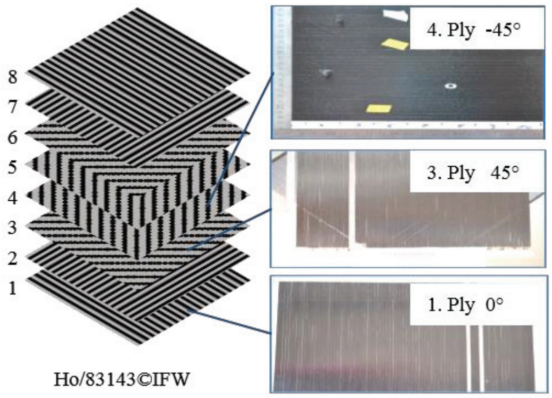

Fig. 6. Placed laminate and occurring events

† High performance production of cfrp-structures

Events per ply:
1. Ply 0°: course 15 and 16 the fourth tow was dropped.
2. Ply 90°: No events
3. Ply 45°: course 5 the third and fourth tow was dropped.
4. Ply -45°: Foreign bodies (Fuzz-balls, glove peace, washer, film)
5. Ply -45°: No events
6. Ply 45°: Tow twist course 1 tow 3 (not in the evaluated region)
7. Ply 90°: No events
8. Ply 0°: No events

As said before the tow localization and the surface inspection depend on the temperature contrast between the tows and the surface on the one hand and temperature anomalies within the inspected ROIs on the other hand. The main parameters, which can influence the contrast, are:
- Tow temperature in the head (constant room temperature 20°C)
- Surface temperature (variation 35-55°C)
- Placing speed (0.03-0.23 m/s)
- Surface material (Aluminum + vacuum foil, Prepreg)
- Compaction force (approximate 35 N per Tow)

4. Results

For the evaluation of the monitoring system, a 400*400 mm region in the middle of the laminate was chosen (Fig 5). In this region, the laminate is homogeneous except of the included faults.

Tow localization

For a reliable edge detection a minimum placing speed is required which is defined to be 0.1 m/s. Standard AFP systems are normally able to cut on the fly, so they do not have to reduce speed in the cutting operation like the test system has to in this setup. The placing speed in the validation area of this experiment is normally faster than 0.1 m/s.

The temperature difference between the tow and the surface was evaluated during the experiment. To do so a pixel line right behind the compaction roller was selected (Fig. 4) and regions of 10 pixel on the left and right surface as well in the region of tow 1 and 4 were defined. For the evaluation, the mean value of the four pixel regions were taken frame by frame. All frames within the evaluation area, which had a minimum placing speed of 0.1 m/s and a surface temperature between 40-55°C where taken into account. The plot in figure 7 shows the temperature difference and the standard deviation between the tows and the surface in dependence of the layer number. The difference between tow 1 and the left surface is higher than the difference between tow 4 and the right surface (see also Fig. 3).

Tow 1 is always placed next to an already placed course except for the first course, so there is already shortly laid-up material existing, which increases the heat insulation in this area. Looking at the temperature distribution the temperature on the left side is approximate 5°C higher than on the right side due to the previous course. These two effects can be an explanation for the higher difference of tow 1.

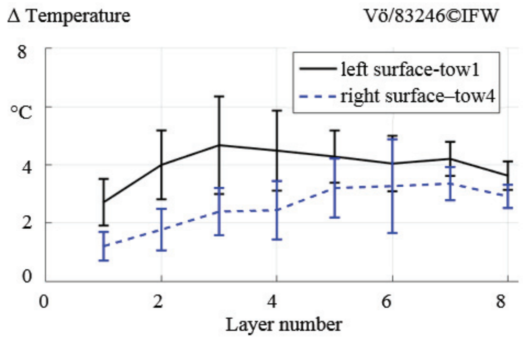

Fig. 7. Temperature difference between tows and surface

Investigating the first two plies, the temperature contrast between tow 4 and surface is lower than on the following plies. The first ply was placed on the vacuum foil, which is drawn on the aluminum tooling. Reasons for the contrast drop must be further investigated but they are probably linked to the good heat transfer of the aluminum tooling. On the first ply it might be as well an unfavorable combination of reflection coefficients of the tooling surface and the prepreg.

Table 1. Detection rate of edge detection at minimum speed of 0.1 m/s.

Ply number	Left course edge (%)	Right course edge (%)	Gap edge (%)
1‡	99.6	92	6.5
2‡	100	99.5	2.3
3	100	97	0.6
4	100	97.5	1.5
5	100	100	0.8
6	100	100	1.3
7	100	100	1.6
8	100	100	0.8

To achieve a good edge detection rate in ply one and two it is necessary to modify the threshold value for the edge detection algorithm. Doing so it is possible to detect the outer edges of the courses of ply one with a rate of 92 % without detecting phantom edges (table 1). The detection rate of the second ply is already better and from the third ply on no modification is necessary and a good detection rate is achieved. The edge detection between single tows is not possible with tow gaps set to 0.15 mm. In this setup gaps bigger than approximate 0.7mm are detectable. By transferring the detected edges in the camera coordinate system into the tooling coordinate system, using the position of the AFP head, it is possible to plot the detected edges in the tooling coordinate system (Fig.

‡ Modification of threshold value

8). A green line connects the found edges and detected faults are marked with a red dot. Inspecting ply one the two missing tows as well as the not detected outer course edges are visible.

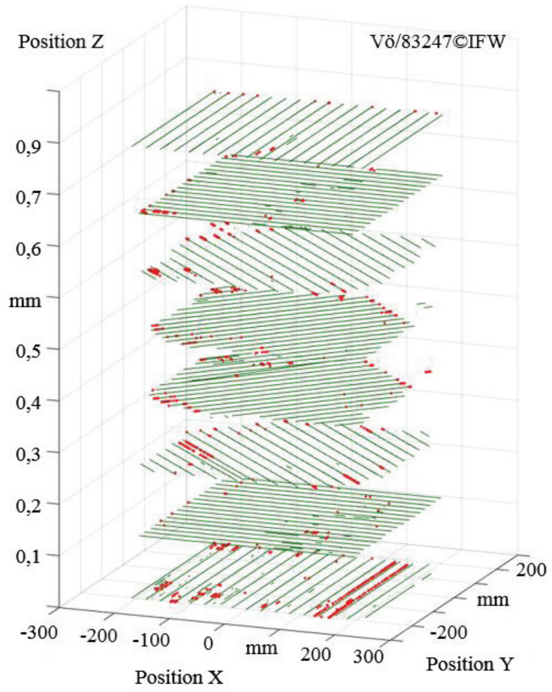

Fig. 8. Tow detection over all plies

The missing tow of ply three is visible at the end of the course. In the beginning of the course, tow 3 and 4 start winding around the compaction roller.

Fig. 9. Tow 3 and 4 winded around the compaction roller

The slack reaches into the region of interest of the edge detection and they were detected as correct edges (Fig. 9). By evaluating the mean temperature of the ROIs of tow 3 and 4 this fault can be detected earlier.

Surface inspection

The surface inspection searches for temperature anomalies in the different ROIs shown in figure 3. The two main parameters to adjust the detection sensitivity are the temperature difference to the expected value, which is calculated every frame and the size of the anomaly. In the fourth ply a variety of foreign bodies were placed to study the capabilities of the surface inspection (see table 2).

Table 2. Temperature contrast of foreign bodies to the surrounding

Foreign Body	Right to course [°C]	After covering [°C]	Speed [m/s]
Fuzz ball 1	6	20	0.05
Fuzz ball 2	56.7	9.8	0.2
Backing film 1	3.1	0.7	0.2
Backing film 2	0.3	0.5	0.2
Washer	-3	3.6	0.05
Glove peace	7	8.9	0.1

In figure 10, the different foreign bodies placed on the surface and the corresponding thermal images are shown. The objects can be detected in two different states, before they are covered and after covering. The black spots inside the ROIs indicates a hot or a cold spot detected by the surface inspection.

It could detect the temperature anomalies of the placed objects reliable except of the backing film 2. The temperature difference between the backing film 2 and the surrounding surface is very low (table 2). The other objects show a temperature contrast over 2°C and are detectable before and after covering. Especially the glove peace and the Fuzz balls show a good contrast. The washer appears in the thermal image colder than the surrounding. Placing next to the already covert washer the inspection detects a hot spot (Fig. 10c). The placed tows are bridging in the washer area and without thermal conduction to the lower ply the area is heated up more.

This experiment was carried out in a homogeneous laminate defined in figure 5. Looking outside the defined region there is a step from a two-ply thick laminate to a 6 ply laminate and back in ply number 7. The thermal image shows colder triangle shaped areas under the placed tows (Fig. 11a). In this areas the tows are not well compacted and the thermal conduction to the surface is insufficient. Thus, the heat transfer is disturbed and the tows are not heated from the warm surface.

a)
b)
c)
d)

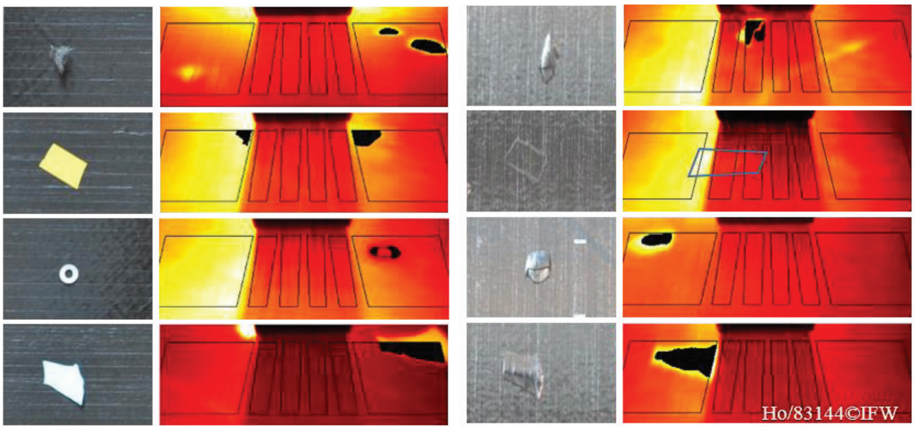

Fig. 10. Example of foreign body detection before and after covering with tows a) fuzz-balls, b) backing film, c) washer, d) glove peace

In the previous course the same bridging occurred which results in hot spots because the heat from the infrared heater cannot pass over to the lower ply. In ply three is a material change from tooling surface to a two-ply strong laminate (Fig 11b). In this case, the same bridging effects occur and the temperature difference between the tow-ply + one course and the one-course strong laminate is visible. To conclude, changes in the surface material or major steps in ply thickness have to be known in advance and the surface inspection has to be adjusted in this area. Therefore, the path planning must not only provide information about the planed tow positions including gap width and tow start and stop positions but also need to provide information for planed temperature anomalies.

a)
b)

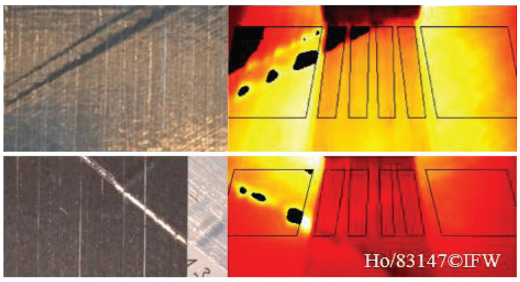

Fig. 11. a) Step down from 6 ply strong laminate to 2 ply strong in ply 7
b) Material change from laminate to tooling surface in ply 3

5. Summary and Conclusion

As demonstrated by the results the thermographic monitoring system is able to localize the position of the single lay-up courses in each ply independent of the previous ply and the fiber orientation. Considering the information from the path planning and the process knowledge the algorithm detects not closed gaps between single tows and can monitor the gap width. This can be checked with the specified tolerance range. Furthermore, the surface inspection detects foreign bodies before lay-up, when they are visible next to the laying course, and directly after the lay-up, when they got visible directly behind the compaction roller of the AFP head.

In summary the combination of the tow localization and the surface inspection determine the tow position and detects relevant manufacturing issues. Hence, online thermographic monitoring of the AFP process is possible. Never the less some effects have to be studied closer in terms of their failure characteristic and to determine accurately the monitoring systems limitation of use. To increase the reliability, it is essential to carry out more experiments to generate data for the experience storage. With this data, the detection algorithm must be improved and a reliability study has to be carried out. In addition improved forecasts of temperature anomalies are possible which allows a sensitivity incensement of the surface inspection. Providing the experience data to the path planning a system-dependent optimized path planning can be realized.

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