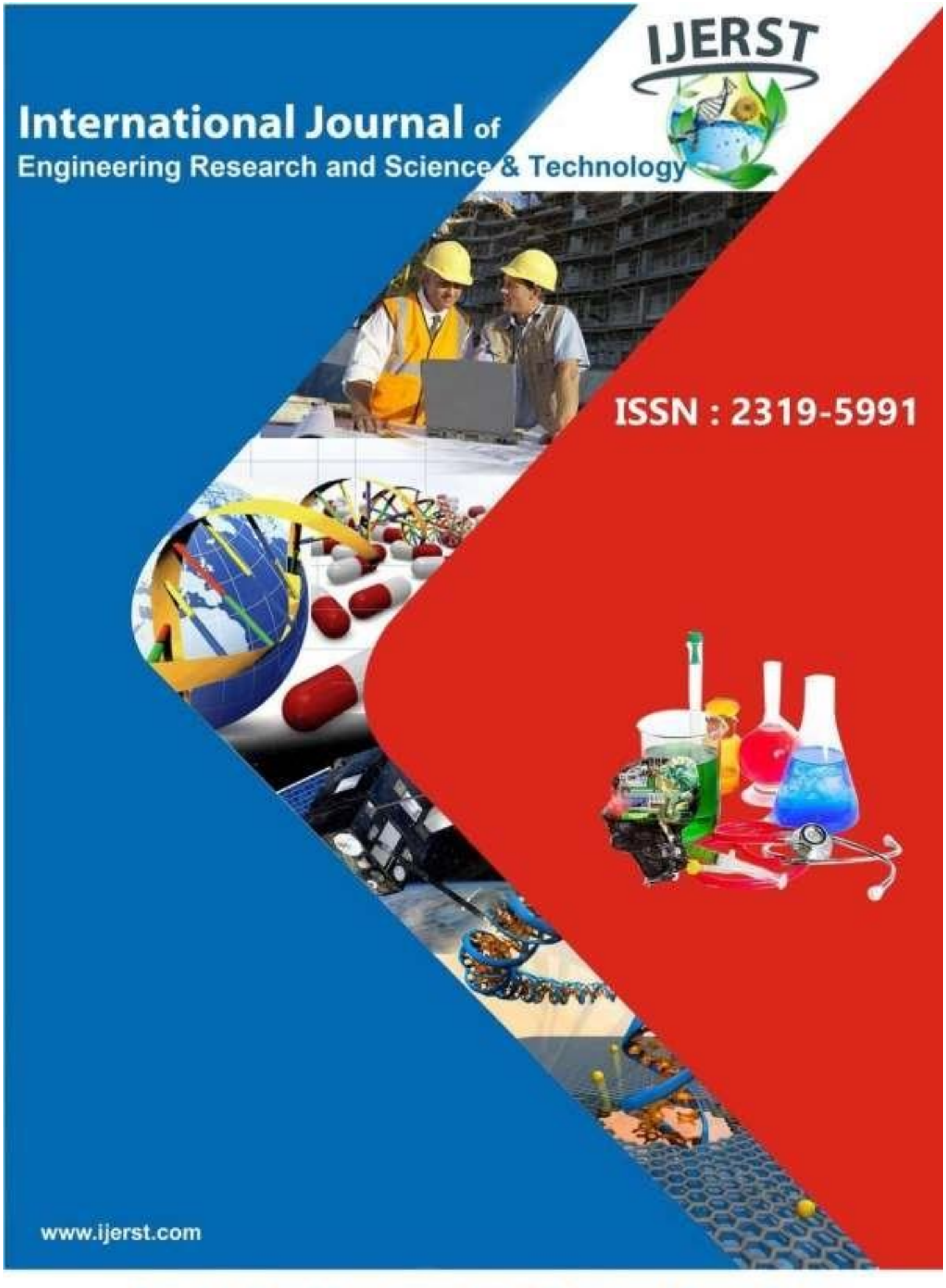

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Thermo-in-process monitoring temperature distribution under the influence of AFP process parameters

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Abstract

The production of aerospace components relies heavily on the automated fiber placement process. An online monitoring system is required to eliminate the need for time-consuming visual examination, hence reducing machine downtime. As a result, a brand-new thermal in-process monitoring system has been implemented. Using the temperature difference between two points, we can pinpoint where we've placed tows and identify any flaws. The thermal contrast between subsurface and tows depend on different process parameters such as lay-up speed, tooling temperature and compaction pressure. In lay-up research, this impact is dissected into its constituent parts so that we can learn more about how to make in-process monitoring and AFP more trustworthy.

Introduction

For the production of lightweight components, such as those used in aircraft, Automated Fiber Placement (AFP) is a crucial manufacturing method. Machine downtime during the AFP process can be reduced with the help of an in-process monitoring system. Right now, the machine operator has to visually verify each ply to make sure it meets quality standards, which might take a long time. Visual detection is difficult because of the large size of the parts and their lack of contrast against the black *carbon fiber reinforced plastic (CFRP) slit tapes* (tows). The time it takes to fix the defects and restart the machines eats up anywhere from 32% [1] to 65%
[2] of the total time available for production. In addition, if faults are not recognized until the cured item is examined using non-destructive ultrasonic testing; the resulting repair costs will be rather significant. According to DIN29971 [3] the below listed defects are crucial for the production as well as for the quality assurance of composite structures: x Positioning defects (gaps/overlaps) [4] x Connection defects (bridging, air pockets) [4, 5, 6] x Tow defects (splice) [4] x Foreign bodies (fuzz ball) [5] In contrast, there is currently no monitoring system ready for use which is capable of detecting this defects reliably. Current research and development projects which consider monitoring the AFP process are using laser triangulation sensors, mounted behind The compaction roller, to determine the height profileof the placed course [7, 8]. Combining the sensor data with the position of the robot a three- dimensional height map can be build. The single profiles include information about the tow edges, the tow width and therefore also about the tow position. Defects such as spliced tows or overlaps can be determined and documented [7]. A first promising solution based on this measuring principle is tested inpilot production [9]. A disadvantage of this method isthat it is affected by the subsurface geometry, especially regions of different laminate thicknesses might lead to wrong defect interpretations.

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Description

As part of the Therm-O-Plan research project, a process thermal control system is being developed [11]. This method consists of an infrared camera that records the temperature distribution caused by cold cables and heated surfaces of the equipment. The two-part monitoring system locates resistance based on edge detection just behind the packer rollers and detects temperature anomalies by analyzing the temperature distribution in a specific region of interest (ROI).) (Fig. 1). It can detect various types of defects such as foreign substances, hairballs, and air pockets [12].

Fig 1. Image of the thermal process within the ROI.

Therefore, the average temperature of the ROI also changes, making it difficult to detect defects associated with continuous temperature changes. To increase the reliability of the developed monitoring system, this article describes the influence of specified process parameters on heating and cooling processes.

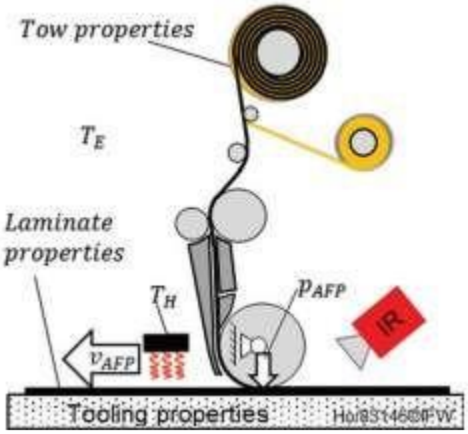

Fig. 2. Relevant process parameters for the AFP process monitoring.

3. Influence of AFP process parameters on the temperature distribution

3.1. Analytical Approach The temperature behavior of the tows during the AFP process is composed to the superposition of the heat flow from the hot subsurface into the colder tows and the cooling effect of the interaction with the environment. Hence, the mean temperature profiles can be described as a double e-function:

$$T(s) = a \cdot \exp(b \cdot t) - c \cdot \exp(-d \cdot t) \qquad (1)$$

Hereby, the parameters a, b, c and d of the thermal model depend on the process condition and parameters which will have an influence on the temperature distribution. The parameters are determined for each of the following experiments to plot semi-empirically fittings. In future, the aim is to determine the parameters depending on the process parameters to set up an analytical approach. This model can be used to generate thresholds online for a reliable process monitoring.

3.2. Experimental set-up a test setup to test the influence of certain process parameters on the temperature behavior is illustrated in the figure. 3. Aluminum tools are insulated from the turntable to store heat from the heating element. Therefore, the tool remains hot to ensure good adhesion between thecable and the vacuum plate above the tool. The in- house developed AFP robot head is designed to placefour CFRP slots in each row [13]. To perform coatingon complex surfaces, the compression roller is separated into four single rollers. However, in this experiment, a flat instrument was used to analyze the effect of one parameter at a time (compression pressure, heater control temperature, creasing rate). The same test will be repeated by changing a single parameter in the parameter configuration (Table 1). Athree-layer [90°, 0°, 90°] (680 mm x 680 mm) laminate is placed for each profile. Previous experiments have shown that the effect of thin layer thickness does not change significantly after the third layer. The environmental effects were nearly constant, the temperature in the experimental area was between 18.8°C and 20.4°C and the relative humidity was between 33% and 40%. In addition, the test setup remains the same and the same CFRP separator material is used.

Fig. 3. Experimental set-up.

Table 1. Parameter configuration of the experimental set-up.

Number	Compaction pressure (*MPa*)	Heater control temperature (°C)	Lay-up velocity (m/s)
1	1.06	40	0.1
2	1.67	40	0.1
3	0.56	40	0.1
4	1.06	50	0.2
5	1.06	30	0.2
6	1.67	40	0.2
7	1.67	40	0.3

3.3. Influence of the path planning the path planning not only defines the play book, the lay-up direction and planned gaps; it also affects the temperature distribution of the tows behind the nip point. The first course of the first ply shows a symmetric temperature distribution due to the fact that on both sides, left and right to the course, the surface detection analyses the symmetric temperature distribution on the aluminum tooling (fig. 4).

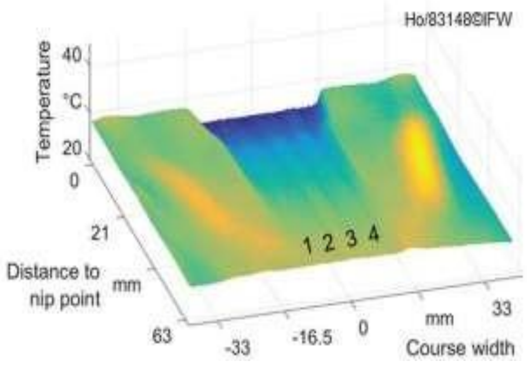

Fig. 4. Temperature distribution in the first play of course 1.

For all other courses the temperature distribution varies. Due to the different thermal properties of the aluminium tooling and the CFRP laminate, the previous placed tows store the heat and further influence the heat-up behavior of the current placed tows (fig. 5).

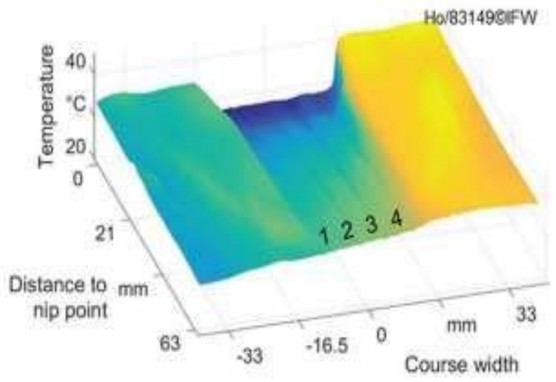

Fig. 5. Temperature distribution in the first play of course 10.

One course is laid up next to the other, so that the previous warm tows to the right of the current placed course cause a temperature gradient between the single tows within one course (fig. 6). The time- depended mean temperature profiles of the four tows of the first course in the first ply are similar. For all other courses (e. g. course 10), the temperature gradient cause, that the tows near to the previouscourse (e. g. tow 4) are warmer compared to the othertows (see also fig. 5). Furthermore, the tooling surface is getting warmer during the lay-up of each ply.

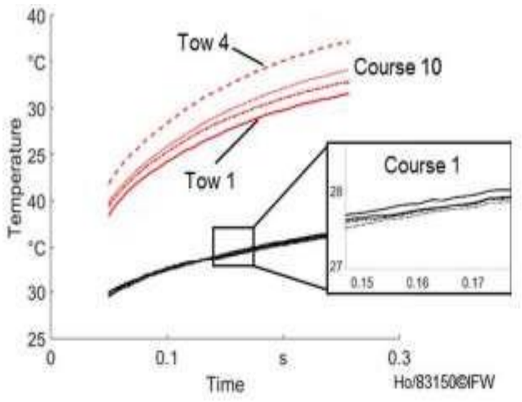

Fig. 6. Influence of the path planning on the mean temperature profile.

Fig. 7 shows the mean temperature distribution of tow 4 for a whole ply. The mean temperature is nearly constant for different tow width. Hereafter, thesmall temperature gradient depending on the tow width is disregarded. To evaluate the experiments for all process parameter configurations and to compare the thermal behavior, the time-depended mean temperature profiles of tow 4 (comparable to fig. 7) is analyzed and the parameters of formula (1) are determined for each parameter configuration (table 2).

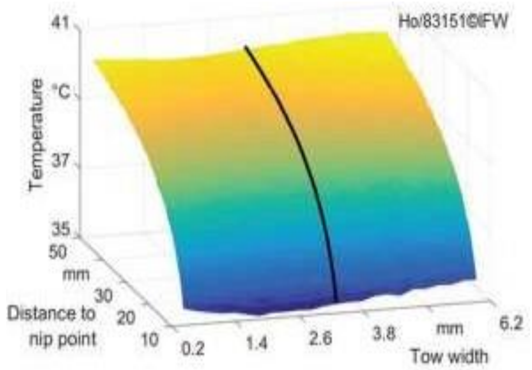

Fig. 7. Mean temperature distribution for one ply of a single tow.

The corresponding temperature standard deviation increase with a longer distance to the nip point but the maximum temperature deviation is still smaller than 1.2 °C (fig. 8). The trend of the standard deviation equals the trend of the mean temperature sothat the reliability of the thermal monitoring concept decreases with an increasing distance to the nip point.

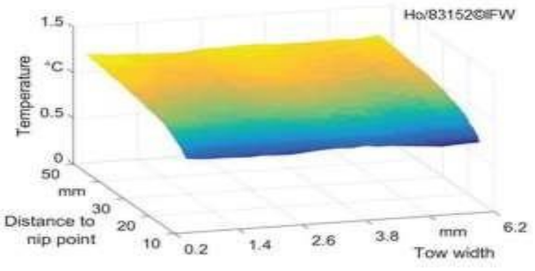

Fig. 8. Corresponding standard deviation of the temperature distribution.

3.4. Influence of the lay-up velocity

Infrared image showing a tow rope stretched

Under the water next to the current course past the pinch point. Therefore, the speed of the suspension determines the time interval. In each image, the pinch point is shown with an overlap length of approximately 50 mm. To ensure this, a minimum descent speed must be achieved thermal contrast. Maximum speed depends on AFP System and heat flow lags until temperature raises the motion of the trailer can be seen in the IR camera image. The Average temperature profile as a function of various times Passages do not start and end at the same time. Figure 10 shows the average temperature profile for a 4 inch cable. The third time is process parameter settings 2, 6, and 7. Depending on your speed, the track will start and end at different speeds. After that, the static temperature state Compression does not merge average temperature profiles. In this Pegboard drape rate affects crowd Apply heat to the laminate. Heat flow from Laminate for drawing on tool surfaces or surfaces a delay occurs in the thickness direction. Various experiences various speeds should also be measured for confirmation hypothesis. The semi empirical double-electron function corresponds to average temperature profile

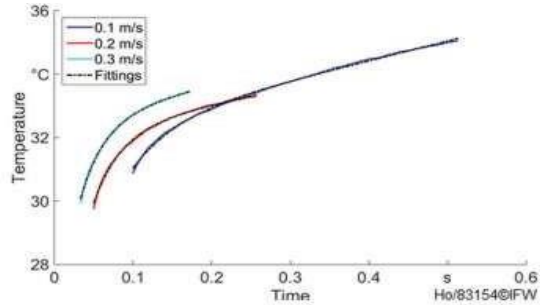

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Fig. 10. Influence of the lay-up velocity on the mean temperature profile.

4. Results

Experiments show that some processes parameters affecting the temperature distribution of the cable right after lay-up. Other process parameters only affect Configurable temperature for thin sheets or not. THE laminate, especially the previous course, causes a temperature gradient depends on the width of the cable. THE temperature distribution for a single process parameter the configuration is veryuniform with a small standard deviation. ONE increasing laminate thickness results in closer laminate temperature at controlled temperature heater. Therefore, the temperature Warmer profiles for thicker layers. Pleating speed, as stated before, does not affect heating behavior significantly. The draping rate determines the time range of the temperature profile is displayed on the camera image. These process parameters do not affect heating behavior significantly, but the shape of the average temperature profiles mainly depends on the temperature of the basement. Do not continuous heating capacity, configurations do not merge with some moment, but this effect is expected over a constant period of time basement temperature. At download start processing of various profile shapes by heat flow Occurs over time with the development of the construct speed. Heater Control Temperature Affects Process Direct determination of the maximum temperature of the laminate Temperature records are coming. Minimum seal as pressure is required to ensure good adhesion, high laminate quality. However, for thick plates, the compression pressure higher than this minimum compression pressure It affects the temperature distribution of the stripped cable. Board 2. Parameters of the temperature model for the semi-empirical method temperature profile.

Number	Ply	a [°C]	b [1/s]	c [°C]	d [1/s]	R^2
1	3	32.14	0.176	9.13	16.12	0.999
2	3	32.06	0.178	9.01	17.31	0.999
3	3	30.34	0.098	4.20	8.09	0.999
4	1	33.89	0.283	7.53	13.06	0.999
4	2	34.50	0.479	8.72	27.12	0.999
4	3	39.00	0.220	10.57	24.06	0.999
5	3	23.37	0.152	1.05	33.94	0.996
6	3	31.96	0.166	9.48	28.50	0.998
7	3	32.31	0.207	7.37	33.03	0.999

5. Conclusion and Outlook

The temperature approach is based on the double function Equation (1) can be used to determine and set the threshold. Monitoring system according to process parameters and form the basis for future temperature models. Figure 13 shows the effect of heater control temperature, folding speed at thermal model parameter ‘a’ 3rd class of all experiments with higher packing pressure 1 MPa or more. End temperature of heating operation (parameter a) increases with heating command the temperature, and therefore the temperature of the cellar, also influences. Pleating speed does not affect parameter 'a'. Important. Influence of specific process parameters further deepening of the thermal model is required.

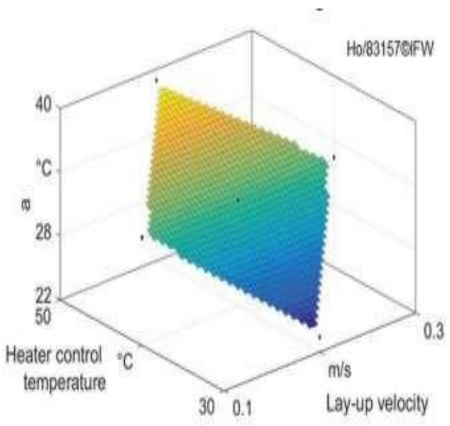

Fig. 11. Influence of the heater control temperature and the lay-up velocity

On parameter a of the thermal model. The process parameters based determination of threshold values allows the detection of temperature anomalies with a lower temperature deviation and helps to analyze characteristics of defects. The process parameters also influence the laminate quality depending on the position of the ply in the laminate leading to a variation of the process parameters for the first ply. For laminates with a thickness greater than a certain value, the process parameters can be set to known values. Further experiments are planned to validate the gained knowledge and to examine the influence of other parameters such as the material temperature. Moreover Hypothesis that mean temperature changes towards confluence Different speeds, all compression pressures are higher nor does it apply as a minimum required compression pressure affects the temperature distribution of thick laminates to be analyzed. Additionally, the planning temperature model should be: Predict temperature distribution fora given process Parameters forms the basis for reliable and robust thermal control online surveillance system.

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