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3D-Printed On/Off Sensors for Resin Flow Monitoring in Composite Manufacturing Processes

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Abstract

In this paper novel flow monitoring sensors made of continuous carbon fibres of different thicknesses and layers were manufactured with 3D carbon fibre printing technology. VARI (Vacuum Assisted Resin Infusion) was performed in order to test these sensors. They were integrated inside a vacuum bag with the aim of detecting the position of the resin front advance during the VARI process.

These sensors, when integrated in out-of-autoclave processes as flexible electronics for detecting and controlling the resin front advance, may become key elements in producing high quality final composites with a low concentration of voids and dry spots.

1. Introduction

Vacuum Assisted Resin Infusion (VARI) [1] is one of most common composites manufacturing processes. Conversely to autoclave manufacturing techniques, fabrics are covered by a vacuum bag that is hermetically closed so that vacuum is preserved. In most of the cases, resin is injected in one of the sides of the laminate and propagates along the fabrics in the direction of the negative pressure gradient between the resin inlet and the vacuum port. Once fabrics have been wetted by the resin, composites can be cured at room temperature with an optional postcure. Several advantages in composite manufacturing can be obtained using this method: its low cost, laminates are faster to obtain compared to autoclave processes, they must not be stored in a freezer like prepregs and they have longer shelf-life. Another reason is because their own fibres can be multifunctional [2] and be used as smart sensors.

There are critical physical magnitudes to be studied in a VARI process. Fluid velocity, resin temperature and pressure supported by the fabrics must be measured and controlled with the aim of monitoring the resin front advance that has to be uniform and homogenous. In case these parameters are optimum, high quality laminates will be obtained, with low concentration of voids and dry spots which are in detrimental of final mechanical performance of the composite material. With the purpose of reducing manufacturing costs and increasing the quality of the laminates, different sensing techniques [3] such as cameras [4], ultrasonic transducers [5], optical fibres [6] and pressure sensors [7] are placed at different positions of the mold in order to monitor the resin front advance.

On the other hand, the design and fabrication of these monitoring sensors play a key role for their proper placement on the fabrics and consequently these issues will affect the final quality of the laminate. They should be little intrusive, in most cases flexible and have the sensitivity enough to measure resin pressure and velocity along the fabrics, so that a high control of the front advance is performed. Between the many different fabrication techniques, the novel additive manufacturing (AM) technology [8] of continuous carbon fibre reinforced polymer (CFRP) offers the possibility of fabricating flexible electronics composite sensors because of the electrically conductive nature of the carbon fibre. This work presents a 3D printed On/Off sensor system for resin flow monitoring during a VARI process. The sensor design and the orientation were optimised in order to obtain a clear output signal. The accuracy and reliability of this novel sensor system were confirmed by comparing the *in situ* sensor data with the visually recorded resin flow

This work presents the results of four experiments. The first and the second experiments were performed to analyse the effects of sensor orientation (longitudinal and transversal direction) on the resin front advance. On the other hand, the effects of the sensor design, such as layer thickness, wall layer number and the distance between the two filaments, were studied comparing second and third experiments. Finally, the accuracy and reliability of optimised system (fourth experiment) were evaluated by comparing experimental data with visual recorded tracking and fitting the positions of the front vs time. It was shown that the resin front advance during the infusion process followed the Darcy's Law.

2. Methods

2.1 Vacuum assisted resin infusion (VARI), 3D printed sensor and smart peel ply.

In this experiment a conventional vacuum assisted resin infusion configuration was carried out. Resin employed was Derakane 8084 without catalyst agent. The experiment was carried out at room temperature. Glass fibre fabrics were paced on a metallic plate that lay on a table and they were covered by a vacuum bag hermetically sealed. Along and resting on the fabrics, the 3D printed on/off carbon sensors, fabricated with a Markforged Composite 3D printer, were fixed with their two ends coming out of the vacuum bag. These standing parts were connected to an electronic circuit based on the voltage divisor concept and that amplified and filtered the signal change produced when the resin front advance was in contact with them. The input of the resin was placed at the beginning of the laminate and the outlet was placed at the end, where one perforated tube was fixed and connected to a vacuum pump.

With the purpose of monitoring the resin front advance, a scale was drawn on the top of the vacuum bag and a video camera was placed above the infusion table in order to film the resin front advance during the infusion process and to compare it with the 3D printed sensors voltage drop signal vs length. The printed sensor system, presented in this work, consists of continuous carbon fibre open circuits encapsulated in Nylon but at the end, which isolates the carbon filaments from the environment. When resin arrives at this point, the low electrical conductance of the resin is able to close the circuit and subsequently the voltage signal drops (Figure 1). The innovative additive manufacturing technology allows printing the sensor system on a Nylon peel ply, which is an integral part of the manufacturing process and it is used to separate the reinforcement from the surroundings, such as distribution medium and vacuum bag.

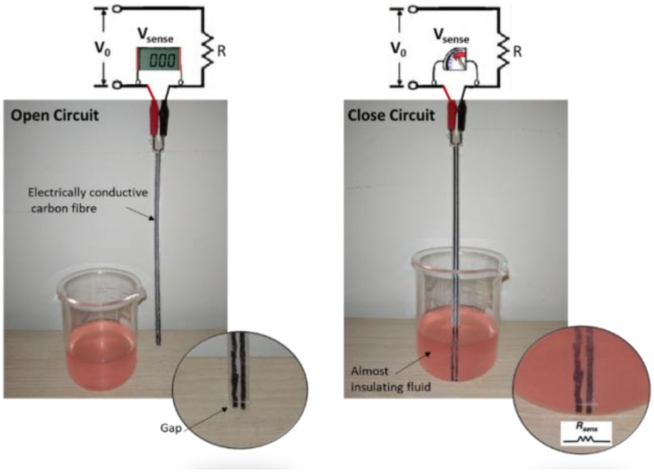

Figure 1: On-Off printed sensor performance. The gap between the two parallel carbon fibre filaments acts as an electrical resistor. Initially, the electric circuit is open. As the flowing resin covers this gap, the output voltage signal, V_{sens}, changes

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2.2 Electronic acquisition system

In order to detect the change of voltage signal with low noise when the tips of the filaments were in contact with the resin, a low pass filtered amplifier was integrated in a voltage divisor. The schematics of the electronics are presented below.

Regarding the electrical working principle, 3D-printed on/off sensors are electrical circuits of continuous carbon fibre in which the two poles of the sensor are separated and when resin wets the end sensor, the signal drops. The electrical conductance of the liquid resin causes circuit gets closed. The sensor is based on the voltage divider principle and is made of a 5 GΩ resistor and the sensor itself that behaves as a variable resistance. An amplifier used as a buffer allows the signal change being detected by the DAQ (USB, 6008, National Instruments) when the sensor is firstly wetted by the resin. This electronic design will be coupled to 9 carbon 2D printed sensors and will allow monitoring the resin front advance along the fabrics when the infusion is taking place.

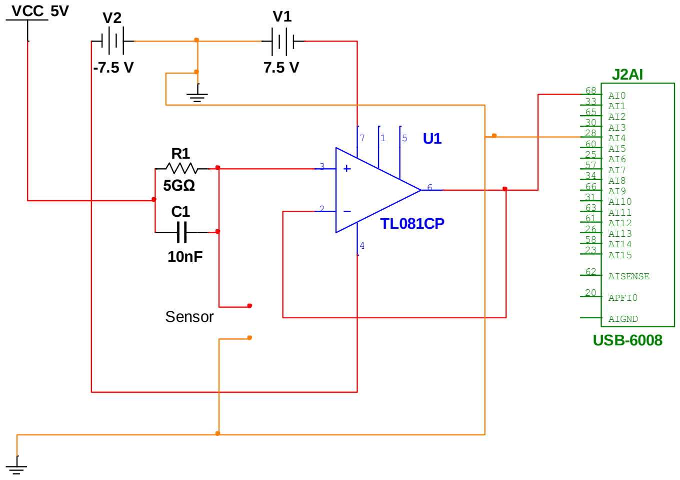

Figure 2: Electronics schematics of the voltage divisor used to measure the voltage drop when the two tips of sensor are wetted

2.3. Darcy's Law

Darcy's law [9] is a phenomenological derived constitutive equation that describes the flow of a fluid through a porous medium [10] and it is commonly used to describe the factor of influencing impregnation of the fibre laminates by the matrix resin for composite manufacturing [11]. In this work, the position of the front detected by each sensor and the difference in time measured from the first moment the resin is in contact with the fabrics and the time its position is measured, was fitted with a polynomial function. This analysis allowed studying the grade of similarity between this fit and the Darcy's law. In case the polynomial function has an exponent value of 0.5, it will mean that the position of the resin front advance will depend on the root mean square of the time, and consequently this front will follow with high accuracy the Darcy's law.

3. Results and discussions

3.1 Sensor design and orientation optimisation

3D printed sensors were oriented along (Figure 3 (a)) and perpendicular (Figure 4 (a)) to the direction of the resin front advance.

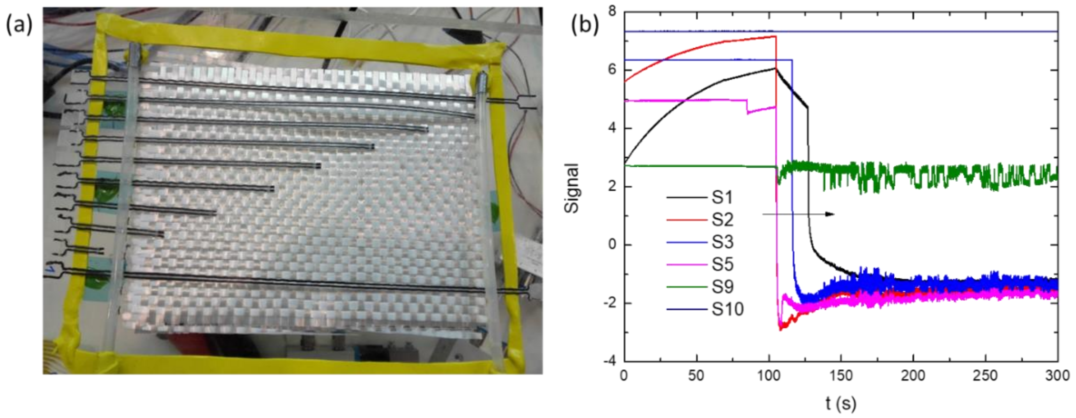

Figure 3: (a) Experimental set-up of the VARI with the 3D printed sensor system integrated in the same orientation of resin front advance. (b) Signal drops occur at the same time, indicating trace tracking phenomenon.

Race-tracking phenomena were observed along the longitudinal sensors leading the system to evaluate wrongly the resin front advance, misleading the user. Indeed, Figure 3 (b) shows how voltage signal drops occur at the same. Hence, all following experiments were performed placing the sensors in perpendicular direction to the resin front (Figure 4 (a), Figure 6 (a) and Figure 8 (a)). Subsequently, the effect of sensor geometry on its performance was evaluated varying the thickness of Nylon layer, wall layer numbers and the distance between the two filaments (3D designs on Figure 4 (b) and Figure 6 (b)). In the second experiment the nylon thickness and wall layer number were reduced at minimum allowed by the 3D printer, 125 μm and 1 respectively, and the distance between the filaments was 3 mm. Figure 4 (c) shows some variability on the voltage signals, probably due to resin infiltration during the infusion. Indeed, several incongruences were observed between in situ sensor data and visually recorded resin flow. In the third infusion, the thickness of nylon layer and wall layer number were duplicated (250 μm and 2 layers) and the gap between the filaments was reduced up to 1 mm. In this experiment, sharp and clear signal changes were recorded (Figure 6 (c)) in contrast to the second experiment (Figure 4 (c)). Despite of a constant mismatch between sensor and visual sensor, this optimised sensor system offers more accuracy data than the previous one. Therefore, the following experiment was carried out with the optimised design sensor.

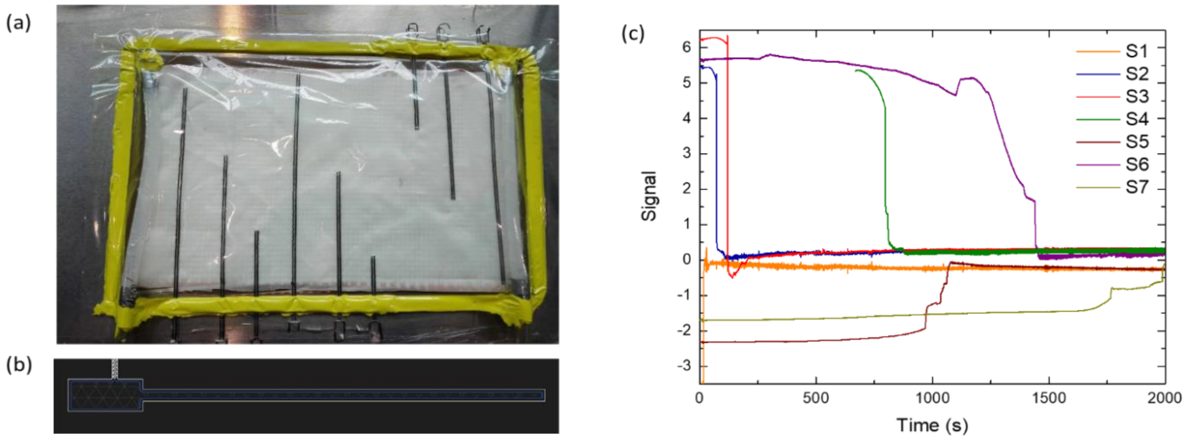

Figure 4: (a) Experimental set-up of 3D printed sensor system integrated at traversal direction of the resin flow. (b) Sensor design (125 μm nylon thickness, 1 wall layer, 3 mm of distance between filaments) (c) Variability on the voltage signals drops

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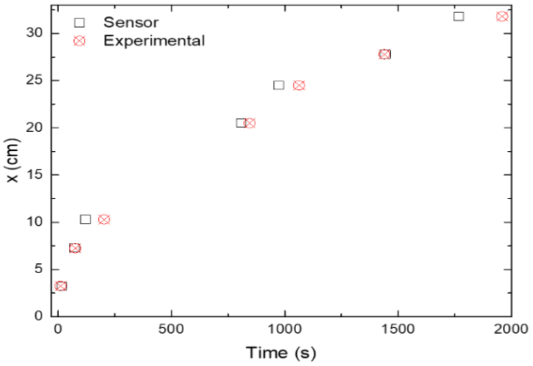


Figure 5: Comparison of sensor data with visual recorded resin flow shows some deviations for the sensor design presented in the Figure 4

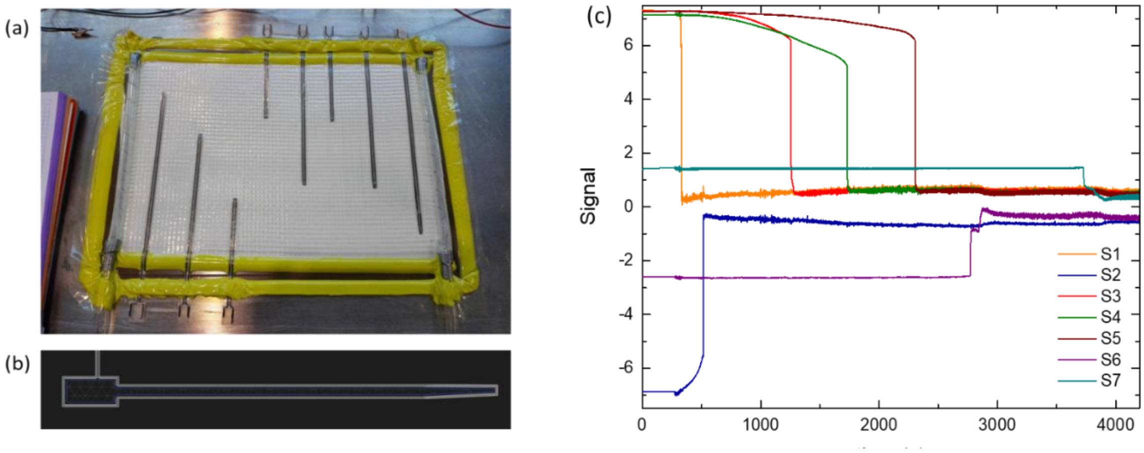


Figure 6: (a) Experimental set-up of 3D printed sensor system integrated at transversal direction of the resin flow. (b) New sensor design (250 μm nylon thickness, 2 wall layers, 1 mm of distance between filaments) (c) Sharp and clear signals drops

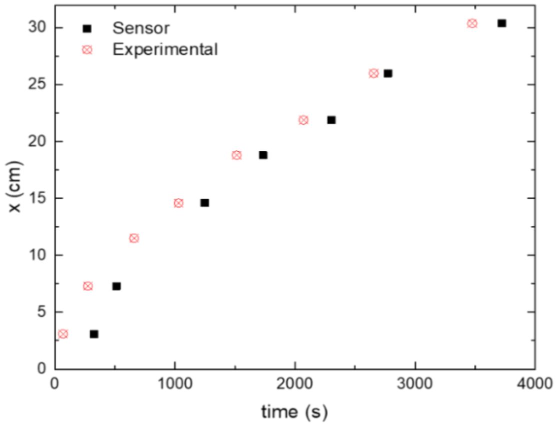
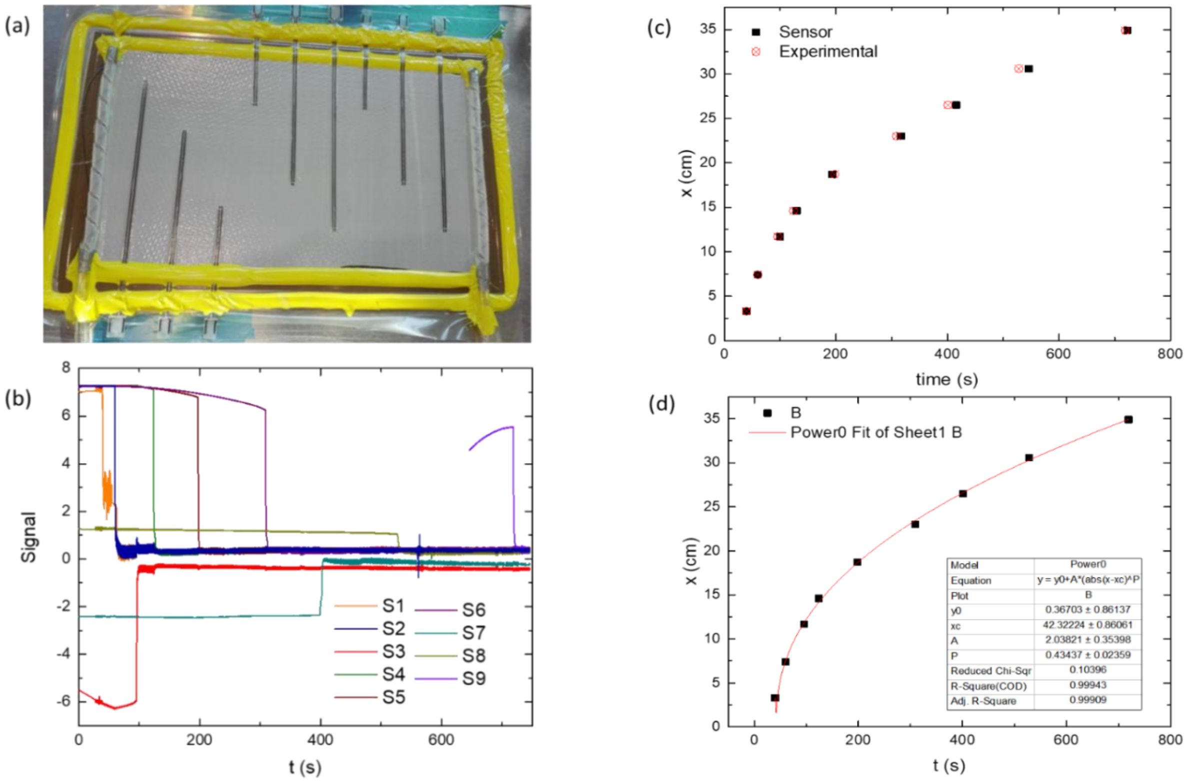


Figure 7: Comparison of sensor data with visual recorded resin flow. It is more accurate for the sensor design presented in the Figure 6 than for the presented in Figure 4

3.2 Resin infusion process

Once the best design sensors (250 μm nylon thickness, 2 walls, 1 mm of distance between filaments) and their positions respect to the sensors flow were chosen, a definitive infusion with this configuration was performed to analyse with these sensors the behaviour of the resin front advance.



Model	Power0
Equation	y = y0+A*(abs(x-xc)^P
Plot	B
y0	0.36703 ± 0.86137
xc	42.32224 ± 0.86061
A	2.03821 ± 0.35398
P	0.43437 ± 0.02359
Reduced Chi-Sqr	0.10396
R-Square(COD)	0.99943
Adj. R-Square	0.99909

Figure 8: (a) Experimental set-up of 3D printed sensor system integrated at transversal direction of the resin flow. (b) The times of resin arrivals at the nine sensor locations indicated by voltage signal drops. (c) The comparison of sensor data with visual recorded resin flow and (d) Darcy law fitting

In Figure 8, it is shown the experimental setup of the last resin infusion (Figure 8 (a)) and the times of resin arrivals at the nine sensor locations (Figure 8 (b)). The accuracy and the reliability of the new sensor system was definitely verified by comparing in situ sensor data with the visually recorded resin flow (Figure 8 (c)) and experimental data were satisfactory refined by Darcy Law (R-square of =0.99943).

4. Conclusions

In order to control the fluid front advance in out-of-autoclave processes, novel 3D printed on/off sensors were designed and fabricated with an Additive Manufacturing 3D composite printer. The optimal design of these sensors consists of 250 μm of nylon thickness, 2 walls layers and 1 mm of distance between the filaments. Neither race-tracking nor deep structural marking in the laminate after curing once the infusion had been performed was observed. These sensors were integrated to a voltage divider electronic circuit so that a variation of the signal when the resin wetted the tips of the sensors was produced. As a result, they can be considered as flexible electronic circuits. In order to test them, a VARI experiment was carried out and the resin front advance was monitored making of these novel design sensors that were placed on the glass fibre fabrics inside the vacuum bag. The voltage signal drop due to the interaction of the resin with the sensors tip was observed and excellent results were achieved. Furthermore, the resin front velocity could be monitored and the position of the resin front vs time was plotted and fitted. It was shown that the resin from advance followed Darcy's Law.

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This novel design has a great relevance in industry, especially in composite manufacturing processes for which visual inspection is not allowed due to the steel upper half mould that is often used, such as in RTM.

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