ANALYSES AND VALIDATION TESTING OF A PIEZO SENSOR BASED PROCESS MONITORING SYSTEM AS INTEGRAL PART OF AN INTEGRATED PROCESS AND STRUCTURAL HEALTH MONITORING SYSTEM FOR CFRP REINFORCEMENTS MADE BY RTM

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Abstract
Within this paper the authors present detailed simulation and experimental results of the process monitoring part of the developed integrated process and structural health monitoring system based on piezo sensors for CFRP reinforcements made by RTM. Fully coupled multi-physical simulations of the interaction of the vibrating piezo sensor with the curing resin have been performed to analyze the influence of the change in viscosity of the curing resin and the development of the cured resin from the rubbery to the fully cured state on the measured impedance of the piezo sensor. Validation testing of the process monitoring system on pure resin and composite plates showed the ability of the developed system to follow the curing state for pure epoxy systems and CFRP parts. In addition flow front propagation monitoring has been validated by the production of composite plates using a number of distributed piezo sensors.

1. Introduction

In order to bring the advantages of fiber reinforced polymers – high specific strength and stiffness – into applications where mass production is essential e.g. specific aircraft parts such as stringers or frames, automated manufacturing techniques have to replace the wide spread manual production. Depending on the part to be manufactured, infusion methods like Resin Transfer Molding (RTM) or Vacuum Infusion (VI) are such automated production techniques. The most important steps in the production of complex composite parts by resin infusion are to reach a full impregnation of the dry pre-form and to guaranty a full curing of the resin in the form. Therefore the control of process parameters like flow front propagation and the determination of the degree of are important for the production of high quality parts. Currently process monitoring in RTM processes are done by different type of sensors such as temperature sensors, pressure sensors, dielectric sensors or conventional ultrasonic sensors for the monitoring of the flow front and the determination of the degree of cure which are mostly integrated directly in the mold [1, 2, 3]. In order to be able to monitor the structural integrity during use (SHM), further type of sensors such as piezo sensors, which are mainly glued to surface of the structure are

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under investigation [4, 5, 6]. In some works fiber optic sensors such as fiber Bragg grating sensors were used for process monitoring. These sensors will remain in the part and can be used for structural health monitoring [7]. A critical aspect is the ingress / egress point from the part and the connection of the fiber optic sensors.
In order to overcome the above mentioned problems the authors recently developed a novel integrated process and structural health monitoring concept based on piezo sensors. The basic idea is to place a number of piezo sensors on predefined positions over the RTM mold. In a first step the piezo sensors are operated as pressure sensors to monitor the flow front propagation in the mold. Once the whole pre-form was impregnated by the resin and curing starts, the impedance of the piezo sensors are measured over the time. The change in the impedance spectrum is used to determine the degree of cure. Finally, when the during process is finished, all piezo sensors are co-cured on the surface of the part and remain on the part to be used for structural health monitoring either in passive mode as acoustic emission sensors or in active mode using guided ultrasonic waves. [8]

2. OVERALL MONITORING CONCEPT

Figure 1 shows the overall process and structural health monitoring concept. In a first step the piezo sensors are placed at pre-defined positions in the RTM mold. Then the dry preform will be placed in the mold. After closing of the mold, all sensor are operated as pure pressure sensors to measure the pressure built up due to the flowing resin. The time of pressure rise will be used to determine the position of the flow front. Once the whole mold has been filled, the piezo sensors are connected to the impedance analyzer to measure the impedance spectra of the individual sensors. During curing the impedance spectra are measured over time and the change of the spectra – impedance and resonance frequency – were used to determine the hardening of the resin and subsequent the degree of cure. When the curing cycle has been finished and the mold was cooled back to room temperature, the part together with the co-cured sensors will be deformed. The co-cured piezo transducers are than ready to be used as sensors and / or actuators of a passive (Acoustic Emission) and / or active (Guided Ultrasonic) SHM system.

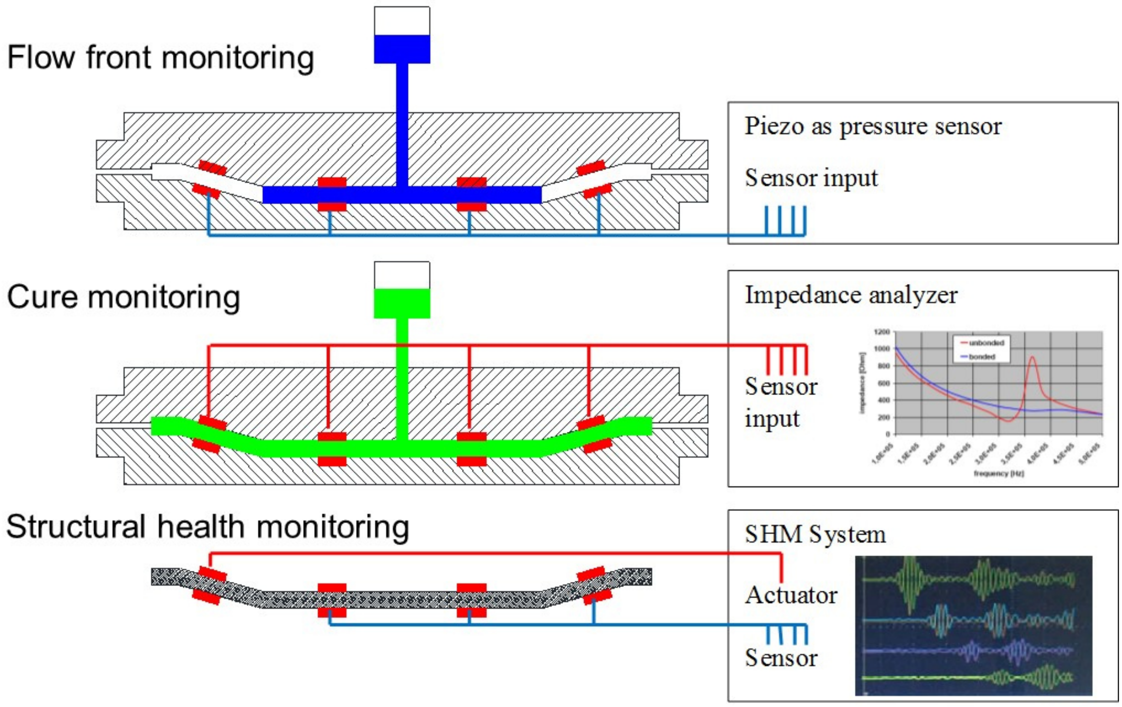

Figure 1. Illustration of the working principle of the integrated process and structural health monitoring system..

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2.1. Sensor concept

The developed sensor consists of piezo disc of 15 mm in diameter and 2 mm in thickness with wrapped around electrodes connected to co-axial Lemo connecter all embedded in epoxy resin cylinder, used as housing. The whole assembly is embedded in PTFE cylindrical ring, that is used to tighten the sensor in the RTM mold. Figure 2 shows a picture of the developed sensor.

Figure 2. Manufactured Piezo – Sensors for integrated process and structural health monitoring.

3. Analyses of the Impedance of the Sensor for Cure Monitoring

The basic idea of the developed Sensor for cure monitoring is to use the change of its electromechanical impedance due to the presence of curing resin in contact to the sensor. This principle has already been used before to assess the integrity of structures. The electrical impedance of a bonded piezoelectric layer can be described as a combined function of the static stiffness of the piezo actuator k_{piezo} (ω) and that of the host structure k_{str} (ω) [9]. In a simple linear model the correlation for the electrical impedance can be given as shown in formula (1).

$$Z(\omega) = \left[j\omega C \left(1 - \frac{d_{31}^2}{s_{11} \cdot \varepsilon_{33}} \cdot \frac{k_{str}(\omega)}{k_{str}(\omega) + k_{piezo}(\omega)} \right) \right]^{-1} \tag{1}$$

C is the zero-load capacitance of the piezo layer, d31, s11 and ε33 are the material properties of the piezo layer and k_{str} and k_{piezo} are the static stiffness´s of the structure and the piezo layer. As the stiffness of the structure will change during curing the measured impedance of the piezo layer will change as well. This is the basic concept used for cure monitoring. To assess the influence of the curing resin on the change of the impedance, two different models have been used:

1. Pure piezo disc surrounded by the curing resin
2. Piezo sensor (described in chapter 2.1) attached to a curing resin plate or a fully cured CFRP plate

The determination of the behavior both models has been done using a coupled field finite element harmonic simulation approach in ANSYS 14.5. The used piezo-electric part was a disc of 15 mm in diameter and 2 mm height made of PIC-255 from PI. The total dimensions of the sensor – size of epoxy

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housing was 20 mm in diameter and 15 mm in height. The following figure show the two different models.

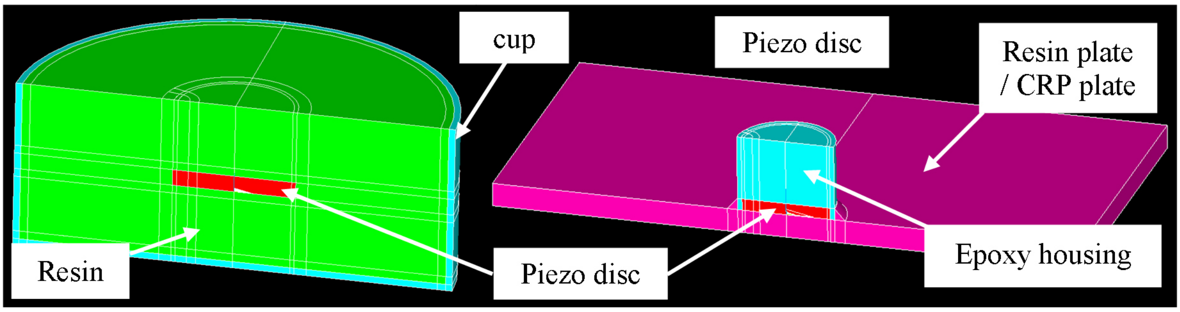

Figure 3. Used models for the simulation of the interaction of a pure piezo with curing resin and the piezo sensor with a curing resin plate and fully cured CFRP plate.

The used material properties for the piezo material, the epoxy resin of the housing and the CFRP structure are summarized in the following tables. The damping coefficients have been optimized to fit the measured impedance spectra of the pure piezo disc and the sensor.

Table 1. Material data of PIC-255 (Piezo).

Stiffness tensor [GPa]						Coupling coefficients [N/C]			Relative permittivity	Damping (stiffness)
135	88.7	84.9	0	0	0	0	0	-6.24	874	$3x10^{-9}$
	135	84.9	0	0	0	0	0	-6.24	874	
		113	0	0	0	0	0	14.6	631	
			23	0	0	0	0	0		
				20	0	0	11	0		
					20	11	0	0		

Table 2. Material data of cured Epoxy (left) and cured composite [0/90] (right).

EPOXY		CFRP [0/90]	
E [GPa]	3.0	E_{xx}, E_{yy} [GPa]	71.8
ν	0.38	E_z [GPa]	10.9
Damping stiffness	$1x10^{-7}$	G_{xy} [GPa]	12.1
		G_{yz} G_{xz} [GPa]	3.04
		$\nu_{xy,}$,$\nu_{xy,}$	0.013
		ν_{yz}	0.423
		Damping stiffness	$5x10^{-8}$

The behavior of the curing resin has been modeled assuming a damped isotropic solid material. The properties of the material in dependence of the degree of cure have be derived out of a measurement of the complex shear modulus and loss factor of typical curing resin [10] and are shown in Table 3. The stiffness damping coefficient β has been calculated out of the loss factor assuming first radial resonance frequency of around 150 kHz (typical value for the used piezo disc) using formula (2).

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$$\beta = \frac{\tan(\delta)}{2 \cdot \pi \cdot f_{resonance}} \quad (2)$$

Table 3. Material data of resin during curing (time of curing is arbitrary).

Time of curing [a.U.]	G´ [Pa]	Tan δ	β	E [Pa]
1	5.99E+05	3.01	3.19E-06	1.69E+06
2	1.47E+06	3.97	4.21E-06	4.04E+06
3	5.81E+06	2.93	3.11E-06	1.60E+07
4	1.70E+07	1.96	2.08E-06	4.70E+07
5	8.49E+07	1.03	1.10E-06	2.34E+08
6	1.22E+08	0.87	9.24E-07	3.35E+08
7	1.72E+08	0.75	7.96E-07	4.75E+08
8	3.80E+08	0.48	5.05E-07	1.05E+09
9	7.44E+08	0.21	2.25E-07	2.05E+09
10	9.01E+08	0.11	1.18E-07	2.49E+09

The following figures show the impedance spectra (Impedance as function of the frequency) around the region of the first radial anti-resonance frequency of the piezo disc during resin curing and the piezo sensor during resin plate (CFK plate) curing and the impedance at the first radial resonance und the anti-resonance frequency as function of the resin stiffness for the pure piezo disc and the developed sensor.

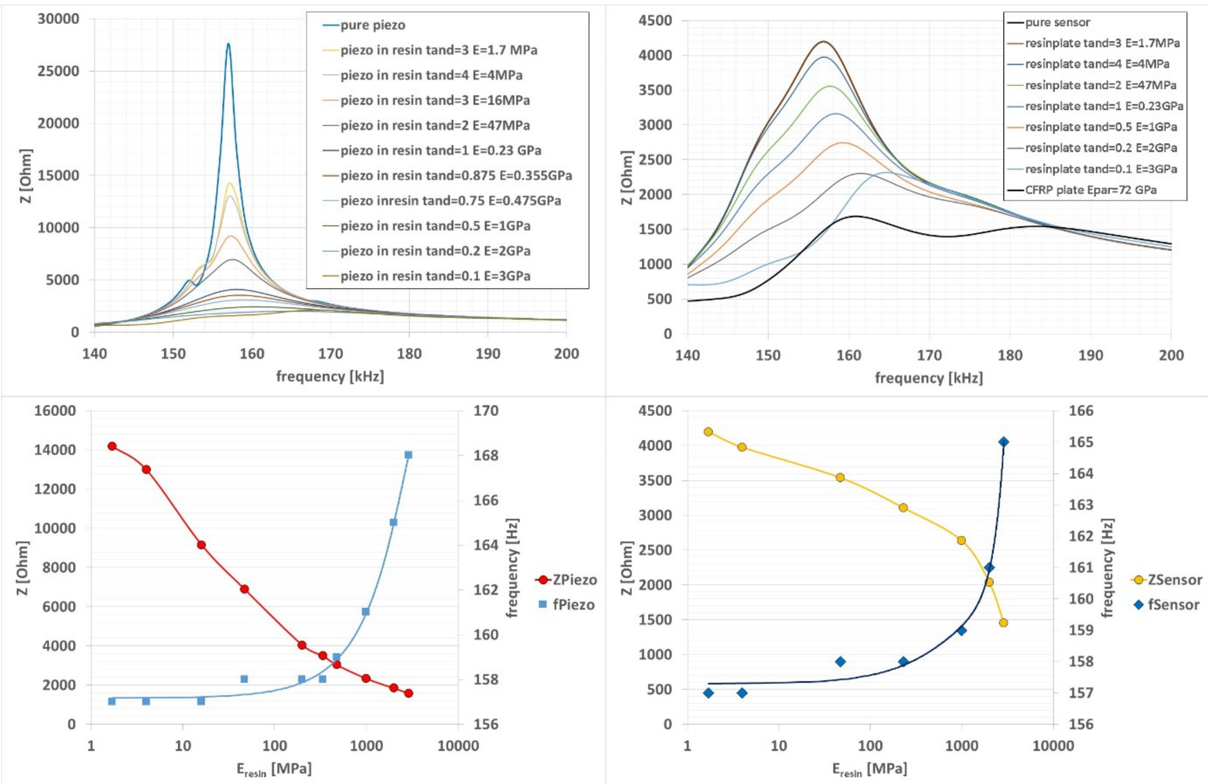

Figure 4. Impedance spectra around the region of the first radial anti-resonance frequency of the piezo disc during resin curing (top right) and the piezo sensor during resin plate (CFRP plate) curing (top-left) and the impedance at the first radial resonance und the anti-resonance frequency as function of the resin stiffness for the pure piezo disc (bottom left) and the developed sensor (bottom right)

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Out of Figure 4 one can clearly see the effect of the change of the material properties of the resin during cure (increase in stiffness and decrease in damping) on the impedance spectra. The higher the stiffness and the lower the damping of the resin the lower is the measured impedance at the first radial resonance. In addition the anti-resonance frequency will be shifted towards a higher frequency with higher stiffness. The behavior of the developed sensor is similar compared to the pure piezo disc but the impedance at the first radial resonance of the pure sensor is clearly smaller due to the presence of the sensor housing. This effect is caused by the additional damping of the epoxy housing. When looking at the behavior of the fully cured CFRP plate with its higher stiffness compared to the resin plate the damping of the first resonance frequency is higher leading to a lower impedance at anti-resonance frequency.

4. Verification Testing

4.1. Resin Curing

Verification testing of pure resin curing has been performed using a pure piezo disc placed in a bath of liquid resin (simulation case 1) and during the production of a pure resin plate in a single sensor mold (simulation case 2). Figure 5 show the embedded piezo disc after finalization of the curing process, the resin plate with the co-cured sensor after finalization of the curing process and the used single sensor mold for the production of the resin plate.

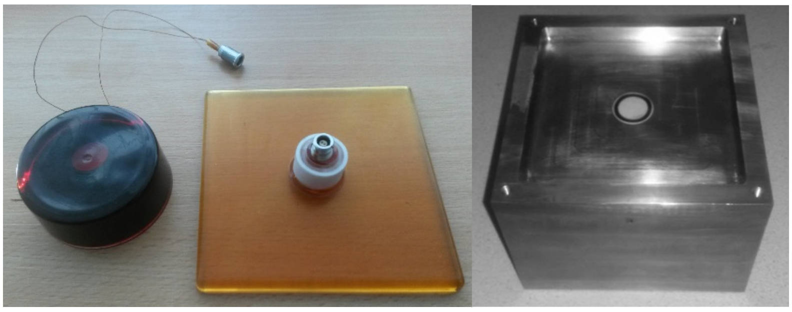

Figure 5. Embedded piezo disc after finalization of the curing process (left), the resin plate with the co-cured sensor after finalization of the curing process (middle) and the used single sensor mold for the production of the resin plate (right).

Figure 6 show the measured impedance spectra around the region of the first radial anti-resonance frequency of the piezo disc during resin curing and the piezo sensor during resin plate curing.

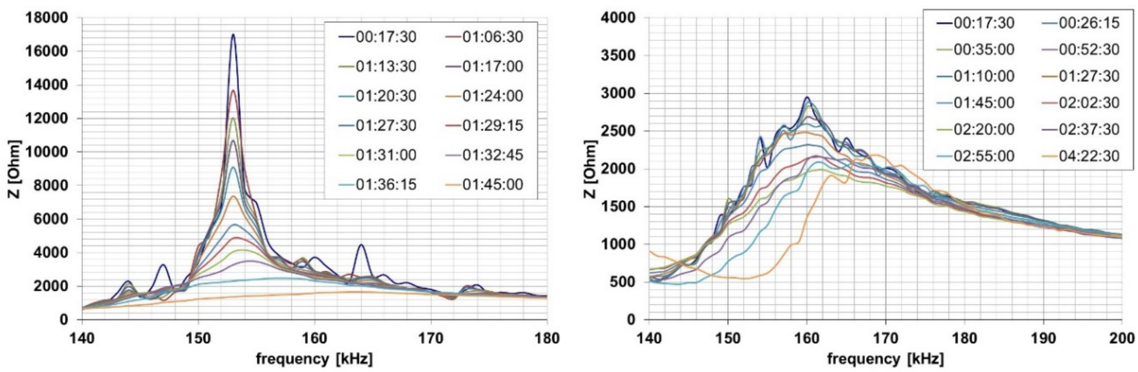

Figure 6. Measured impedance spectra around the region of the first radial anti-resonance frequency of the piezo disc during resin curing (right) and the piezo sensor during resin plate curing (left)

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Figure 7 shows the impedance at the first radial resonance und the anti-resonance frequency as function of the resin stiffness for the pure piezo disc and the developed sensor.

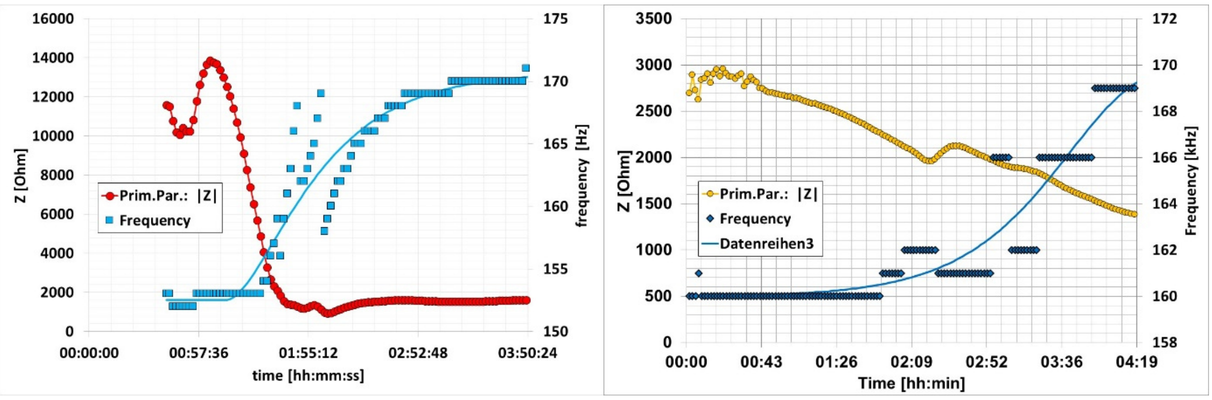

Figure 7. Measured impedance at the first radial resonance und the anti-resonance frequency as function of the curing time for the pure piezo disc and the developed sensor

Especially the behavior of the piezo disc in the resin shows the predicted behavior – drop of the impedance from around 14 kOhm in the fully uncured state to 2 kOhm in the fully cured state and rise of the resonance frequency from 153 kHz to 170 kHz. The behavior of the sensor during resin plate curing in the mold differs slightly from the predicted behavior. The staring impedance is somewhat lower: 3 kOhm compared to 4 kOhm for the uncured state. Such behavior could be explained by the interaction of the sensor with the mold, which was not part of the simulation. However the resulting impedance of 1.5 kOhm and the rise of the resonance frequency from 160 kHz to 169 kHz (total 9 kHz) are well in line with the predictions.

2.1. CFRP Curing

Verification testing of CFRP curing has been done by the production of a CFRP plate with 8 piezo sensors, where sensor 6 was used to monitor resin curing. The next figure shows the used 8 sensor mold, the injection strategy, the indication of the flow front at three sensors (4, 5, 7), the impedance / resonance frequency as function of the curing time during curing and the final plate with 8 co-cured sensors.

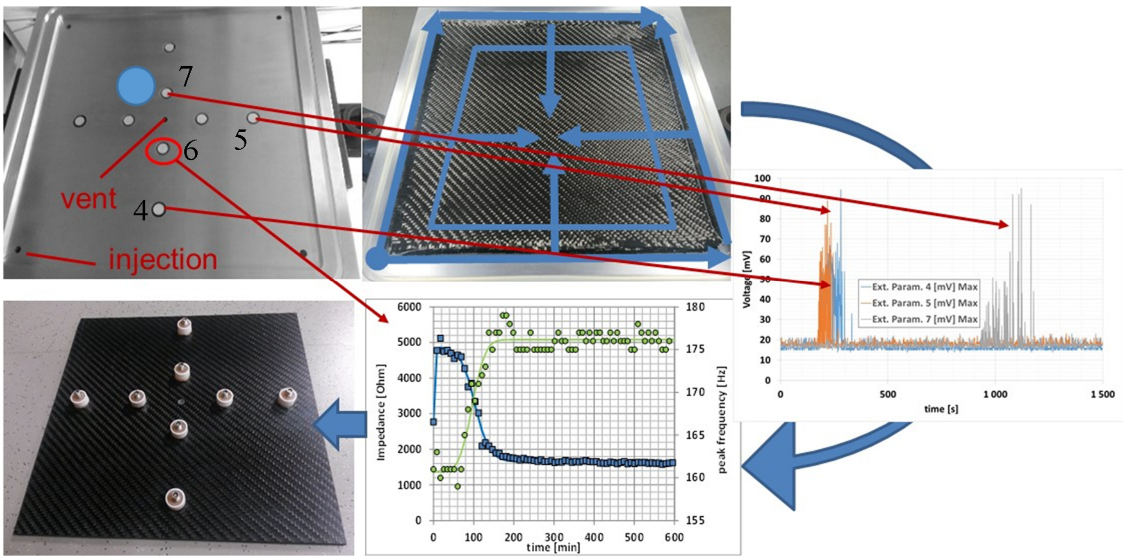

Figure 8. Flow front and cure monitored production of an 8 sensor mold

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Injection of the resin was performed from 1 edge of the mold. Due to the cavity at the edge of the mold, the resin propagates quickly on the circumference and starts to infiltrate the mold from all edges at nearly the same time. The voltage spikes measured by three sensors indicate the arrival of the flow front at the different sensor positions – first arrival at sensors 4 and 5 at 70 mm distance from the edge (orange and blue signal) after around 250s, last arrival at sensor 7 after around 1000s at 155 mm distance from the edge. The measured arrival times are in good agreement with predictions made by PAM-RTM. The measured impedance and resonance frequency show the expected behavior confirming the applicability of the proposed cure monitoring concept on CFRP´s.

5. Conclusions

Within this paper the authors presented the analyses and verification results of the process monitoring part of a novel concept for an integrated process and structural health monitoring system for CFRP parts made by RTM. The analyses and verification tests successfully demonstrated the ability of the developed sensor and method to monitor flow front propagation and cure monitoring for the production of CFRP parts.

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