



**HAL**  
open science

# REAL-TIME MONITORING OF THE INFUSION PROCESS OF A POLYMER-MATRIX COMPOSITE WITH AN EMBEDDED PIEZOELECTRIC TRANSDUCER

Corentin Tuloup, Walid Harizi, Zoheir Aboura, Yann Meyer

► **To cite this version:**

Corentin Tuloup, Walid Harizi, Zoheir Aboura, Yann Meyer. REAL-TIME MONITORING OF THE INFUSION PROCESS OF A POLYMER-MATRIX COMPOSITE WITH AN EMBEDDED PIEZOELECTRIC TRANSDUCER. SMART 2019: IX ECCOMAS Thematic Conference on Smart Structures and Materials, Jul 2019, Paris, France. hal-02963209

**HAL Id: hal-02963209**

**<https://hal.science/hal-02963209>**

Submitted on 9 Oct 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/337717612>

# REAL-TIME MONITORING OF THE INFUSION PROCESS OF A POLYMER-MATRIX COMPOSITE WITH AN EMBEDDED PIEZOELECTRIC TRANSDUCER.

Conference Paper · July 2019

CITATIONS

0

READS

77

4 authors:



**Corentin Tuloup**

Université de Technologie de Compiègne

10 PUBLICATIONS 20 CITATIONS

[SEE PROFILE](#)



**Walid Harizi**

Université de Technologie de Compiègne

32 PUBLICATIONS 195 CITATIONS

[SEE PROFILE](#)



**Zoheir Aboura**

Université de Technologie de Compiègne

111 PUBLICATIONS 1,034 CITATIONS

[SEE PROFILE](#)



**Yann Meyer**

Université Savoie Mont Blanc

74 PUBLICATIONS 244 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



ESCOTH Project [View project](#)



MIREPOix : Study of the influence of internal Mechanical compResion on the Electrical PerfOrmance of a PEM fuel cell [View project](#)

# REAL-TIME MONITORING OF THE INFUSION PROCESS OF A POLYMER-MATRIX COMPOSITE WITH AN EMBEDDED PIEZOELECTRIC TRANSDUCER

CORENTIN TULOUP<sup>\*</sup>, WALID HARIZI<sup>\*</sup>, ZOHEIR ABOURA<sup>\*</sup> AND YANN MEYER<sup>\*†</sup>

<sup>\*</sup> Département Ingénierie Mécanique, Laboratoire Roberval FRE UTC-CNRS 2012  
Sorbonne Universités – Université de Technologie de Compiègne  
Centre de Recherches de Royallieu - CS 60319 – 60203 Compiègne Cedex FRANCE  
e-mail: corentin.tuloup@utc.fr

<sup>†</sup> : Univ. Bourgogne Franche-Comté - UTBM  
90010 Belfort Cedex FRANCE  
e-mail: yann.meyer@utbm.fr

**Key words:** Polymer-Matrix Composite, Process Monitoring, In-situ Piezoelectric transducer, Liquid Resin Infusion, Smart Materials.

**Abstract.** This article investigates the Liquid Resin Infusion (LRI) manufacturing of glass fiber/polyester composite plates embedding a thin piezoelectric (PZT) disk. The real-time in-situ Process Monitoring (PM) of this technique is performed using the electrical capacitance signature of the embedded PZT transducer. To help with the understanding of capacitance variations, an internal/external multi-instrumentation (Infrared Thermography, thermocouples, Acoustic Emission, Z-displacement sensing, pressure sensing) was set on the infusion systems, so that it was possible to make couplings between the various obtained measurements and the PZT capacitance curves. Rheological tests were also performed on resin samples to find correlations between the matrix chemo-physical transitions during curing and PZT capacitance inflections during its final decrease. It was shown that the PZT capacitance is sensitive to several key moments of the infusion process, such as the end of preform impregnation, the isolation of the system at the end of resin injection, and the different resin curing stages such as gelation and vitrification. It is therefore a cheap and quite powerful in-situ Non-Destructive Testing device for the PM of the LRI manufacturing.

## 1 INTRODUCTION

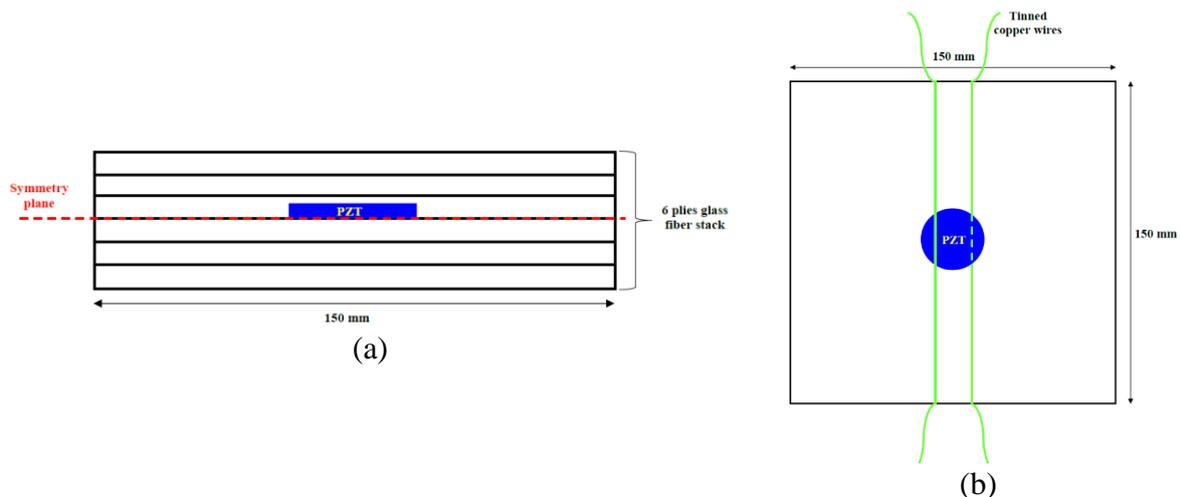
In the Polymer-Matrix Composite (PMC) materials industry, the parameters of Liquid Composite Moulding (LCM) manufacturing processes such as mould filling rate, fiber impregnation quality, resin curing kinetics or internal temperature gradients are relatively difficult to evaluate, especially in real time. Knowledge of these parameters can be of great help in order to optimize these processes and thus obtain parts having better mechanical properties and good dimensional tolerances. Various research teams have already undertaken the study and control of these parameters, called “Process Monitoring” (PM), ([1] - [5]). However, there

is still little work on PM using Non Destructive Testing (NDT) techniques, the latter being mainly used for monitoring the life in service of composite structures already manufactured ([6] - [8]). Current contributions to the PM of PMC by NDT use a variety of techniques, both internal and external. External (or ex-situ) techniques, which are more common, may involve the use of pressure sensors [9], thermocouples [10], electrical measurements ([11] - [13]) or ultrasound ([14] ] - [17]). In-situ techniques, on the other hand, allow the measurement to take place at the heart of the part being manufactured, by inserting the NDT system inside the composite. It is thus possible to integrate them with optical fibers ([18], [19]), piezoresistive systems ([20], [21]) or also dielectric analysis sensors (DEA) ([18], [22] ).

In the continuity of the works related to in-situ PM of PMC, this paper focuses on the insertion of a thin piezoceramic disk (PZT) inside a fiberglass / polyester matrix composite plate realized by infusion, with the objective of real-time follow-up of this process thanks to the PZT electrical capacitance information. To understand the evolution of this capacitance during manufacturing, a multi-instrumentation with both internal (2 thermocouples) and external (1 infrared camera, 4 acoustic emission sensors, 1 pressure sensor and 2 vertical displacement sensors) NDT systems is set around the infusion system, allowing to highlight the potential multi-physical couplings existing between these data and those provided by the PZT. The sensitivity of the PZT to the state transitions of the resin during its curing was also investigated using oscillatory rheology tests performed aside on the polyester resin alone. The details of the experiments are explained in the next section.

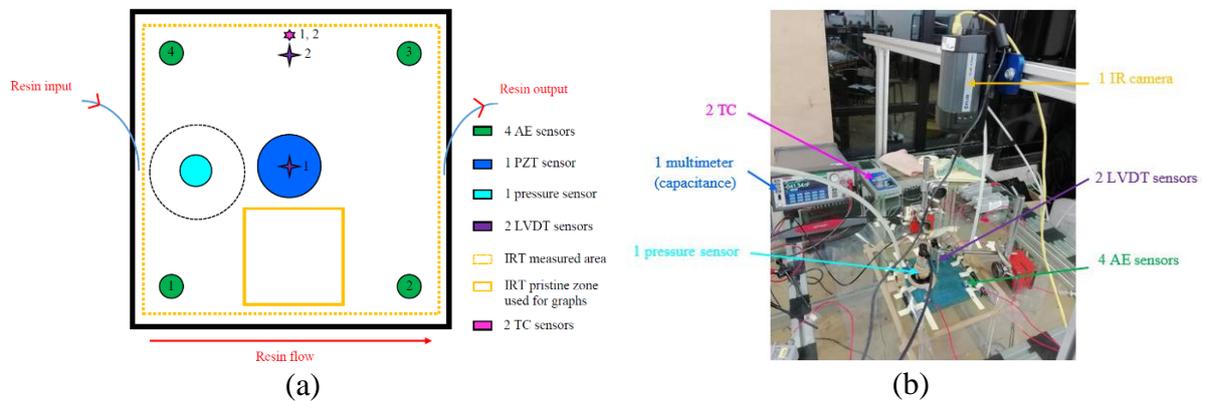
## 2 MATERIAL AND METHODS

PZT discs (Wealthland - China) of 25mm diameter and 0.135mm thickness were used for this study. Their static capacitance was measured and compared to the manufacturer's information before integration into the fibrous preform consisting of 6 fiberglass (twill weave 2/2) plies of dimensions 150 \* 150mm<sup>2</sup>, as shown in Figure 1. The wiring of the PZT is made using tinned copper wires with a diameter of 210µm.



**Figure 1:** (a) PZT location inside the fiber stack, (b) Wiring of the PZT

The infusion is then performed at room temperature using an unsaturated polyester resin mixed at fixed concentration (1% wt) with a Methyl Ethyl Ketone Peroxide (MEKP) type hardener. During infusion, both internal and external multi-instrumentation is used to retrieve real-time information on the manufacturing process. This multi-instrumentation composed of 1 infrared thermography (IRT) camera, 4 acoustic emission (AE) sensors, 1 pressure sensor, 2 vertical displacement sensors (LVDT) and 2 thermocouples (1 at the heart of the preform, 1 on its surface) is shown schematically in Figure 2 a. A digital multimeter is used to measure the electrical capacitance of the in-situ PZT. The injection of the resin conditions the simultaneous triggering of all the instrumentations, to be able to work on the same time base. The stop of the acquisitions and the demolding of the plate are carried out 6 hours after the injection, to have the certainty of the quasi-complete curing of the resin. The complete experimental setup is presented in Figure 2 b. Three plates were made to ensure the repeatability of the experiment.



**Figure 2:** (a) Sketch of the multi-instrumentation system, (b) Complete setup before resin injection

The oscillatory rheology tests (3 repeatability) were carried out at room temperature on resin samples mixed with the same MEKP hardener with a concentration identical to the one used for the infused composite plates. The test consists of a dynamic shear of the mixture between two parallel planar plates held at a constant distance (1mm) from each other, at a constant shear strain  $\gamma = 1\%$  and at a constant oscillation frequency  $f = 1\text{Hz}$ . The test is conducted until the complex viscosity modulus  $|\eta^*|$  is stabilized. To be able to plot the rheology and infusion curves together and detect the potential couplings, a constant  $\Delta t$  was maintained between the resin + hardener mixing and the start of the test for both types of experiments.

### 3 RESULTS AND DISCUSSIONS

#### 3.1 Multi-instrumented infusion: couplings between in and ex-situ signatures

Typical results obtained for the multi-instrumented infusion are shown in Figure 3 a.

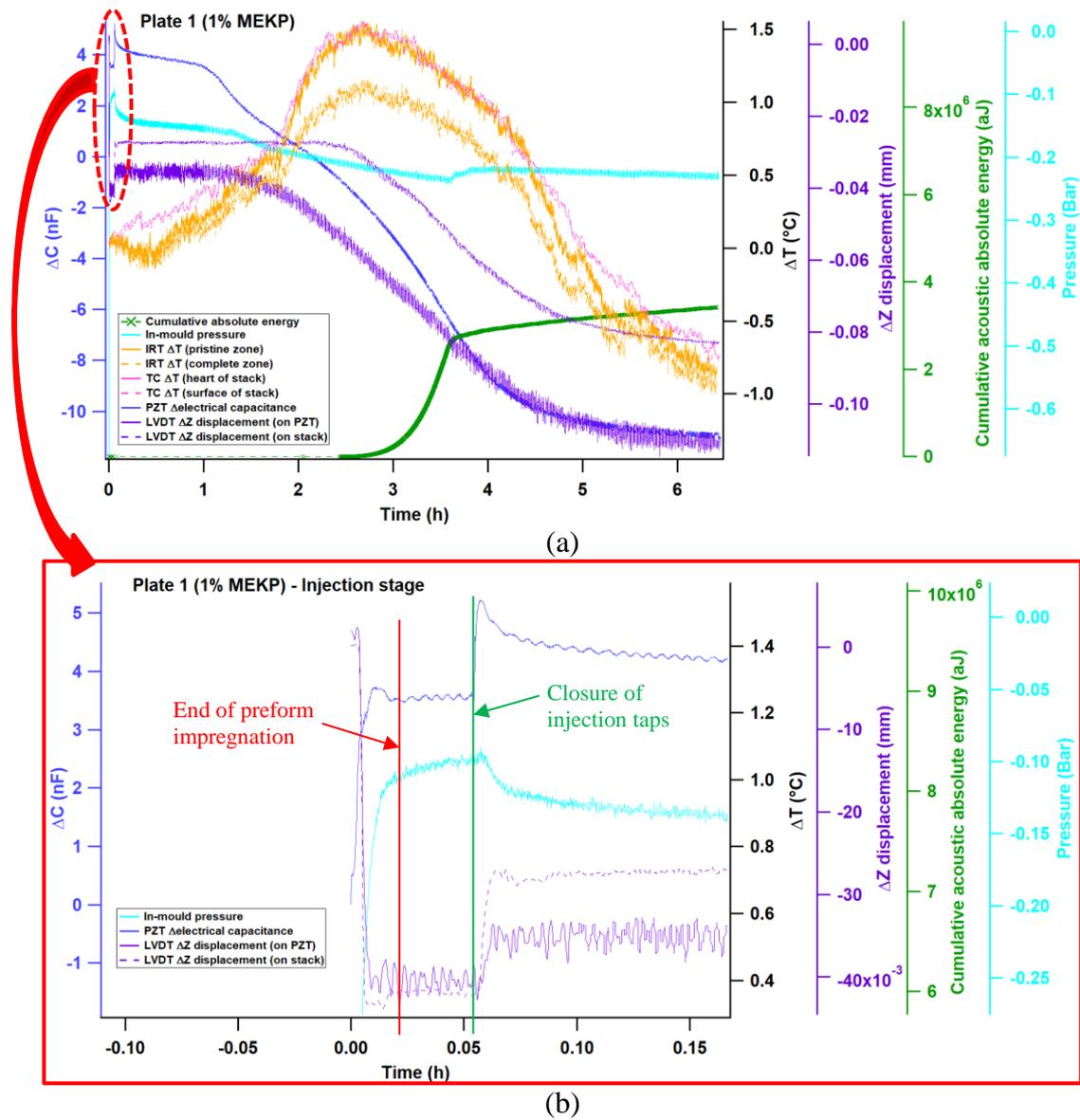
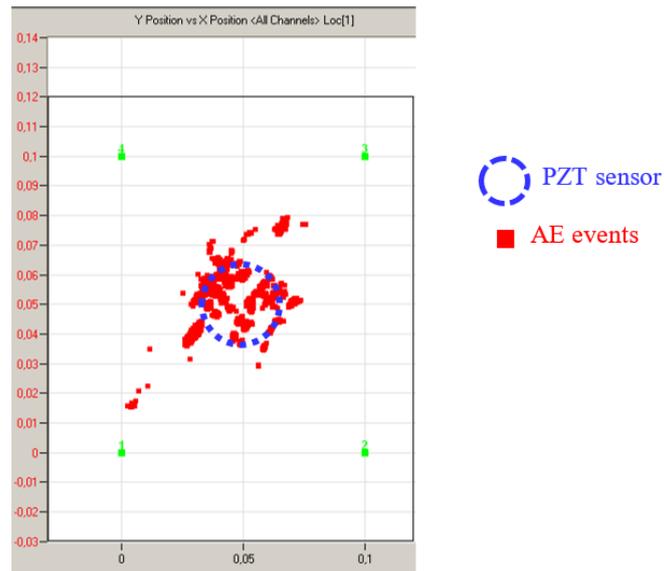


Figure 3: Results of the multi-instrumented infusion: (a) full experiment, (b) resin injection step (plate 1)

It is easy to see on Fig. 3. a) that the signatures of the TC placed at the heart of the preform and the IRT ones taken in the virgin zone of the plate are similar. It is therefore justified to trust IRT to measure thermal phenomena inside the plate, and this will be the case for the rest of this work. However, it is necessary to perform IRT measurements on a virgin zone (no instrumentation placed on it), not to disturb the camera with parasitic reflections and differences in thermal emissivity, which results in underestimated temperature measurement when it is taken on the full plate. Several couplings are observable between the various in and ex-situ signatures. The beginning of each curve appears chaotic, which corresponds to the step of resin injection into the infusion system. Figure 3 b allows highlighting the various phenomena occurring during this stage. The arrival of the resin in the preform causes a fall in the vacuum created by the vacuum pump, associated with an increase in the electrical capacitance ( $\Delta C$ ) of

the PZT and a descent of the LVDTs. The behavior of the capacity is explained by the progressive release of the pressure applied on the PZT by the vacuum during the impregnation of the preform [23], whereas the fall of the LVDT is due to their sliding in one of the cavities of the draining fabric positioned under the vacuum bag. A stabilization of these signatures is then observed, corresponding to the end of the impregnation of the fibrous stack (red demarcation on the Figure 3 b): a steady state begins then, during which the resin continues to flow through the preform to eliminate potential air bubbles as much as possible. The end of the injection is associated with the closing of the two resin inlet and outlet taps, which isolates the preform from the vacuum pump (green demarcation on the Figure 3 b). This results in an immediate response of the 3 signals, related to a gradual stabilization of the pressure in the isolated system: the PZT reacts to the closure (peak) and is then gradually compressed again, this reasoning going hand in hand with the reaction of the LVDTs. The rest of the manufacturing (Figure 3 a) shows new behaviors and couplings. The IRT (virgin zone) shows a progressive exothermal behavior associated with the curing of the resin, which decreases thereafter once the reaction on its end. After a plateau, the capacitance drops continuously until the end of the experiment. The beginning of this fall being associated with the rise in temperature, it is clear that the PZT is sensitive to the start of the curing of the polyester matrix. Indeed, the more a PZT is constrained in its environment (here the progressive contraction of the curing resin), the more its electrical capacitance drops [23]. The signature of the LVDTs provides information on the vertical displacement of the vacuum bag on which they are positioned: it is notable that when the resin contracts during curing, the associated shrinkage causes a negative Z-displacement of the plate, and therefore a reaction of LVDTs. However, it should be noted that LVDTs are less sensitive to the start of the crosslinking than the PZT, their fall occurring later in time than the one of  $\Delta C$ . This is due to the fact that the PZT is directly surrounded by the resin, which makes its measurement much more local and sensitive than those of the LVDTs. The capacitance and LVDTs signatures appear to stabilize after the end of the exothermal peak, which means that the curing is not complete yet at the temperature peak. The AE signals are also rich in information: after some signals initially sensed corresponding to the passage of the resin front during the injection step, no signal is noticed until the exothermal peak, from which the acoustic activity reappears in the form of an increase in the cumulative absolute energy (CAE) of detected AE bursts. This behavior is associated with the variation of the physical properties of the resin during manufacturing: before the exothermal peak, the resin attenuates the acoustic signals too much so that they can be detected by the 4 AE sensors on the surface. It is necessary to wait for a sufficient degree of cure for the signals to be transmitted through the plate, which suggests that the exothermal peak / CAE rise coupling corresponds to a major state transition of the resin. The acoustic activity related to the rise of the CAE is mainly due to the vibration of the PZT, this being confirmed by the location of the corresponding AE bursts in the integration zone of the PZT (Figure 4). Two slopes are observable in the CAE curve, the transition from one to the other occurring at the beginning of the temperature decrease. Given the quasi-constancy of the second CAE regime, it is clear that at this stage the properties of the resin are stabilized, thus providing information on the end of the curing matrix curing.



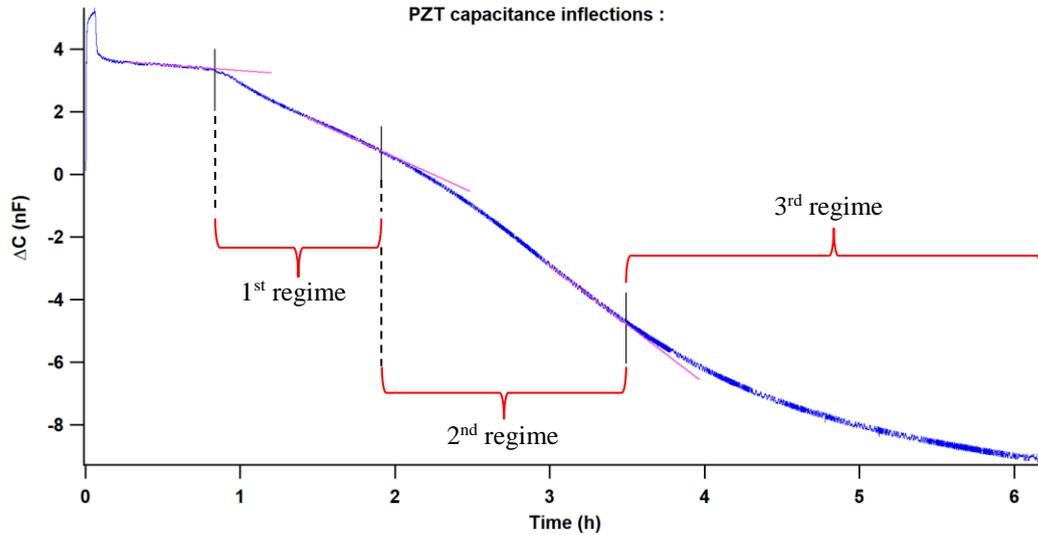
**Figure 4:** Location of AE events on a plate being cured (AEwin software)

The pressure variation can finally be combined with the other measurements: it follows the trend of the capacitance and LVDTs signals, thus linking the curing of the resin to a progressive depression in the infusion system. A point of interest corresponds to a not negligible increase in pressure at the end of the test, correlated with the previously described temperature drop and second EAC regime, thus confirming the existence at this stage of another transition in the resin curing.

The multi-instrumentation has shown the reaction of the PZT to the resin curing and the existence of state transitions inside it, the next part focuses on the sensitivity of the PZT to detect these transitions.

### 3.2 Sensitivity of the PZT to the state transitions of the curing resin

The capacitance decrease being related to the crosslinking of the polyester matrix, the study focused on the analysis of this decrease. The observation of Figure 5 reveals three regimes, separated by inflections (regime changes). The existence and the temporal appearance of these regimes and inflections being repeatable for each manufactured plate, the hypothesis was emitted that these inflections corresponded to state transitions of the resin during its curing, and that they therefore framed different chemo physical states (stable or unstable) of the resin.



**Figure 5:** Methodology for the measurement of regime changes (inflections) of the PZT electrical capacitance

These inflections were subsequently correlated with the signatures coming from the multi-instrumentation for each of the manufactured plates. The first inflection had already been attributed to the start of resin curing in § 3.1. The second inflection appears just before the exothermal peak and the increase in the CAE, which confirms the hypothesis emitted earlier that a major state transition of the resin occurs at this time. The third capacity inflection occurs after the exothermal peak, following the start of the second (almost constant) growth regime of the CAE associated with the final pressure re-increase described above: it therefore corresponds to another transition state, this one leading to the near-final state of the resin (chemical reaction substantially completed). At this time, the resin is almost completely cured, which is also confirmed by the progressive stabilization of the plate retraction measured by the LVDTs.

Since strong hypotheses have been put forward on the sensitivity of the PZT to the resin curing and to the various transitions that compose it, it remains to characterize these transitions and to confirm their direct link with the inflections and regimes detected on the decay of PZT electrical capacitance. Consequently, chemo physical characterization tests of the resin alone by oscillatory rheology were undertaken. A thermoset such as the polyester resin passes through different states during its curing, the two main ones being gelation and vitrification [24]. Gelation allows the resin to change from a liquid state to a gel state, then this gel gradually hardens until it becomes a glass (vitrification stage). After the vitrification stage, the chemical reaction slows down (even stops), even if the system temperature is increased [24]. Other events, such as devitrification or phase separation may occur during curing, but these do not occur in this study. The objective is to characterize these two main states, to be able to correlate them with the signatures obtained during infusion. Since the chemo physical characterization of the infused plates is not possible in real time, several pure resin samples (with MEKP) were tested in oscillatory rheology as detailed in section 2. The tests were carried out under conditions as close as possible from those used during infusion manufacturing, namely at room temperature and shear and oscillations as low as possible to reproduce the stable state of the resin when it cures in the plate. These dynamic tests, highlighting the viscoelastic behavior of the resin, make it possible to reveal the gelation by the crossing of the storage modulus ( $G'$ )

and loss modulus ( $G''$ ) curves if the test is conducted at constant oscillation frequency ([25] - [27]); this crossing goes hand in hand with an increase in the viscosity complex modulus  $|\eta^*|$ . The vitrification is determined by the maximum of  $G''$  [28], and each result is normalized with respect to its own mass. The tests are conducted until the appearance of a plateau of  $|\eta^*|$ , associated with a significant slowing of the curing reaction. This plateau is considered as the end of the vitrification, knowing that it is associated with a drop of  $G''$  meaning that the resin (reticulated) no longer has viscous properties (elastic solid with a maximized  $G'$ ). The obtained results being repeatable, only those of sample 1 are presented below. These results were then correlated with those obtained in infusion, as shown in Figure 6. Analysis of the latter makes it possible to associate the first inflection of electrical capacitance with the  $G' / G''$  crossing, that is to say gelation. This confirms that when the resin goes from the liquid state to the gel state, it begins to compress the PZT transducer, effectively lowering its capacitance. In the gel state, the resin is a medium in which the acoustic waves are strongly attenuated (and thus not transmitted to the external AE sensors), which is why the CAE signal is flat during this period. The pressure is decreasing at the first inflection because the resin is gradually curing (increased exothermal behavior), consequently the depression of the infusion system is increased. At the beginning of the vitrification (maximum of  $G''$ ), the second inflection of capacitance appears. This coupling is coherent because the vitrification makes the resin go from a gel state to a much more rigid glass state, which increases the compression seen by the PZT and thus induces a change in the decrease of its capacitance. This second inflection also sees the temperature coming close to its peak, while the CAE prepares to enter its first rise. These other couplings are also consistent: since the chemical curing reaction generates heat throughout its duration, the associated temperature will be close to its maximum when the appearance of the final state change (vitrification) of the resin will occur. Moreover, since the resin gradually transforms into a glass state, its physical properties become more and more similar to those of a sufficiently continuous propagation medium able to transmit the acoustic waves generated by the vibration of the PZT, explaining the rise of CAE to come. However, the resin still being cured at this stage, the depression continues its decline. The third capacitance inflection occurs more than three hours after the resin injection step: at this point, the  $G'$  has already converged to a final plateau, and the  $G''$  has returned to zero. It should be noted, however, that this last inflection always happens at a time never reached in rheology, due to the risk of breakage of the rheometer when a very rigid sample is tested too long. The behavior of  $G'$  and  $G''$  indicates that the resin is almost completely cured at this stage because as a purely vitreous solid, it has only an elastic behavior and no more viscous properties. This third inflection of electrical capacitance is associated with the change in slope of the CAE (previously mentioned) towards a quasi-linear behavior until the end of the infusion manufacturing, which confirms the hypothesis that at this stage the resin possesses its final properties and therefore always transmits acoustic waves in the same way. A correlation with the temperature drop following the exothermal peak as well as with the final rise in pressure is also observable. This means that since the resin is almost completely cured, the almost complete chemical reaction releases practically no more heat (hence the gradual decrease in temperature), and that the opening made in the vacuum bag to perform the pressure measurement has partially obstructed by the vitrified resin. An important point is the continuity of the decay (albeit much slower than before) of the electrical capacitance after this last inflection, a sign that the curing, although practically complete, is still active. There are still some residual percentages of resin to be cured at this stage.

It is henceforth possible to associate each of the three inflections of the in-situ PZT electrical capacitance with the start of a chemo physical transformation of the polyester resin in crosslinking: gelation, vitrification and finally the slow transformation of a small amount of residual resin still uncured after the end of vitrification.

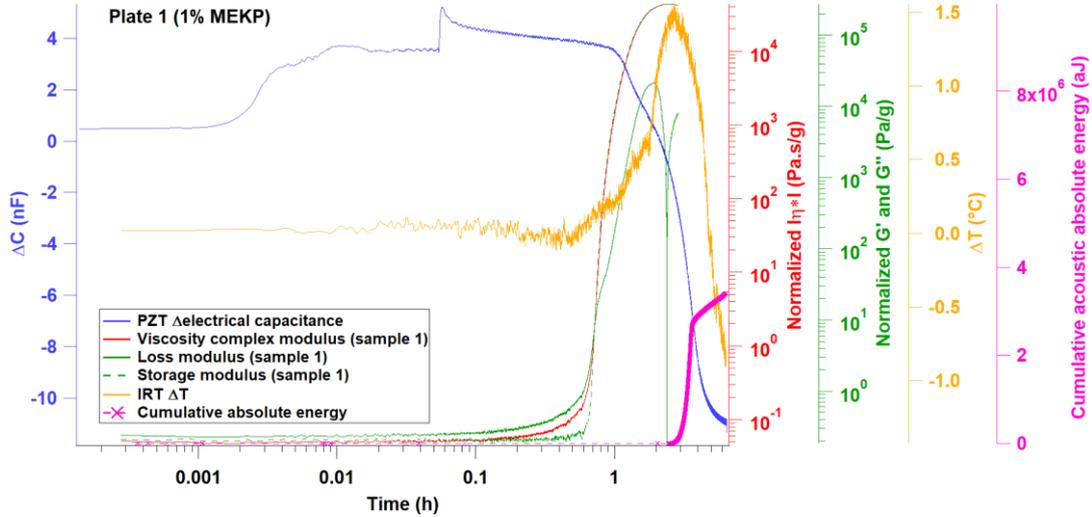


Figure 6: Comparison of the infusion and rheological measurements

#### 4 CONCLUSION AND OUTLOOK

This article studies the interest of inserting a thin piezoelectric ceramic disc (PZT) inside a PMC preform in order to carry out an in-situ and real-time monitoring of its infusion manufacturing. Several in and ex-situ NDT instrumentations are used in addition to the PZT to obtain correlations between the different signatures. Multiple couplings are observed, providing information both on the impregnation of the preform during the injection stage and on the curing of the resin. The electrical capacitance signal of the PZT has three different inflections during its final decay phase, and these have been studied thanks to the multi-instrumentation data associated with oscillatory rheology measurements made on resin samples alone. These last tests made it possible to associate the first capacitance inflection with the beginning of gelation of the resin, the second with the beginning of its vitrification and the last with the curing of the last resin percentages still not transformed at the end of vitrification. The in-situ PZT giving repeatable and relatively accurate information about the various major transitions (chemo physical or not) occurring during the infusion process, its potential is obvious. The end of vitrification (third capacitance inflection) is particularly interesting because it can be used in industrially to determine when to unmold composite parts without risk of damaging them, and thus increase production rates. These information on transitions can also be very useful for processes using closed molds, such as Resin transfer Molding (RTM), where it is impossible to visualize the progress of manufacturing. This work has also demonstrated the interest of using a multi-instrumentation to monitor this process in real time, and in particular the use of the PZT (transducer) - AE (sensors) couple to detect the presence of the vitrification phase by the

acousto-ultrasonic method. The ultimate interest of this study lies in obtaining a "smart" composite material with an embedded and functional PZT transducer after manufacturing. The PZT can then be used for health monitoring applications of composite structures in use, when the latter are subjected to various physical loads. Finding thresholds to know when to stop the structure to control it more accurately or replace it completely, all without having to use the external and cumbersome NDT techniques available on the market, would be a major breakthrough in the composite materials industry.

## REFERENCES

- [1] A. Hautefeuille, S. Comas-Cardona, and C. Binetruy, "Mechanical signature and full-field measurement of flow-induced large in-plane deformation of fibrous reinforcements in composite processing," *Compos. Part A Appl. Sci. Manuf.*, vol. 118, no. December 2018, pp. 213–222, 2019.
- [2] B. Gourichon, C. Binetruy, and P. Krawczak, "Experimental investigation of high fiber tow count fabric unsaturation during RTM," *Compos. Sci. Technol.*, vol. 66, no. 7–8, pp. 976–982, 2006.
- [3] D. May *et al.*, "In-Plane Permeability Characterization of Engineering Textiles Based On Radial Flow Experiments: A Benchmark Exercise," *Compos. Part A Appl. Sci. Manuf.*, vol. 121, no. March, pp. 100–114, 2019.
- [4] V. H. Nguyen, M. Deléglise-Lagardère, and C. H. Park, "Modeling of resin flow in natural fiber reinforcement for liquid composite molding processes," *Compos. Sci. Technol.*, vol. 113, pp. 38–45, 2015.
- [5] S. P. Bancora, C. Binetruy, S. G. Advani, E. Syerko, and S. Comas-Cardona, "Effective permeability averaging scheme to address in-plane anisotropy effects in multi-layered preforms," *Compos. Part A Appl. Sci. Manuf.*, vol. 113, no. July, pp. 359–369, 2018.
- [6] W. Harizi, S. Chaki, G. Bourse, and M. Ourak, "Mechanical damage characterization of glass fiber-reinforced polymer laminates by ultrasonic maps," *Compos. Part B Eng.*, vol. 70, pp. 131–137, 2015.
- [7] A. T. Martins, Z. Aboura, W. Harizi, A. Laksimi, and K. Khellil, "Structural health monitoring for GFRP composite by the piezoresistive response in the tufted reinforcements," *Compos. Struct.*, 2018.
- [8] K. Hamdi, Z. Aboura, W. Harizi, and K. Khellil, "Improvement of the electrical conductivity of carbon fiber reinforced polymer by incorporation of nanofillers and the resulting thermal and mechanical behavior," *J. Compos. Mater.*, p. 002199831772658, 2017.
- [9] S. Leonard-Williams, "The crossover from RTM to resin infusion," *Reinf. Plast.*, vol. 52, no. 10, pp. 28–29, Nov. 2008.
- [10] M. Deléglise, C. Binétruy, P. Castaing, and P. Krawczak, "Use of non local equilibrium theory to predict transient temperature during non-isothermal resin flow in a fibrous medium," *Int. J. Heat Mass Transf.*, vol. 50, no. 11–12, pp. 2317–2324, 2007.
- [11] K. Hoes *et al.*, "New set-up for measurement of permeability properties of fibrous reinforcements for RTM," *Compos. - Part A Appl. Sci. Manuf.*, vol. 33, no. 7, pp. 959–969, 2002.

- [12] R. Matsuzaki, S. Kobayashi, A. Todoroki, and Y. Mizutani, “Cross-sectional monitoring of resin impregnation using an area-sensor array in an RTM process,” *Compos. Part A Appl. Sci. Manuf.*, vol. 43, no. 4, pp. 695–702, 2012.
- [13] S. Kobayashi, R. Matsuzaki, and A. Todoroki, “Multipoint cure monitoring of CFRP laminates using a flexible matrix sensor,” *Compos. Sci. Technol.*, vol. 69, no. 3–4, pp. 378–384, 2009.
- [14] N. Ghodhbani, P. Marechal, and H. Duflo, “Ultrasonic broadband characterization of a viscous liquid: Methods and perturbation factors,” *Ultrasonics*, vol. 56, pp. 308–317, 2015.
- [15] R. Kline, N. Parasnis, and R. Konanur, “Ultrasonic monitoring of the dynamic properties of composites during manufacture,” *Ultrason. Symp.*, vol. 9, no. 6, pp. 0–87, 1992.
- [16] N. Samet, P. Maréchal, and H. Duflo, “Ultrasound monitoring of bubble size and velocity in a fluid model using phased array transducer,” *NDT E Int.*, vol. 44, no. 7, pp. 621–627, 2011.
- [17] N. Samet, P. Marechal, and H. Duflo, “Monitoring of an ascending air bubble in a viscous fluid/fiber matrix medium using a phased array transducer,” *Eur. J. Mech. B/Fluids*, vol. 54, pp. 45–52, 2015.
- [18] E. Marin, L. Robert, S. Triollet, and Y. Ouerdane, “Liquid Resin Infusion process monitoring with superimposed Fibre Bragg Grating sensor,” *Polym. Test.*, vol. 31, no. 8, pp. 1045–1052, 2012.
- [19] L. P. Canal, M. Benavente, M. Hausmann, and V. Michaud, “Process-induced strains in RTM processing of polyurethane/carbon composites,” *Compos. Part A Appl. Sci. Manuf.*, vol. 78, pp. 264–273, 2015.
- [20] M. A. Ali, R. Umer, K. A. Khan, Y. A. Samad, K. Liao, and W. Cantwell, “Graphene coated piezo-resistive fabrics for liquid composite molding process monitoring,” *Compos. Sci. Technol.*, vol. 148, pp. 106–114, 2017.
- [21] J. M. Park, S. Il Lee, and J. H. Choi, “Cure monitoring and residual stress sensing of single-carbon fiber reinforced epoxy composites using electrical resistivity measurement,” *Compos. Sci. Technol.*, vol. 65, no. 3–4, pp. 571–580, 2005.
- [22] U. Müller, C. Pretschuh, R. Mitter, and S. Knappe, “Dielectric analysis as a cure monitoring system for UF particle boards,” *Int. J. Adhes. Adhes.*, vol. 73, pp. 45–50, 2017.
- [23] N. Elvin, A. Elvin, and B. Z. Senderos, “Capacitance changes in thin piezoelectric transducers embedded in isotropic host materials,” *J. Intell. Mater. Syst. Struct.*, vol. 29, no. 5, pp. 816–829, Mar. 2018.
- [24] M. C. Kazilas, *Acquisition and Interpretation of Dielectric Data For Thermoset Cure Monitoring*. 2003.
- [25] H. H. Winter and F. Chambon, “Analysis of Linear Viscoelasticity of a Crosslinking Polymer at the Gel Point,” *J. Rheol. (N. Y. N. Y.)*, vol. 30, no. 2, pp. 367–382, Apr. 1986.
- [26] M. Haider, P. Hubert, and L. Lessard, “Cure shrinkage characterization and modeling of a polyester resin containing low profile additives,” vol. 38, pp. 994–1009, 2007.
- [27] S. Dev, P. N. Shah, Y. Zhang, D. Ryan, C. J. Hansen, and Y. Lee, “Synthesis and mechanical properties of flame retardant vinyl ester resin for structural composites,”

- Polymer (Guildf)*., vol. 133, pp. 20–29, 2017.
- [28] B. Van Mele, H. Rahier, G. Van Assche, and S. Swier, “The Application of Modulated Temperature Differential Scanning Calorimetry for the Characterisation of Curing Systems,” pp. 83–160, 2006.