AUTOMATING RESIN TRANSFER MOULDING

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Keywords: Resin Transfer Moulding, Process Monitoring, Process Control

Abstract

An automated intelligent Resin Transfer Moulding (RTM) system has been developed and has been demonstrated for the manufacturing of aerospace grade composite parts. The resin's temperature and electrical resistance was measured at 8 different locations in the mould cavity. This allows for intelligent process monitoring of the cure via the electrical resistance measured at the sensors. The injection process is also monitored via the simultaneous measurement of the arrival of the resin at the sensors. This, in conjunction with pressure measurements at the inlet and outlet gates provides all the necessary information for controlling the injection stage.

After the completion of the injection stage the part is cured under increased temperature. The 8 cure sensors are used to provide a real-time prediction of the evolution of the viscosity, the degree of cure and the glass transition (T_g). It is then possible to guide the cure process allowing for automatic cooling as soon as the cure criteria have been met at all sensors. The method is proven using correlation of the electrical resistance with the viscosity and the degree of cure evolution of a common two component resin (LY556-XB3917, Huntsman International LLC). The results demonstrate the accuracy and the repeatability of the cure measurement from the start of injection to the end-of-cure for aerospace grade components. The accuracy of the estimated T_g has been validated in comparison with DSC analysis of samples from the produced parts.

1. Introduction

Research work has shown that the cure process of thermosets in composite materials' processing can be followed in real-time and *in situ* using a dielectric cure monitoring method [1]. In industrial applications data post-processing, difficulty in isolating the electrically conductive carbon-fibres, and the integration of sensors in the mould present real challenges. The Direct Current (DC) monitoring system used in this project (Synthesites Ltd) was developed [2] with the aim of optimising monitoring performance towards industrial cure monitoring. This technology was launched in 2010 and it has proven that direct measurement of the electrical resistivity of reactive resin provides valuable data such as the resin's cure progression during

composites processing. This information can be retrieved in real-time and can be used for quality control and process optimisation [3, 4, 5 and 6].
Although intelligent monitoring of composites processing has attracted significant attention, process monitoring and automatic process control is still at its infancy. The current state of the art in composite manufacturing relies simply on measuring the injection pressure and on controlling the temperature to ensure that the recipes for injection and cure are followed. It is inevitable, however, that temperature varies significantly across a composite part. As a consequence a considerable safety time margin is always added to the cure cycle to compensate for localised deviations and other process uncertainties. In order to minimise this safety margin while ensuring product quality, a new intelligent process control system was developed at the National Composites Centre (NCC).
The intelligent process control system is based on real-time feedback from the sensors. In addition this is made more robust by using intelligent algorithms in the Optiview software (Synthesites Ltd software) to guide the process based on actual process milestones rather than recipes and a fixed process cycle.
In this paper an intelligent system for the optimal process monitoring and automatic control is successfully applied to an RTM manufacturing process. The process cycle can be fully controlled using the in-line feedback from the in-mould sensors in combination with new automation of valves which open and close the feed and evacuation lines.

2. Development of the control system

Several subsystems for the intelligent composites manufacturing control system have been developed in order to monitor and control an RTM cure cycle. These subsystems consist of a process monitoring system, real-time data processing, control algorithms and automated valves. In addition the in-line communication with the press was developed so that the software which monitors the outputs from the cure and in-line pressure sensors is also able to send an output signal which enables it to control the press equipment, however for the purposes of this investigation these controls were applied manually.

2.1 In-situ cure monitoring

In composites manufacturing conventional process monitoring includes common temperature sensors that are in contact with the mould and possibly the recording of the injection and cavity pressures. The limitation of this approach is that none of these measurements can provide feedback about the actual state of the resin into the cavity. To solve this problem process monitoring systems have been developed by Synthesites Ltd which directly measure the resin's electrical resistivity and temperature. It has been extensively shown that the electrical resistivity of a reactive resin is directly related to its degree of cure. Through this methodology the intelligent process monitoring platform is able to estimate the T_g and the degree of cure of the resin in real time. Based on this fact a calibration technique has been developed and successfully applied in the cure monitoring of various epoxy, vinylester and polyester resin systems. This is referred to as an Online Resin State (ORS) module.

The ORS module is able to estimate in-line the resin's viscosity before resin's gelation, Glass Transition temperature T_g and the degree of cure until full cure is reached. At present in order to demonstrate the automatic process control, a common two component epoxy resin (LY556-

XB3917, Huntsman International LLC) has been modelled by the NCC and used in the manufacture of parts. A calibration model for this resin was developed by Synthesites Ltd in parallel with this activity. Figure 1 shows the in-mould measurements overlaid with off-line Differential Scanning Calorimetry (DSC) tests results carried out at the NCC. All testing was carried out using a DSC Q2000 test machine (TA Instruments). Samples of LY556-XB3917 resin were firstly part cured at an isothermal temperature, 140°C or 160°C, for various lengths of time. The same resin samples were then cooled to room temperature and then ran on a straight DSC ramp rate of 10°C/min from 20°C to 300°C. It was then possible to analyse the heat flow (W/g) v temperature (°C) trace from the ramp to find the glass transition temperature (T_g). As expected the T_g of the resin develops proportionally with time. Figure 1 shows good agreement between the evolution of the DSC-measured glass transition temperature and the evolution calculated by software governing the data collection for the in-mould monitoring system in two isothermal cases.

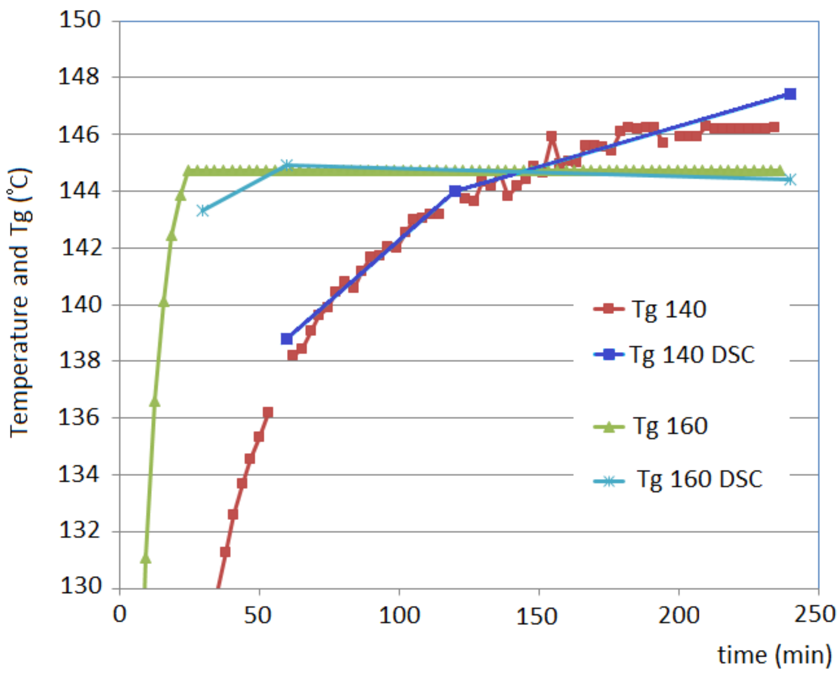

Figure 1. *In-mould measurements of T_g using the calibration model and the resistance and temperature measurements for two isothermal cases (140°C and 160°C) and T_g as measured by DSC afterwards.*

2.2 In-situ injection control tool

In addition to the eight resistance sensors (Optimould, Synthesites Ltd) the injection is monitored by inlet and outlet gate pressure sensors and temperature sensors (thermocouples). As can be seen in Figure 2 the absolute pressure sensor is located at the inlet valve in order to monitor the injection pressure while a vacuum sensor (absolute pressure sensor) has also been installed at the outlet gate.

Figure 2. *Image of an automatic valve with a pressure sensor located at the feed line to measure the injection pressure in order to control injection*

The automation of the RTM process requires a reliable control of the opening and closing of the feed and evacuation lines. An automatic system has been developed to control this as shown in Figure 3. This system shown in Figure 3 can be controlled automatically, using signals from the Optiview software which opens and closes the valves using a data received from the sensors at the feed and evacuation lines. The control of these lines is logged within the software against time in such a way that the lag between the command to open the valve and the actual opening of the valve is captured fully.

Figure 3. *The automatic valve mechanism for the robust and secure control of the opening and closing of the feeding line.*

2.3 Intelligent cure cycle control software for optimal RTM processing

The cure cycle can be optimised in two ways through the Optiview software. Firstly the injection process is controlled via sensing which determines when the resin injection is complete. This is achieved via feedback from the resistance sensors which shows when the resin has arrived at those. This data is then used in concert with the data from the feed and outlet lines to determine when the injection has been completed. At this stage the software automatically progresses to the next stage of the injection process where the heating ramp to the cure temperature begins.

The second stage of optimisation takes place during the cure process itself. The resistance sensors are able to determine the T_g of the resin at their locations using data from ORS module which has been verified using DSC as discussed previously. Once a T_g threshold has been reached in all cure sensor locations the software is able to send a command to the press equipment allowing to start cooling. The press can also potentially start the de-mould process once the part has reached a prescribed temperature.

At this stage the data recorded by the Optiview software has been used to manually input changes to the injection and press equipment. This functionality is already in place however the integration with the press equipment has not yet been demonstrated.

3. Resin Transfer Moulding (RTM) equipment

All panels at the NCC were manufactured using a 100T hydraulic press (P.J. Hare Ltd) with a maximum temperature capability of 400˚C. The injection process for the specific resin system in use is isothermal and the temperature increased after injection completion to achieve the cure of the moulded composite part. The injection machine CIJECT-3 (Composite integration Ltd) was used with demand value for the injection pressure p=4 bar (absolute) and resin temperature and resin feeding line temperature are both set to T=60°C. The reference temperature profile for the cure step following injection completion is detailed on Figure 4. An image of the press equipment is shown in Figure 4. The panels were made using a specially designed and manufactured circular steel mould tool (Figure 5). This tool incorporated a new sensor [9] the sensor was specifically designed with a housing which minimises the thermal field disturbance caused by the sensors. The sensors also incorporate a glass fibre pad in order to electrically isolate the sensors from the carbon fibres in the preform.

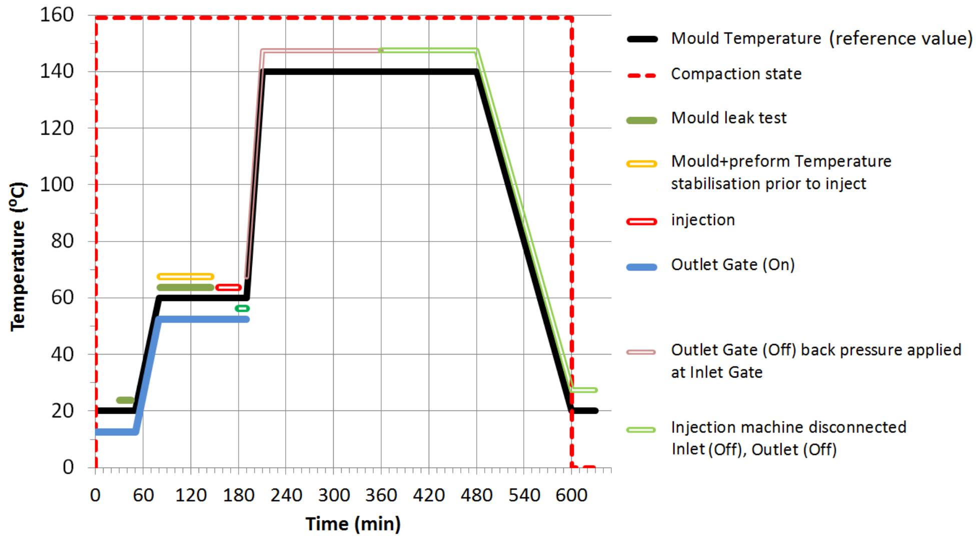

Figure 4. *The RTM equipment and the process map.*

Eight sensors were installed in the steel mould as shown Figure 5. The pattern was chosen in order to provide information about the resin arrival time at the two main axes: sensor 1 at the inlet gate and sensors 2 and 3 aligned to the 0˚ direction of the composite preform. Sensors 4 and 6 are aligned to the 90˚ axis whilst sensors 5 and 7 are at 45˚. For verification purposes, there is also a sensor at -45^{o} (sensor 8). The purpose of this configuration is to account for variations in the permeability of the preform in different directions which would be expected to arise due to the alignment of fibres within the preform.

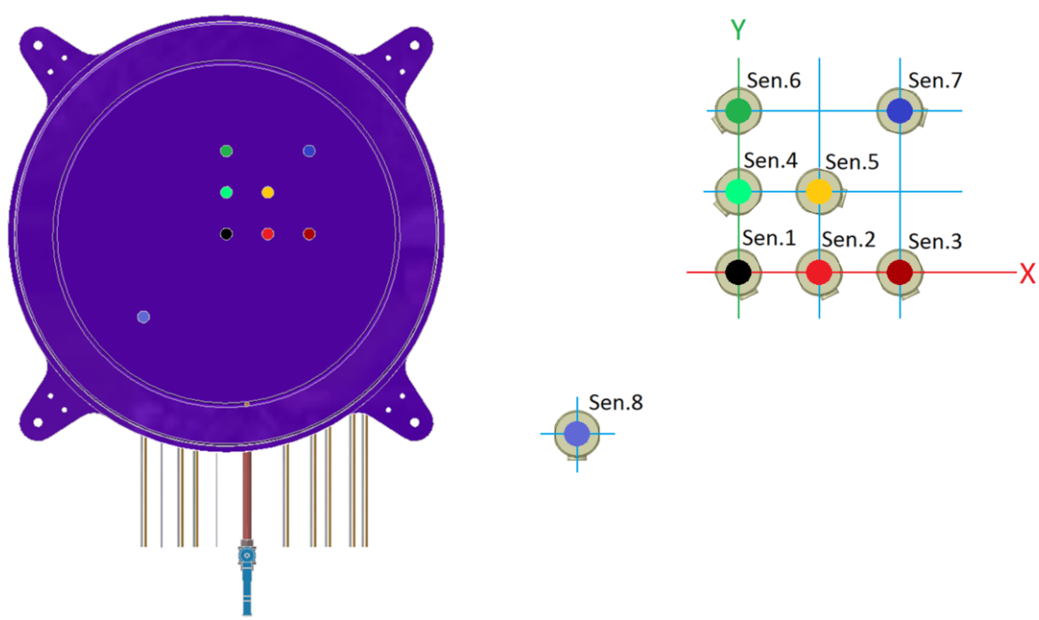

Figure 5. *Image of the open mould showing the location of the 8 cure sensors*

Data from the eight resistance sensors were recorded and displayed on a laptop using the Optiview software together with the injection pressure and vacuum measurements. Online calculation and the display of the resin's properties and the control actions are also recorded and displayed by the same laptop shown also in Figure 4. After recording the resin arrival, the cure sensors continuously measured the resin's resistivity and temperature and through the resin calibration model (ORS) the resin's viscosity before gelation and degree of cure and T_g after gelation were calculated.

4. Results

Using the industrial set-up described in previous sections numerous trials have been successfully executed. A typical recording of one of the injection and cure trials can be seen in the Figure 6 below where the history if resistance and temperature for the eight resistance sensors together with the inlet injection pressure are shown. Before the resin enters the mould cavity the start of the injection can be seen as the pressure recorded by the sensor at the inlet line increases. At the injection stage the resin arrival at each sensor can be identified at the point where the resistivity shown by the sensor drops significantly (Figure 6).

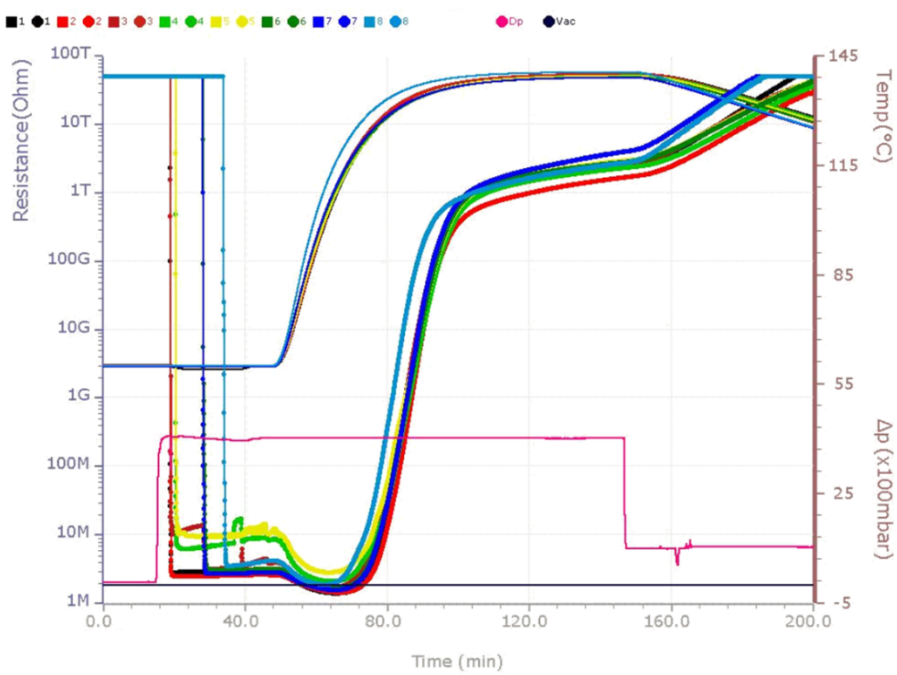

Figure 6. *Resistance and temperature at the eight sensors together with the inlet and outlet pressure readings during the complete duration of an injection for one of the RTM trials*

Following the injection phase, the press platens are heated to the cure temperature of 140˚C. At this stage the viscosity of the resin is recorded until gelation occurs. Furthermore the calibrated values of T_g are recorded after gelation occurs. This is calculated using the validated data inputted in to the ORS calibration model. Figure 7 shows an overview of the data monitored within the ORS as well as a closer plot of the T_g development during the cure process.

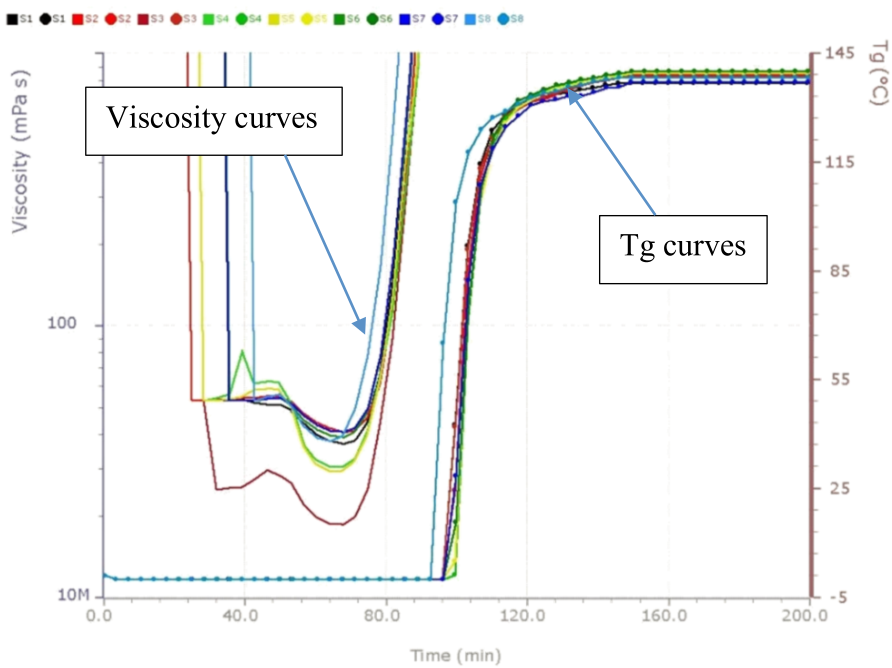

Figure 7. *Display from ORS tool showing In-line viscosity and T_g monitoring at the curing phase*

5. Concluding remarks and future work

The in-situ process correction tool has been developed to optimise and automate composite manufacturing processes. The developed process control tool ensures near-optimal performance, robustness and is applicable to any liquid composite moulding process. In the present case the in-line corrective capability of the control system has been successfully demonstrated in an RTM process where the resistivity signals from the in-mould sensors were recorded by the Optiview software. The software provides live data about the process and it is also capable to connect to the press equipment enabling it to be automatically controlled such that the cure time can be optimised.

The next achievement will be implementing the enhanced liquid composite moulding process so that the data taken from the in-mould sensors is used to control the process itself. An example of this will be using the in-mould sensor data and the inlet/outlet pressure values to control the flow during injection. It would also be possible to control the temperature of the press platens such that isothermal phase ends once the T_g has reached a predetermined level. This approach would result in optimising equipment time, which would in turn achieve process cost reduction.

Additional sensors could be used at the outlet gates in complex part generation. Within the EIROS project the next step will be to continue to test the developed process control system using a modified resin material which will incorporate functionalised nano-materials. This case will demonstrate the effect of the nano-particles upon the cure characteristics of the resin.

Acknowledgements

The authors acknowledge the support of Nedas Zvirblys, Georgios Stamatopoulos and Mindaugas Sasnauskas in performing the RTM manufacturing process. The support and advices from Miroslav Stojkovic are also thoroughly acknowledged. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 685842. Paper clearance and collaboration with the EIROS partners is gratefully acknowledged.

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