Automatic process monitoring and control for composite production

In composite materials production, there is an urgent need for non-intrusive process monitoring and control systems that would automatically optimize and tune production in real time. Previous research has shown that the dielectric monitoring technology can be used to monitor the processing of thermoset [1] and thermoplastic [2] matrices for composite materials production. So, by combining electrical and temperature measurements with material models, resin viscosity and degree-of-cure can be calculated in real time in the mould or die. These models can be used either offline to provide the optimal process cycle, or online to provide optimal, real-time process control [3]. This is the target of the iREMO project (www.iremo.eu), an EC-funded collaborative European project that involves CEMCAT, Sora Composites Group and Atoutveille (Fr), NTUA and Synthesites (Gr), Inasmet and Acciona (S), BIBA (D), UNewcastle (UK) and Karnic (Cy).

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In the iREMO project, the electrical resistance of the resin is measured directly using a steady-state (DC) electrical excitation instead of a range of sinusoidal excitations (AC). This gives a context similar to dielectric cure monitoring, but with improved performance. Although several sensors and DC amplifiers have been proposed in the past [4,5], the first commercial system was only recently made available for use in lab and industrial-scale applications.

Process monitoring

In dielectric cure monitoring, a frequency range of sinusoidal voltage or current excitations are applied to a pair of electrodes, which are in contact with the material being investigated so that the post-processed feedback provides information about the material state. The use of DC conductivity for process monitoring purposes is even older, although no significant progress in monitoring the complete composite processing cycle has been made known until recently. Synthesites recently presented a new DC-based process monitoring system with a clear focus on industrial applications for composite materials. The new system measures the material's resistivity and temperature using durable sensors and suitable electronic systems capable of in-situ monitoring the full transformation of a thermoset resin; i.e. from very low viscosities at high temperatures to fully cured resins where the measured resistance varies from 106 ohms up to 1014 ohms. Comparisons between DC

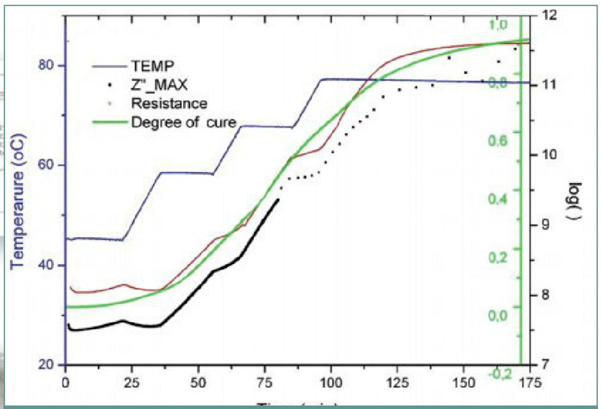

Fig. 1: Simultaneous measurements of imaginary impedance max (Z'' max) and electrical resistance on the black right axis and temperature (left axis) together with the theoretical degree-of-cure (green right axis) during the mid-temp curing of an epoxy system

sensing and commercial dielectric systems measuring resin impedance showed the superiority of DC sensing, particularly after gelation, as can be seen in Fig. 1. Obviously, there is a deficiency of the dielectric system in measuring higher than 0.80 degree of cure, whereas the measurement quality of the DC monitoring system is very stable, even in the end-of-cure region and at temperatures as low as 20°C. Besides the end-of-cure area, the electrical measuring system can be used for monitoring resin viscosity in the cavity in order to verify the onset of viscosity rise, the quality of the resin matrix or other process deviations. The viscosity of a polymer is closely related to its electrical resistance. This was experimentally shown [6] using DC monitoring for a polyester with 2% MEKP (Fig. 2). Furthermore, DC sensing is cheaper than dielectric monitoring and uses more flexible, robust sensors which can be installed in several locations in the mould, in the die, in the feeding or evacuation lines, so that global process monitoring is feasible. All these advantages provided iREMO with appropriate tools to deal successfully with optimised process control of composite manufacturing in the whole range of industrial applications.

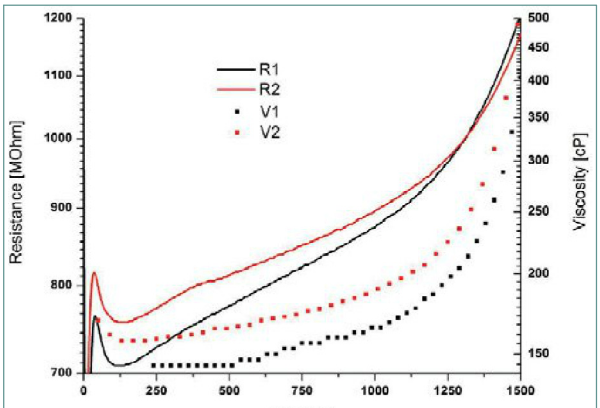

Fig. 2: Simultaneous monitoring of electrical resistance (left axis) and viscosity (right axis) in two experiments with slight temperature variations for a polyester resin with 2% MEKP

Process deviations

The widespread use of composites and the need for cost reduction have pushed materials and craftwork in composites manufacturing to the limits, so there is an evident need for automation to increase productivity and minimize rejection. The latter is especially important as materials and recycling are very costly, especially for carbon-fibre parts. Changes to reduce costs and increase productivity have included moving production from autoclaves and prepregs to heated moulds, dry fabrics and low-viscosity resins. These changes introduced several deviations in the manufacturing process that need to be kept

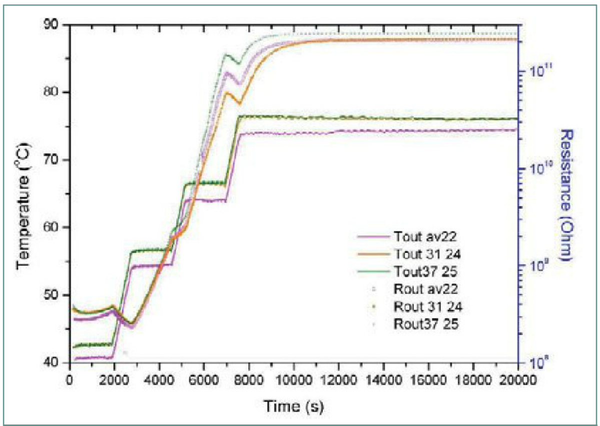

Fig. 3: Resistance (right axis) and temperature (left axis) history in curing an epoxy system with nominal mixing ratio (av22), 2.2% more hardener (Rout37 25) and 2.2% less hardener (Rout31 24)

under control for optimum output. At present, the industrial approach focuses, for example, on extending the cure cycle to ensure full consolidation, but this is obviously not the optimum approach. However, several deviations will emerge when we try to reduce the cure cycle. For example, the in-situ mixing of two or three different components of a resin system just before injection may result in variations in the mixing quality or mixing ratio in some instances. In a fixed cure cycle, these variations, even if they are small, might cause some quality deviations. With the DC-based process monitoring system, as can be seen in Fig. 3, we can clearly see when the mixing ratio deviates from the set-point as little as 2.2%, so corrective action can be taken to maintain quality and productivity. Other deviations include temperature set-point deviations and expired resins. The challenge involved in the iREMO project is to deal with these deviations in real time.

Process control

A process control algorithm is under development to take full advantage of the process monitoring capabilities. The control platform will consist of several control algorithms, from fairly simplified ones based on a combination of events and rules [2] to very complex ones using real-time process models [3] that will cover the whole range of composites processing. The former can be applied in a straightforward manner using basic knowledge of the process and existing experience but it cannot be optimal. The rules need to be updated for each process and the specific rules need to be tested and verified. On the other hand, model-based control requires detailed information and process models as well as quantified targets and process constraints but it can be optimal and can be used in more complicated processes such as curing of thick components with significant exotherms. A rule-based control system was developed for the present study as it is more general and can be applied directly. One of the main control variables that can be used during the process is the thermal cycle, i.e. the temperature profile that can be extended, shortened or increased to maximum temperatures.

Besides the productivity increase, the main advantages of the iREMO project are energy reduction and scrap reduction. Furthermore, a new type of sensor (Synthesites' Inline sensor) will be used to further enhance environmental protection by controlling and eliminating resin purging and acetone cleaning after each production cycle.

Industrial applications

To check the performance of the process monitoring and control systems in industrial applications, the system was installed in a fast RTM production system for epoxy/glass/carbon-fibre body panels that has been operating for ten years at a Sora Composites production site in France. In this set-up, the resin is injected through a periphery feed line at one end of the cavity and exits from the middle of the cavity under constant flow, so injection pressure reaches up to 20 bar. For process monitoring, a single durable sensor was installed at the periphery of the cavity (Fig. 4) to measure the resin's electrical resistance and temperature.

Fig. 4: Flash-mounted sensor at the periphery of the cavity

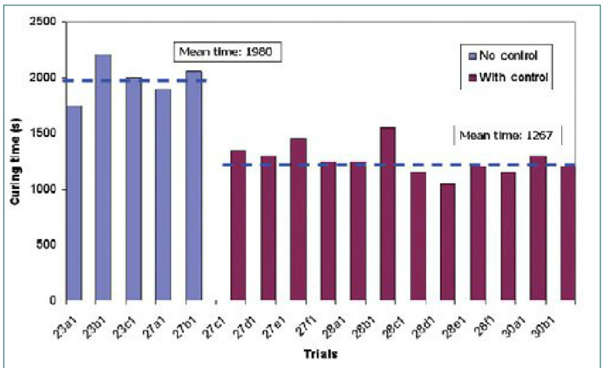

Fig. 5: Curing times for an RTM production line before and after cure monitoring and control – mean cure cycle time is 36% faster

During normal production, the sensor did not receive any special treatment from the operator and did not present any problem related to the presence of carbon fibres in the mould cavity. Based on the experts' knowledge and experience, it was possible to raise mould temperature by 20°C without any problem, but with obvious advantages. The real-time validation of the resin state in the mould during processing was supported and confirmed by the use of this monitoring system.

In another RTM industrial application, a 36% faster cycle time (Fig. 5) was achieved [7].

Conclusions

Real-time monitoring of production can provide the foundation for process automation in a variety of composite processes. The advantages and robustness of the system ware proved in practice, and its results helped to improve the production performance at first hand. The aim of the iREMO project is to use this foundation to provide composite manufacturers with intelligent tools and systems that can improve production without the burden of extended and expensive analytical investigations. ■

More information: www.iremo.eu

Acknowledgments

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