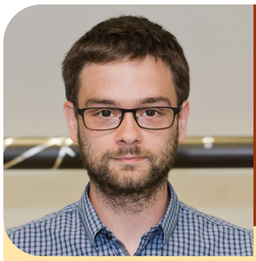

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ABSTRACT

PRESENTATION

PAPER

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CURE MONITORING OF FIBRE REINFORCED COMPOSITES USING INFRARED IMAGING AND DATA ASSIMILATION

Efficient utilisation of resources and optimisation of processes are critical in reducing the environmental impact of the manufacturing industry. One example of such a process is the large-scale production of fibre-reinforced polymer (FRP) composites using thermosetting polymers. This process requires additional heating to elevated temperatures in industrial autoclaves to enable the polymerisation (known as curing) of the matrix material. The curing process is typically carried out with fixed, predetermined parameters to ensure a certain level of material quality. However, the lack of monitoring systems necessitates the inclusion of a safety margin in the curing time. This approach, while ensuring quality, does not consider aspects of energy efficiency and suggests the potential for significant energy savings. The Degree of Cure (DoC) and the rate of cure are highly dependent on temperature and follow an Arrhenius law. Therefore, if there is an inhomogeneous temperature distribution in the autoclave or if the part experiences an increase in temperature due to exothermic heat generated during polymerisation, it can lead to uneven curing. Therefore, continuous and spatially resolved monitoring of the DoC would enable the operator to optimise process parameters and stop the process early if there are unacceptable deviations in quality, thereby reducing waste and saving energy. As the polymerisation of the matrix material affects various material properties, the DoC can be measured through different methods (e.g. dielectric sensors). However, these methods only allow for local measurements of the DoC. Active NDT approaches like Active Thermography, which can be used to monitor the spatial distribution and evolution of material properties, cannot be used since excitation sources (e.g. lasers, flash lamps) are hardly integrable in an industrial autoclave.

In this work, a passive monitoring system for autoclaves was developed. It predicts, in a spatially resolved manner, the DoC of FRP parts based on infrared imaging and thermal measurements. Although the temperature is a major influencing factor that affects the curing behaviour, in general it is not possible to directly extract the degree of cure only from the part temperature. Only if the exothermal reaction is large enough it could be used to solve an inverse problem. Therefore, a method was developed that does not rely on the exothermal reaction but is still able to predict the DoC. Utilising Ensemble Kalman Filter theory, a predictor step, which involves a finite element simulation and thermal measurements, was combined with a corrector step based on infrared imaging data. The finite element model simplifies the complex heat transfer problem and allows for a fast prediction of the DoC. Together with the heat conduction model, the curing behaviour (i.e. the kinetic model) is encoded in the predictor step of the Kalman filter. To accurately predict the DoC, a material characterisation using dynamic scanning calorimetry (DSC) was carried out to estimate the parameters for the kinetic model. Since the curing process takes several hours and the prediction and correction steps take only a few minutes, the developed method can be considered as real-time capable. The monitoring system utilises a microbolometer camera enclosed in a cooled housing. It can withstand ambient temperatures up to 200 °C and atmospheric over pressures up to 8 bar.

The system was tested on carbon FRP samples in an industrial oven. Several experiments with different process parameters were conducted to qualitatively evaluate the sensitivity of the developed method. For validation a reference sensor which measures the dielectric properties of the thermoset during cure is used. The comparison between the reference sensor and the prediction shows in general a similar behavior. The reference measurements show artifacts due to the susceptibility of the sensor to effects like the viscosity of the resin matrix and a strong temperature dependency of the dielectric properties of the material. This makes the interpretation more difficult but allows a higher sensitivity to later stages of the cure, compared to the developed prediction system. Due to the local measurements of the reference sensor only a single point can be monitored. In contrast to this, the imaging system can visualise an inhomogeneous curing process, especially in the early stages of the process due to an inhomogeneous temperature distribution and the properties of the part.

The experimental validation and comparison between the results of the Kalman filter and the dielectric reference sensor carried out in this work is an important step towards implementing the developed method in real-world applications. The ability to adapt the prediction step to complex and large structures is a clear advantage when monitoring large composite structures. A potential extension of the method is to combine the dielectric sensor with the thermal imaging in order to improve the accuracy of spatial predictions.