Identification of thermal properties and process parameters of quasi-isotropic CFRP under uniform in-plane conditions of induction heating

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Abstract. Control of thermal processes in composite manufacture requires an assessment of the entire temperature field at any given time throughout the heated area. This can be achieved by constructing a digital twin of the process that can predict the temperature in the regions that are not covered by sensors. Digital twinning requires knowledge of thermal properties and process parameters such as the heat transfer coefficients. These need to be assessed in real time and specifically to the manufacturing arrangements, so accurate identification of thermal properties is a key step for the optimisation of the process. Hence, a concurrent experimental modelling protocol is developed that enables efficient process identification in the context of inductive curing of composites. This entails (i) thermal excitation of the structure by an induction heater, (ii) acquisition of temperature through-thickness of composite laminate with thermocouples and/or in-plane field with thermal camera; (iii) numerical identification procedure of material properties and process parameters, (iv) process modelling and in-situ model validation. The identification process deploys minimisation of the difference between the model output and the sensor measurements using nonlinear least squares. It updates (using an iterative calculation) the initial estimates of the process unknowns. The method is currently applicable to cases of relatively small in-plane heat transfer and is tried for a quasi-isotropic carbon fibre reinforced plastic (CFRP) panel, but can be extended to more general cases.

Introduction

Anisotropic behaviour of composites is not limited to their mechanical properties but also includes their thermal properties. Knowledge of the material thermal properties is a necessity for monitoring thermal manufacturing processes. Methods used so far to attain knowledge of the thermal properties are lengthy operations occurring at laboratories. Laser flash analysis method (LFA) is able to measure thermal diffusivity by applying heat on one side of a sample and measuring the time needed for rise of the energy to the other. Heat capacity could also be found through differential scanning calorimetry method (DSC). The existing measuring techniques operate with relatively small samples and require elaborate processes for sample preparation and data processing. In composites manufacturing, it is important to assess the material at the manufacturing stage, flexibly examine various areas in components, and track the evolution of the properties throughout the process. Only then, a digital twin can be constructed that would enable reliable process steering and control.

Motivated by this challenge, this study proposes a new concurrent experimental-numerical method to identify thermal properties of a composite part. This method interrogates material using induction while acquiring a temperature feedback using thermal camera and/or thermocouples. The property identification algorithm is based on in-situ calibration of heat transfer model. The parameters of the model (thermal properties, induction parameters, heat transfer coefficients) are determined through least squares regression calculations and Latin Hypercube sampling [1] of initial parameters. The induction generator supplies heat in short pulses to sufficiently challenge the parameter identification procedure and provide rich data for the fit. Induction used in these approaches operates in specific resonant frequency (available range 150-400 KHz of the equipment used) and hence, relies on Joule heating in electrically conductive susceptor. This is directly applicable for conductive composites, such as carbon-fibre based, and may need backing metal sheet, for non-conductive composites, such as those that are glass-fibre based.

The methodology for the inverse calculation of material properties is known and has been successfully demonstrated in past. Humfeld et al. [2] used a machine learning methodology based on tailored physical modelling of autoclave heating process of composite. This methodology is also able to capture unknown process parameters (i.e. convective heat transfer coefficients) and manages to control the heating process in real time giving an optimised curing solution during resin infusion. In the current work advantage is taken of the rapid, localised, volumetric heat supply [3] and direct delivery of the heat to material. These are major advantages of this technique, promising responsive interaction with the material and hence, fast parameter identification routine. The current study departs from the thermal problems assumption, where the through thickness heat transfer is dominant over that for the in-plane, having a relatively uniform in-plane distribution of temperatures.

For many applications, it is pragmatic to minimise the number of sensors for the data acquisition. Hence, the study explores the minimal number of the acquisition points required to achieve correct representation of material properties. This is done by a virtual experiment (where properties are known but kept hidden from the algorithm). The response of the material is modelled using a heat transfer model coded as one-dimensional PDE with predefined heat transfer coefficients, through thickness thermal conductivity, heat capacity, induction heating parameters and convective boundary heat transfer coefficients. The interrogation module then attempts to decode the hidden material properties and process parameters. There are seven unknown parameters that must be deduced through the interrogation procedure. The algorithm was proved to capture the unknown properties with a very low error tolerance with little computational expense. The success of the virtual exercise prompted the application to a physical experiment on a CFRP panel under specific cyclic heating while having feedback from thermocouples and thermal camera (Figure 1), in an attempt to validate the effectiveness of the algorithm under realistic conditions. The placement of thermal acquisition is with thermal camera on the surface and with thermocouples (TC) buried through the laminate thickness. A bespoke induction heating coil is used, which was designed to provide uniform in-plane heating satisfying the assumption of dominant through thickness thermal conductivity.

Once the digital twin is established, the system can be used in closed loop control to steer the process (Figure 2). The coil current is adjusted to tune supplied heat and uses temperature feedback not only at the measurement points but throughout the thickness of the laminate.

Conclusion

In this study a methodology is proposed for the identification of the thermal properties and the process parameters of a material under induction heating. Virtual testing showed very good performance with convergence of the initial estimations of the unknown parameters to their true values at little computational expense with high precision tolerance. The tool is applied in an experimental induction setup for optimisation of its performance.

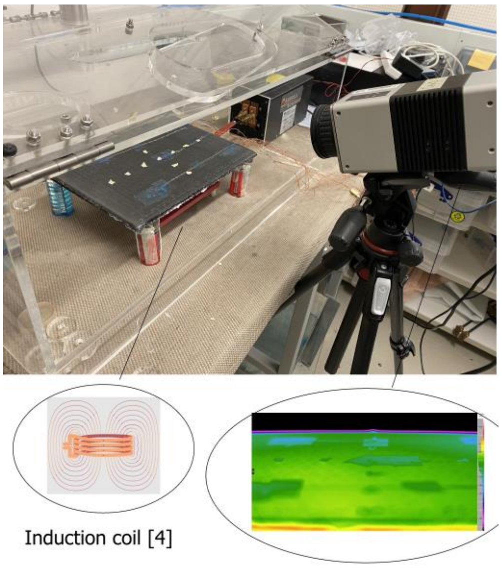

Figure 1. Experimental setup in the lab for identification of material thermal properties and process parameters

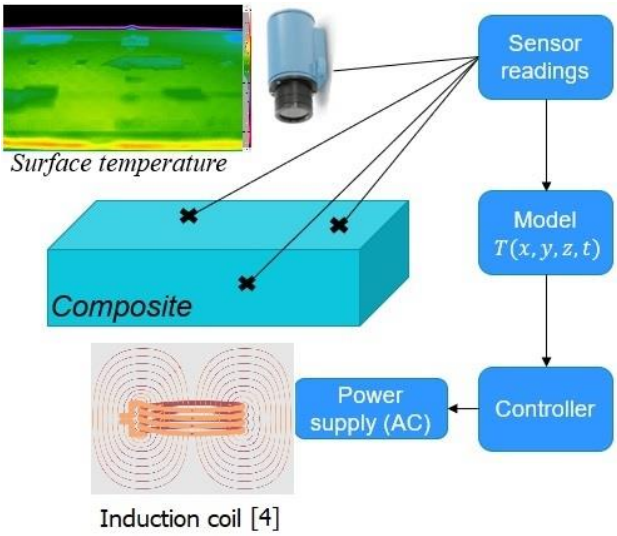

Figure 2. Block diagram of closed loop system configuration

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