On the Embedding Vascular Networks into Thick Composite Parts as Thermal Management Tools for Cure Processing: Experimentally Proving its Feasibility

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The management of thermal conditions and processes during the cure of advanced composite parts is critical to the quality of the item produced. In thick sections thermal management becomes an especially major challenge, as due to the through thickness temperature gradients defects such as warpage, delamination and residual stresses can occur, which particularly develop at features such as thickness changes and complex double curvatures [1]. Currently, autoclave and oven manufacturing techniques of both resin infused and prepreg parts, rely on using cure cycles specified by the material manufacturers and which are obtained via experimental testing. These cycles aim to consistently provide the highest quality part through high temperatures and pressures. However, these cycles are not optimised for every geometry type or extremely thick sections.

Many potential thermal management issues arise in the cure processing of thick sections. Firstly, the heat from the oven or autoclave does not reach all points simultaneously, but leads to significant temperature lags as the part heats up. Secondly as the cure reaction is exothermic due to the formation of bonds as the 3D-network is built-up, issues around heat dissipation can be observed, which leads to thermal spikes which in some cases causes local matrix degradation. Thirdly, the use of conventional cure cycles can create other undesirable effects including physical, chemical, and hydrothermal aging; allowing the formation of a high volume of voids and delamination [2]. Experimentally it has been seen that thick sections show build-up's in residual stresses, and these result from chemical shrinkage during cure that is constrained by the fibres. Thermal mismatch between the fibres and cured resin also contribute to the residual stress seen [1]. The presently accepted industrial route for the cure of thick sections is often limited to low temperature long duration cure, or elevated cure with multiple dwell and ramp steps; to reduce the thermal gradient through the part and prevent excessive thermal spiking. However, when curing a very large part this becomes very expensive and there is increased risk of ensuring a uniform cure in the part has a complex geometry with variable profile.

In recent years numerous studies [2-5] have brought to light potential methods for optimising thick-section curing. The common theme of all the methods is that they aimed for better control of the heat generated in the exothermic reaction, aiming to produce parts with homogenised cure through-thickness; and can be subdivided into cure by external or internal heating. External heating look at methods which heat a part more efficiently, effectively curing the part from the 'inside-out' *i.e.* microwave heating [3], ultra-violet (UV) curing, or electron beam [4]. In contrast internal heating curing methods provide an additional heating source from within the composite, in literature the most widely discussed example of this is resistive heating [5], although vascular networks are gaining recognition. Vascular networks within composites have been exploited in self-healing [6] and in-use thermal management as active/passive cooling pathways though the laminates [7] and have not yet be explored for thermal management during cure. In 2016, O'Donnell *et al.* [2], modelled vascular networks for cure process optimisation. In this work a finite element (FEA) model was developed, using an additional Fortran subroutine (HETVAL) to calculate the heat generated and to track the evolution of the degree of cure with time. Using a gradient approach, the position and temperature of these vascules was also optimised.

This work builds on those modelling results of [2], developing a lab-scale setup as a proof-of-concept that experimentally verifies the optimised through-thickness cure of a thick composite section can be achieved. The proof-of-concept setup, as shown in Figure 1, enables effective pumping of silicone oil at a controlled temperature (volumetric flow rate 27 L/min, 40-200 °C) through a vascular network (hollow pultruded carbon fibre rods) held within an Aluminium mould.

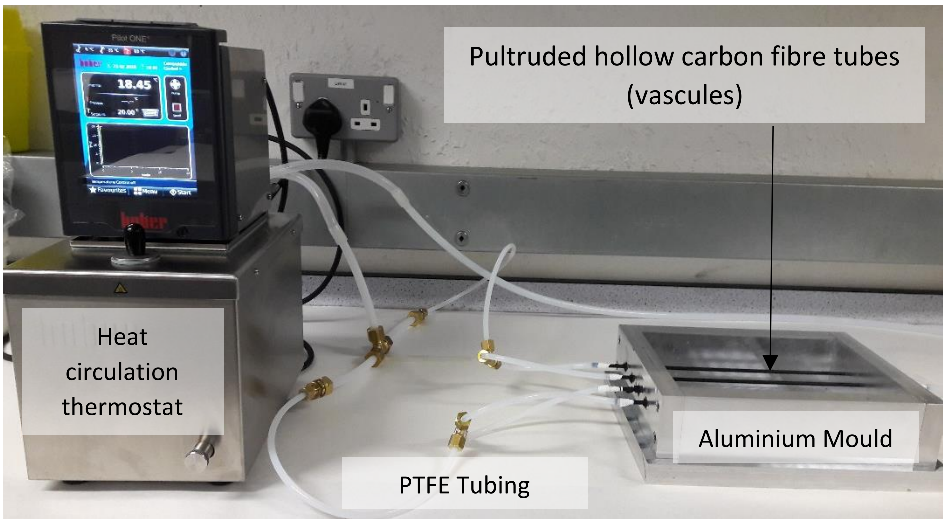

Figure 1: Lab-scale setup.

The work to be presented herein will be focusing on the results from initial experiments, which will demonstrate the proof-of-concept and feasibility of vascular networks to aid curing of thick composite sections. Firstly, thermal imaging of the vascules in a body of silicone oil will be conducted to monitor the temperatures of the silicone oil near the vascules to access thermal efficiency of the vascules and system. And image how the energy is conveyed to the whole body from the vascules. It is vital to assess the systems thermal efficiency to see if the temperature set at the circulator can be seen at the vascule. This will then lead into accessing the ability to achieve better resin cure homogeneity using the vascules. This will start with simple curing systems such as silicone rubber and move towards epoxy resins. The use of these vascules to cure prepreg will also be evaluated as part of these initial investigations. To access cure homogeneity, the degree or cure for samples taken through the cross section of the part will be assessed using differential scanning calorimetry.

Acknowledgements

The author would like to thank Dr Yusuf Madhik and Dr Matthew O'Donnell for their continued help and support with this project. This work was funded by the Engineering and Physical Science Research Council as part of the EPSRC Centre for Doctoral Training in Advanced Composites for Innovation and Science. Grant number: EP/L016028/1. This project is also supported by Hitachi Chemical Company Ltd.

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