NOVEL MANUFACTURING METHOD FOR FRP COMPOSITES WITH A MULTIFUNCTIONAL VASCULAR NETWORK

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ABSTRACT

Fibre reinforced polymer composite materials are becoming more widely adopted for high performance industrial applications. The hierarchical nature of these materials offers a unique opportunity to incorporate multi-functionality whilst maintaining their excellent mechanical properties. Ideally, multifunctional composites can be configured to mimic natural biological systems. For example, the fabrication of an embedded array of hollow channels in the form of a vascular network can be utilised to provide a variety of functions, including self-healing, thermal management or sensing and actuation [1].
Previous research has shown that vascular integration into FRP laminates can be achieved through incorporation of material in-situ (hollow glass fibres [2] or polyether ether ketone (PEEK) tubing [1]), or through a “lost-wax” process using solder [3,4]. This study considers a novel manufacturing method for hollow channel fabrication, with the intention of limiting damage to the FRP laminates during post-cure channel manufacture, using Polylactic Acid (PLA) coated Nichrome wires to produce vascular networks running through multiple levels of the FRP ply stack. Low voltage resistive heating of the Nichrome wires enables their removal from the FRP post cure, even in complex shapes. The successful manufacture of an Animalia inspired network design was achieved within a glass fibre reinforced polymer (GFRP) panel. Furthermore, for panels subjected to steady state heating, the branched network displayed far greater cooling potential than the parallel channel design. This suggests the possibility to manufacture more complex networks within FRP laminate structures, facilitating their multi-functionality, namely for thermal management or self-healing applications.

1. INTRODUCTION

The use of biologically inspired networks within composite laminates has been considered for a variety of functions, including but not limited to: sensing, healing and thermal management [1]. Incorporation of multifunctionality can improve the longevity of components, directly through self-healing, or through increasing permissible temperatures of operation through self-cooling. As the temperature of composite components approaches the glass transition temperature of the matrix, thermal stress induced ageing greatly increases [5,6], thus the incentive for integrated cooling.

The in-situ manufacture of biomimetic vascules within FRP laminates has been considered in some detail, using sacrificial solder or hollow tubing, running parallel to adjacent fibre reinforcement, similar in form to those seen in *Plantae* [3].
This study will look at the concept of multiple bifurcations with hierarchical vascular geometry which is mimetic of the circulatory systems of *Mammalia*, or more broadly of *Animalia*. The key difference is the separation and later coalescence of the introduced fluid flow. As such, this paper considers whether the in-situ manufacture of *Animalia* inspired 3D branched vascule networks within FRP laminates is possible, and investigates the thermal management capability compared to *Plantae* inspired parallel vascules. This study should be considered to serve as a proof of concept of the integration of branched vascular architecture into FRP laminates.

2. MATERIALS AND METHODS

Pseudo vascular network was incorporated into composite prepreg using Nichrome wires “dip-coated” in a 10% PLA solution in 1,4-dioxane, which were subsequently removed post-cure. Figure 1 shows the wire dip-coating process used to produce around a 0.25mm PLA coating.

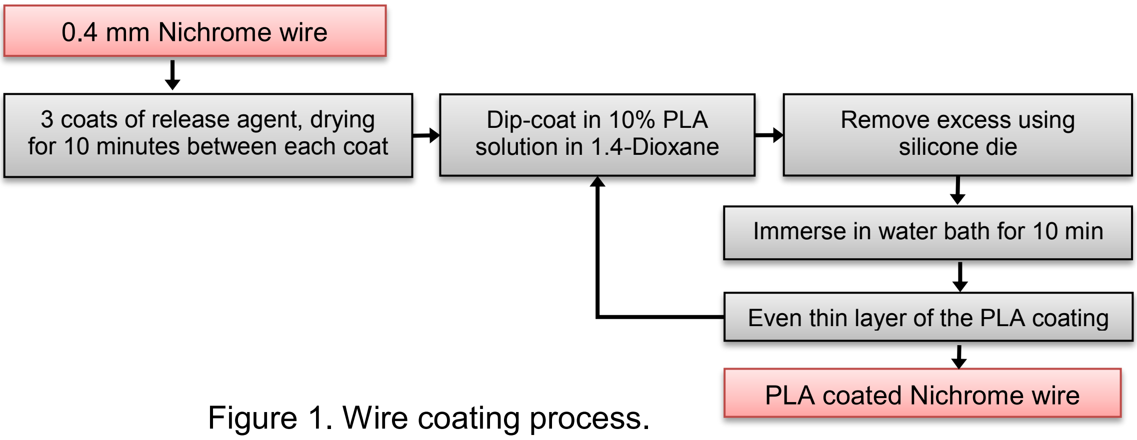


Figure 1. Wire coating process.

The removal of the Nichrome wire was achieved by softening the PLA coating through the effect of resistive heating of the Nichrome. This process significantly decreases the mechanical force needed to withdraw the wire. The remaining PLA can then be removed through injection of chloroform solvent alternated with flushing with water.
E-glass FRP and carbon FRP (CFRP) pre-impregnated with high toughness SE-70 epoxy were used to manufacture two laminated panels with a stacking sequence of (“bottom-up”): [90, +45, -45, -45, +45, 0//0, -45, +45, +45, -45, 90], cured at 70° C for 16 hours.
In order to limit the adverse effect of the incorporation of a network preform, “cut outs” were made into the plies in which the channels will be accommodated, minimising distortion to plies adjacent to the wire inserts.
For the thermal management testing, the panels were heated to temperatures of 50, 60 and 70˚C. The cooling system consisted of a peristaltic pump, pumping iced water held at 0˚C at a total flow rate of 30 ml/minute. In addition to the temperature profiles, values at locations A-G, (Figure 2A), were logged for every second of the test period. The panel cooling profile was observed using infrared imaging for a 5 minute application of the cooling system.

3. RESULTS AND DISCUSSION

GFRP panels where manufactured with branched and straight channels labelled as GB and GS respectively alongside the control panel with no network labelled as GC. Two further CFRP panels with and without network of straight channels were also manufactured labelled as CS and CC.

Figure 2A (bottom, right) shows the successfully produced sample with incorporated branched network (GB). Example microscopy images of the vascules pre and post-chloroform injection are showed in Figure 2B, which provide greater insight into the achieved vascular architecture.

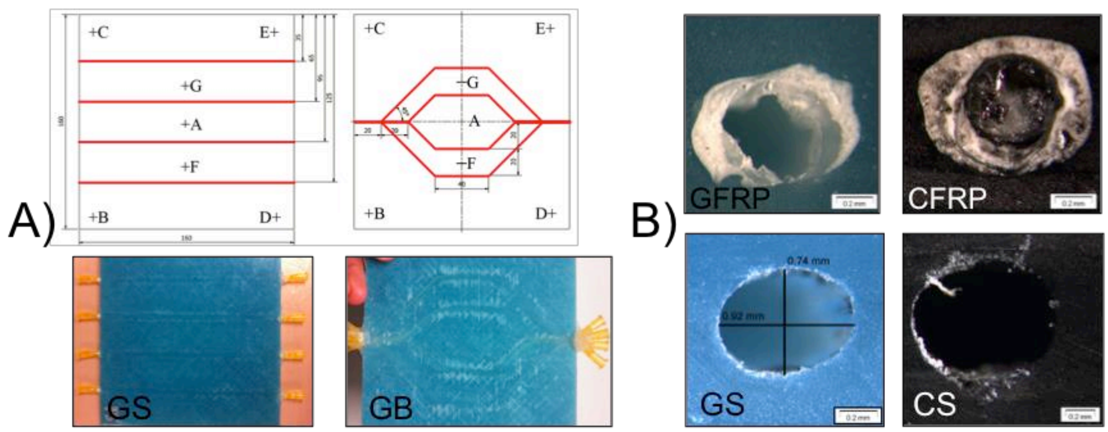
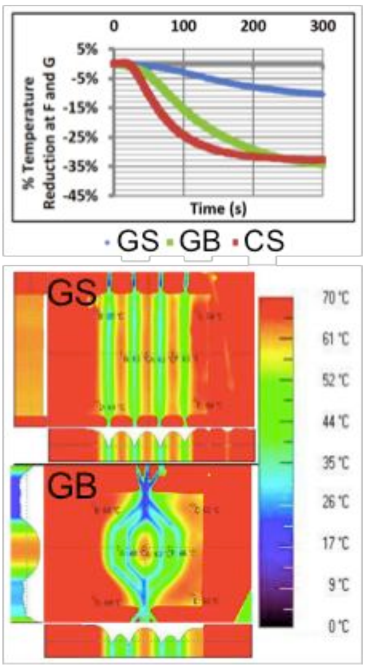


Figure 2: A) *Plantae* (straight) and *Animalia* (branched) inspired vascule configuration (dimensions in mm). Pictures below show a manufactured laminate with visible vasculature. B) Straight vascules before and after PLA removal.

Figure 3 shows the thermal imaging for the cooling patterns of the Animalia inspired network in panel GB compare to the straight channels in panel GS, with the GFRP laminate starting at an approximate steady state temperature of 70˚C



From these it was shown that for the GFRP panels at locations F and G, between vascules produced significantly greater cooling over the 5 minute test period for the branched network design. This can be observed in Figure 3. This resulted from the increased contact time of the cooling flow, in combination with the reduced panel area per vascular perimeter length in these regions. Both of these factors increase the permissible heat transfer between the composite panel and the cooling flow, thus reducing the temperature at these locations. Despite the larger separation of the vasculature at point A at the centre of the branched panel, greater cooling was also observed at this point than for the equivalent on the straight vascule panels GS and CS. The temperature changes observed at the corner locations B-E were comparatively minimal for both tested GFRP panels GB and GS, as the separation of these points from the cooling flow was excessive.

Figure 3: Thermal management tests in panels

4. CONCLUSION

This study shows that using anti-symmetric laminate designs, the in-situ manufacture of complex branched networks, with vascular bifurcations, within FRP laminates is possible. It has been shown that provided adequate coating and post-cure processing, Nichrome wires can significantly facilitate the manufacture of hollow vasculature within the laminate structure. For GFRP panels it has been shown than for a particular Animalia inspired branched network, greater cooling can be achieved for the areas bounded by vascules than for a straight channels. The testing of a CFRP panels with straight vascular channels suggests that even greater cooling could be achieved for a more thermal conductive CFRP panel with an integrated branched vascular network.

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