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Retention of mechanical performance of polymer matrix composites above the glass transition temperature by vascular cooling

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ABSTRACT

An actively cooled vascular polymer matrix composite containing 3.0% channel volume fraction retains greater than 90% flexural stiffness when exposed continuously to 325 °C environmental temperature. Non-cooled controls suffered complete structural failure through thermal degradation under the same conditions. Glass–epoxy composites (T_g = 152 °C) manufactured by vacuum assisted resin transfer molding contain microchannel networks of two different architectures optimized for thermal and mechanical performance. Microchannels are fabricated by vaporization of poly(lactide) fibers treated with tin(II) oxalate catalyst that are incorporated into the fiber preform prior to resin infiltration. Flexural modulus, material temperature, and heat removal rates are measured during four-point bending testing as a function of environmental temperature and coolant flow rate. Simulations validate experimental measurements and provide insight into the thermal behavior. Vascular specimens with only 1.5% channel volume fraction centered at the neutral bending axis also retained over 80% flexural stiffness at 325 °C environmental temperature.

1. Introduction

Polymer matrix composites (PMCs) are susceptible to reduced structural performance at elevated temperatures, such as those experienced during high speed flight [1–3], vehicle transportation [4–6], and during cycling of batteries, fuel cells, and other electronics [7–9]. Typical polymer matrices, such as epoxy, polyester, and vinyl-ester, have glass transition temperatures (T_g) at or below 200 °C, forcing the use of alternative materials such as metals and ceramics at service temperatures [3]. Subjecting a composite to high temperature, even for short time periods, can cause permanent damage, including delamination, matrix cracking, plastic deformation, and ultimately combustion and fire [10–13]. As an alternative, circulation of coolant through microvascular channels embedded directly into the PMC can regulate temperature by removing heat [14–16], potentially enabling safe structural performance under high thermomechanical loading.

In PMCs, vascular networks have been fabricated by solder removal [17,18], manual extraction of a solid wire [19–21], integration of hollow tubules or fibers [22–28], and Vaporization of Sacrificial Components (VaSC) [29–31]. Unlike most other methods which are restricted to straight channels with one-dimensional connectivity, VaSC using sacrificial fibers (SF) allows for three-dimensional, interconnected vascular architectures. To create a hollow channel poly(lactic acid) (PLA) SFs are integrated into textile weaving or braiding operations, survive standard composite manufacturing processing, and then are subsequently removed during a 200 °C post-cure [30]. When manufactured to minimize distortions to the structural fiber architecture, channels had minimal effect on tensile and compressive strength and modulus [21,26,31], interlaminar fracture toughness [19,25,27], and impact resistance [17,18,24,28].

Kozola et al. [14] studied active cooling in a vascularized epoxy fin heated at the base and reported up to a 53-fold increase in the effective heat transfer coefficient compared to an uncooled fin, while reducing the mean field temperature from 60 °C to 30 °C. Soghrati et al. [15,16] computationally modeled active cooling in 3D woven microvascular composites subjected to constant heat flux on one surface. Design charts related the maximum allowable temperature to the coolant flow rate and delivered heat flux. Phillips et al. [25] evaluated thermal transport in an actively heated carbon/epoxy fin subject to free convective cooling using

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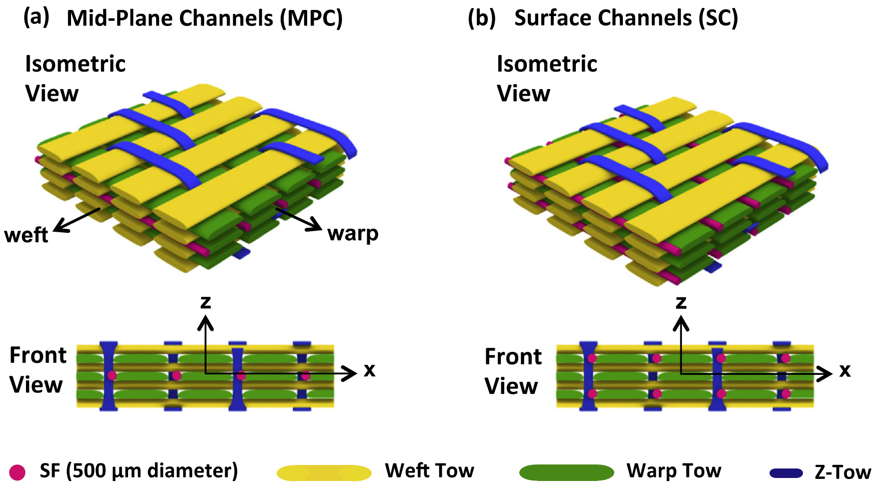

Fig. 1. Vascular composite specimens and channel architectures. The textile is composed of 3 warp layers and 4 weft layers, which are held together by the *z*-fibers. The areal density of the fabric is 4.07 kg/m^2 (120 oz/yard^2). In the warp layers there are 3.0 tows/cm and in the weft layers there are 2.7 tows/cm. The fiber content in the *x* and *y* directions are nearly equivalent as a result of the difference in tow density. (a) Mid-plane channel (MPC) architecture contains four channels located at the mid-plane of the sample yielding a total channel volume fraction of $V_c = 1.5\%$. (b) Surface channel (SC) architecture contains four channels located at each surface of the sample yielding a total channel volume fraction of $V_c = 3.0\%$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

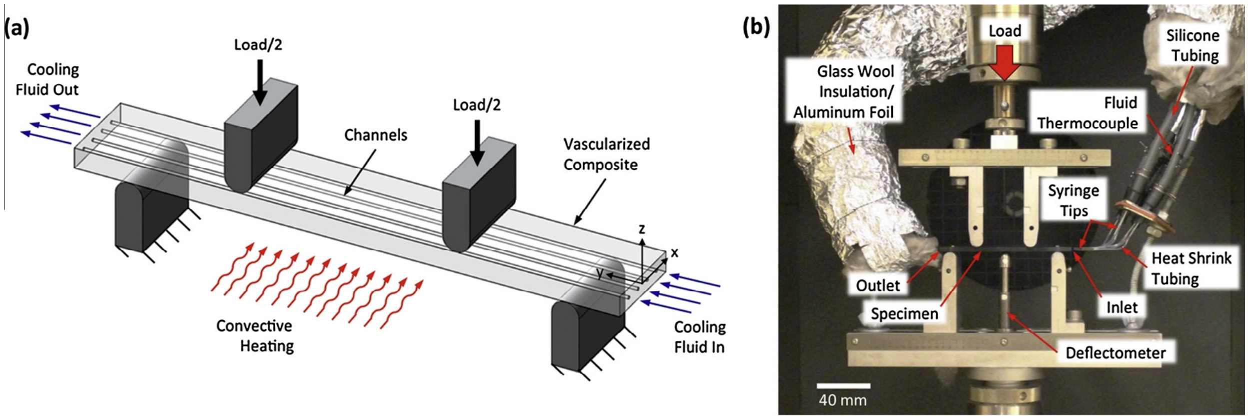

Fig. 2. Active cooling test set-up. (a) Schematic of active cooling test concept. Heat is removed by coolant pumped through the channels at a constant rate, reducing the temperature of the composite and improving mechanical properties. Heat is supplied convectively by the environmental chamber and conductively by the test fixtures. A coordinate axis is included for reference, with the origin centered on the inlet face. (b) Photograph of the test setup inside the environmental chamber showing the placement of the specimen, test fixture, and the coolant delivery system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

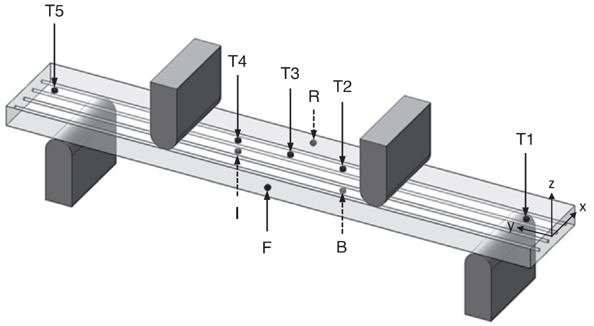

Fig. 3. Thermocouple locations in actively cooled composites. Top surface thermocouples (T1-5) were placed at $(x, y, z) = (0, y, 1.75)$ where $y = 5$, 40, 50, 60, and 95. One each was placed on the front (F) and rear (R) edge of the specimen at $(x, y, z) = (\pm 8, 50, 0)$. One thermocouple was placed inside (I) of the specimen at $(x, y, z) = (0, 60, 0)$ to measure the internal temperature and one on the bottom (B) surface at $(x, y, z) = (0, 40, -1.75)$. Dashed lines indicate thermocouples that are not located on the visible surface in the given view. Dimensions are in mm.

thermography to measure surface temperature. In a related study, Phillips and Baur [32] studied activation and deactivation of a shape memory polymer using microvascular heating and cooling, respectively. The authors developed a non-dimensional analytical model to analyze and predict the heat transfer and temperature fields. None of these prior studies have examined thermomechanical performance during active cooling.

In this study we demonstrate the effectiveness of active cooling through a vascularized composite to reduce temperature and maintain structural performance while subject to a convective environment at temperatures greater than T_g. Flexural testing of vascular specimens in an environmentally controlled chamber was carried out. The vascular composite is composed of a three-dimensional orthogonally woven glass fiber textile infused with epoxy and vascularized using VaSC. Composites containing channels at the mid-plane (i.e. *mid-plane channels* – "MPC") and those containing channels at the surfaces (*i.e. surface channels* – "SC") are compared. Both architectures were tested with active cooling using water for a variety of flow rates in the laminar regime