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Review

Manufacturing strategies for microvascular polymeric composites: A review

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ABSTRACT

A microvascular network within a composite structure can significantly boost its performance. However, properties of microvascular network and host structure largely depend on the manufacturing method, used for vascularization. This paper presents a review on various manufacturing strategies that have been implemented so far to produce vascularized polymer composites. The ways by which polymer composites can be vascularized with isolated or interconnected networks are based on either by incorporating pre-made channels or removing pre-loaded solid performs from the cured laminates. Majority of the techniques were developed for healing and recovery of structural integrity after quasi-static fracture, but microvascular networks also showed promise for enhanced-damage visualization, self-cooling, and damage sensing applications. Each technique has its own merits and demerits but the manufacturing techniques that are not only compatible with current composite manufacturing, but also give the freedom to embed complex channels which can execute multi-functions synchronously still remains the main challenge.

Contents

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1. Introduction

Certainly composites are the present and future of aerospace industry due to their numerous advantages and special hierarchical internal structure that provides immense scope to functionalize them to meet futuristic requirements [1]. In recent years, extensive efforts have been made to functionalize them by the incorporation of nanoparticles particularly CNTs [2–4], piezoelectric materials & sensors [5,6], optical fibers [7,8] and shape memory polymers & alloys [9–11] directly into the matrix during composite manufacturing. However, often their processing puts a limit to overall functionality of resulting composites and provides researchers opportunity to look for new advantageous ways. Inspired by biological microvascular systems, addition of microvascular channels within composites is a new promising approach to functionalize composites with numerous benefits. In living organisms these channels circulate fluids from one place to other to fulfill various purposes, such as damage control and repair, regulate temperature and nourish body and excrete harmful materials. Mimic to these biological microvascular systems microvascular channels of diameter from 1 μm to 1 mm are introduced into polymers or polymer-matrix composites and filled with fluids for additional functionality. Currently, these microvascular channels are providing additional functions of self-healing [12–19], active cooling [20,21] and sensing [22] in composites structures.

Self-healing is a concept in which damage triggers an autonomic healing response, which is most commonly found in biological systems. Many researchers have produced composite structures capable of self-healing by using self-healing matrix [23,24], healing agent (SHA) filled-microcapsules [25–28] and SHA-filled microchannels [29–31]. Among them, self-healing through SHA-filled microchannels is very promising and provides additional benefits of SHA storage, its transport to damage site, continuous supply of SHA for repeated number of damage-healing cycles and multi-functionality at the same time. Such feature in composite structures not only ensures their safe operation but also prevents from catastrophic failure. The area of self-healing of composite structures has received the most attentions of scientific community, which has led to numerous research articles and review papers. Amongst them, Blaiszik et al. has recently reviewed the autonomic–automatic self-healing of polymers and polymer-matrix composites under fatigue, impact, puncture and corrosion damage in a very comprehensive way [32].

Thermal management and heat recovery is an important aspect in designing of modern structures. Materials for microelectronics, high power lithium-ion power supplies, fuel cells, avionics and satellite electronics all require careful thermal management for their efficient operation. Reliable thermal control ensures their proper function and enhances lifetime of the structure. Microchannels embedded in composite structures have also been employed to reduce temperature through fluid (coolant) flow. This active cooling, consequently, optimizes size, cost and increases the capabilities of the structure [21].

A wide variety of nondestructive inspections are inevitably performed to retain and assess the structural soundness of the structure. Mostly, the desired inspected areas of structure are either inaccessible or hazardous and structures are to be disassembled to gain access. The use of in-situ sensors not only facilitate to overcome the accessibility limitations to complex geometries and hidden damages, but also reduce the associated costs. Microchannels in composite structures have not only been used to provide space (inside of a composite structure) for sensors but also as part of sensing system. Many research articles have been reported on self-sensing in recent years, but Swait et al., has concisely reviewed the most recently used methods of self-sensing in composite materials [22].

Manufacturing of microvascular channels in a composite structure to enhance its functionality is itself a great challenge. Many researchers have accomplished this task with the most basic approach of embedding non-removable hollow tubes of different materials [33–35], straight hollow glass fibers [36–38] or removable metallic/polymer wires or mandrels for the creation of simple microvascular networks. However, the recent development of VaSC by Sottos & White has enabled researchers to form more complex microvascular networks in 3D woven composites [39]. Due to numerous benefits of microvascular structures, their demand has increased exponentially and resulted in plentiful published literature. Recently, various aspects of polymers and polymer-matrix composites with microvascular networks has been meticulously reviewed by Olugebefola et al. [40]. This paper aims to review the different manufacturing strategies with most recent fabrication procedures employed to develop microvascular polymer-matrix composite structures, their applications, characterization and effects on performance.

2. Microvascular networks

Every manufacturing technique for the creation of microchannels in a composite structure has its own limitations in terms of network design; simple or complex, discrete or interconnected. Hence, design of a microchannel network largely depends on the fabrication method. However, irrespective of route by which microchannels were generated, the channel diameter, orientation, degree and location of branching are some of the important parameters that affect the overall functionality and performance of a microchanneled structure for a specific application. As optimized values of these parameters vary according to the applications of the structures, i.e. self-healing, self-sensing or self-cooling, and not all the parameters can be optimized through manufacturing & testing. Consequently, researchers employed many computational methodologies such as semi-analytical, gradient-based and evolutionary algorithms to design and optimize these large numbers of variables. Lorente and his associates optimized fluid flow through channels of different architectures and sizes for cooling, sensing, maintenance, repair and self-healing applications by applying constructal theory [41–47]. Constructal theory is a semi-analytical approach for optimization problems that does not involve large number of variables. The premise behind the theory is that the flow systems tend to reach optimum delivery configuration over time. Lorente et al. optimized channel size using two-dimensional grids of interconnected orthogonal channels with two hydraulic diameters ($D1$, $D2$) to provide fluid to every crack site. In their study, they showed that the triangular grid section aided the crack filling, when the damage size coverage and channel diameter ratios were optimum [41]. They also proposed the use of tree-shaped two-dimensional structures (line-to-line flow) and three-dimensional tree structures (plane-to-plane flow) to maximize fluid flow [45,46], two trees-matched canopy-to-canopy structure [42] for flow uniformity and small resistance [43]. They even developed such tree-shaped channels [44], grids and radial channels in composites that the structure can survive without coolant flow [47]. They reported that the flow resistances of alternating tree architectures were lower than those of porous media with same volume and internal (duct) flow volume [45,46]. Kim et al. recommended two trees-matched canopy-to-canopy configuration, with precise numbers of braches and branching levels, for greater access to every section of a finite-size volume [42]. While Lee et al. also optimized the same two trees-matched canopy-to-canopy configuration for small flow resistance (ψ) and small