Composites Science and Technology 101 (2014) 41–61

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

Feature Article

Structural power composites

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ARTICLE INFO

Article history:
Received 6 March 2014
Received in revised form 14 June 2014
Accepted 25 June 2014
Available online 5 July 2014

Keywords:
A. Carbon fibres
A. Functional composites
A. Hybrid composites
B. Electrical properties
B. Mechanical properties

ABSTRACT

This paper introduces the concept of structural power composite materials and their possible devices and the rationale for developing them. The paper presents a comprehensive review of the state-of-the-art, highlighting achievements related to structural battery and supercapacitor devices. The research areas addressed in detail for the two types of material devices include: carbon fibre electrodes, structural separators, multifunctional matrix materials, device architectures and material functionalization. Material characterisation, fabrication and validation are also discussed. The paper culminates in a detailed description of scientific challenges, both generic as well as device specific, that call for further research. Particular reference is given to work performed in national and European research projects under the leadership of the authors, who are able to provide a unique insight into this newly emerging and exciting field.

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http://dx.doi.org/10.1016/j.compscitech.2014.06.020
0266-3538/

1. Introduction

1.1. Concept of structural power

Since their initial introduction into transport applications, composite development has focussed on structural performance, with properties such as compression strength, and delamination toughness being critical. However recently there has been a move to exploit polymer composites in multifunctional roles [1,2]. The focus of this paper is composite materials with both structural and electrical energy storage functionalities.

Consider the concept of multifunctionality, as has been reviewed by Gibson [2]. In many engineering applications minimising weight and/or volume are the critical design drivers, and the conventional approach has been to optimise the individual subsystems, such as the power supply, etc. But considering such subsystems in isolation only gives limited savings, and invariably leads to compromises in parameters such as durability, cost, and performance. A more holistic approach is to consider multifunctional structures [3–7], in which the strategy is to optimise packaging of the different functionalities. For instance, in the context of the research reported here, embedding thin-film batteries within composite laminates [3]. These are essentially sandwich structures, in which such a configuration utilises enhanced structural performance through shape optimisation. Such devices have been reported to operate normally under low mechanical loads [3,5]. However, this approach offers only modest mass/volume savings and issues such as delamination at the device/composite interface are limiting. A detailed review of these composites is presented in [3].

An alternative strategy, which is the focus of this paper, is to formulate multifunctional materials [8–10] that can perform two or more functions simultaneously. In the instance considered here, polymer composites that can simultaneously carry mechanical loads whilst storing (and delivering) electrical energy, as demonstrated in Ref. [11]. These materials consist of multifunctional composite constituents that simultaneously and synergistically provide structural and electrochemical energy storage functions. This is a considerable challenge, since the optimum materials and architectures for such functionalities are usually conflicting, often with cross-cutting phenomena. This means that not only optimising the constituents (fibres/electrodes and matrix/electrolyte) but also the composite architecture, are key. However, the rewards of developing such materials are enormous, offering significant savings in system level mass and volume [18]. This philosophy also offers the opportunity to build in redundancy (such as to accommodate for cell malfunction or in-service/impact damage) and tailor mass distribution over a platform. In fact, materials with such diverse functionalities have considerable ramifications for engineering design. Such materials are relevant to a wide range of applications, particularly in aerospace, electric/hybrid ground transport and portable electronics, where battery life and power management are the limiting issues. In particular, radical new approaches to energy storage are required to progress towards future zero emission electrical vehicles [12,13].

For structural power composites, carbon fibre is an attractive starting point as carbon is commonly used both for electrodes and as a high performance structural reinforcement. Although traditionally different forms of carbon are used, the opportunity to unify these roles with appropriate fibre modification presents itself. Similarly, polymers can be used both as a structural matrix and as an electrolyte; however, performing both roles simultaneously presents considerable technical challenges. Finally, the laminated architecture of structural composites echoes that of many electrical energy storage devices, all of which provides a compelling synergy.

The aims of this paper are to firstly present the state of the art in structural power composites and then to set out the technical challenges and potential strategies for resolving them.

1.2. Structural supercapacitors, batteries and hybrids

Conventional approaches to electrical energy storage include batteries, supercapacitors and dielectric capacitors. Key parameters consider are the energy density (i.e. how much energy is stored) and power density (i.e. how quickly the energy can be delivered). As illustrated in Fig. 1, batteries possess high energy density but modest power density due to the relatively slow kinetics of the redox processes involved. Dielectric capacitors offer limited energy density but high power density as only electrons are transported during charge/discharge. Supercapacitors provide a compromise between batteries and dielectric capacitors, with typical energy and power densities around 3–10 W h kg^{-1} and 3 kW kg^{-1}, respectively. However, hybrids or asymmetric devices are now being developed which sit between supercapacitors and batteries, involving electrostatic and electrochemical processes (pseudo capacitors and hybrid capacitors) [15].

The concept of structural materials which also store recoverable/transferable energy is broad, and would include a host of multifunctional materials. Therefore, to provide a manageable overview, this paper only focuses on structural supercapacitors and batteries. A number of researchers, most notably Wetzel et al. [16–18] and Carlson et al. [19,20], have undertaken significant research on electrostatic capacitors, but the application of