Storage solutions

Composites that can store electrical energy while also performing a structural function could offer dramatic weight savings for devices and vehicles. Dr Emile S Greenhalgh, Reader in Composite Materials at Imperial College London, UK, outlines the progress of research into such materials.

Weight is often at a premium in engineering. Any material that does not contribute to load-carrying capacity is structurally parasitic. Current design practices pursue optimisation of the individual components by using materials with better specific properties. The alternative is to formulate materials that can perform two or more functions simultaneously.

Structural energy storage composites carry mechanical loads while, at the same time, storing electrical energy. Consider a mobile phone – a significant proportion of its mass is the battery. However, by using structural energy storage composites, the casing could store the electrical energy, dispensing with the need for a battery.

Density demands

This design methodology is in its infancy and faces significant challenges, requiring the combination of disparate and, often cross-cutting, phenomena. Conventional approaches to electrical energy storage include capacitors, supercapacitors and batteries. Two parameters are fundamental for energy storage – the energy density (the amount of energy stored for a given weight) and the power density (how quickly energy can be delivered).

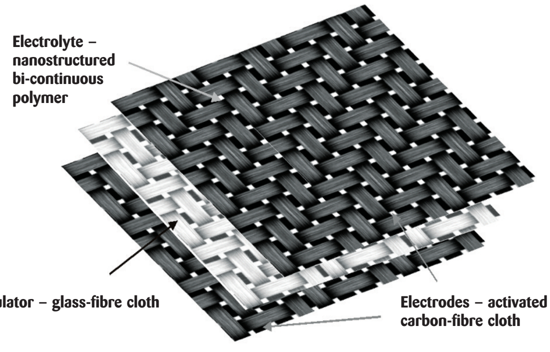
The ideal storage device would provide both high energy density and high power density, but in reality there are compromises. In batteries, the energy density is high, but power density is low, due to high internal resistance, while capacitors offer a limited energy density with a high power density. Supercapacitors offer an alternative to this dilemma, having both reasonable energy and power densities. Supercapacitors can be used directly as power sources, but are particularly useful for load levelling and enhancing battery life.

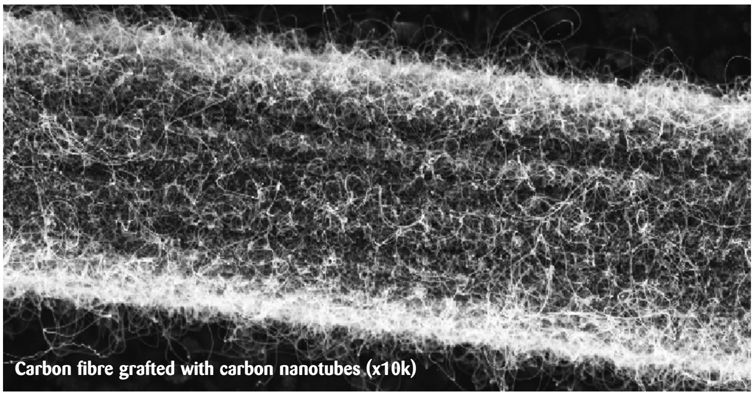
A number of research groups have been developing structural embodiments of energy storage devices. The key here is not simply to bind two disparate components together (such as a sandwich structure), but to produce a single coherent material that inherently performs both roles.

The versatility of composites means they are ideal for developing novel multifunctional materials that can store the electrical energy required to power systems, while meeting the demands of the mechanical loading. Carbon fibres are attractive as they are commonly used as both electrodes and structural reinforcements. Usually, the forms of carbon are different, but in structural energy storage composites, these roles are unified with appropriate matrix and reinforcement tailoring.

The most common form of supercapacitor consists of two electrodes, a separator and an electrolyte, as shown in the image (below left). The energy is stored by accumulating charges at the nanometre-scale boundary between electrode and electrolyte, giving rise to enormous capacitance. The amount of stored energy is a function of the available electrode surface and the electrolyte stability.

Structural supercapacitor





Carbon fibre grafted with carbon nanotubes (x10k)

BAE Systems Mantis UAV that employs structural energy storage composites. Image courtesy of BAE Systems plc

Research at Imperial College London has culminated in prototype laminates (see image far left) consisting of a pair of woven carbon-fibre cloths that sandwich a thin insulating layer (glass-fibre cloth), all of which is infused with a multifunctional resin. As with conventional composites, the research has focused on development of the constituents – the reinforcement (carbon fibres) and the matrix (multifunctional polymer) – and then on ensuring compatibility in the resulting composites.

Pores or hairs

The focus of work on the fibres has been to increase their surface area (improving their electrical energy storage capacity) while maintaining their mechanical properties. The most successful approach has entailed chemically etching nanoscale pores on the fibre surface. This has led to a 100-fold increase in surface area, but the pores are so small that they have a negligible effect on the fibre's stiffness and strength.

A more advanced approach is to graft carbon nanotubes (CNTs) onto the fibre surface (see image left). This offers further increases in the surface area at a scale accessible to the electrolyte, while simultaneously offering mechanical benefits. Such 'hairy' carbon fibres have been shown to give a 45% improvement in fibre/matrix strength, enhancing delamination resistance. Moreover, CNTs extending into the surrounding matrix provide the fibres with additional lateral support for improved longitudinal compression strength – a factor recognised as the Achilles' heel of continuous-fibre composites.

Matrix reloaded

The second aspect of the composite is the matrix, and here the demands to imbue multifunctionality are particularly challenging. From a structural perspective, the matrix needs to be rigid to provide a load-carrying capability and must adhere to the fibres. However, from an electrical perspective, the matrix needs to be compliant to enable rapid electrical ion migration to the fibre/matrix interface.

The approach, therefore, has been to develop a two-phase polymer system that forms a self-assembling bi-continuous nanostructure. One phase provides ionic conductivity, the other structural rigidity. By extending the length-scale into the nanodomain, the two components can perform their roles individually rather than as an average. The team at Imperial has been using a structural resin (bisphenol-A) with an electrical resin (PEGDGE) containing lithium ions. Additives, such as mesoporous silica, enhance both the electrical and mechanical properties.

Material architecture

Polymer composites offer a variety of options for material architecture, on which the resulting mechanical properties are highly dependant. For structural energy storage composites, this architecture will also control the diffusion distances for the ions and therefore the electrochemical performance. Various approaches have been considered, ranging from coating carbon fibres in sheaths of electrolyte to multifunctional structures in which the skins of the conventional composite

Demonstration of structural supercapacitor

Volvo car spare-wheel floor to be replaced with structural energy storage material in the STORAGE project

sandwich act as electrical cores, as in a thin-film battery. However, the focus of the research at Imperial has been to use the laminated architecture shown in the image on p24 (left).

A vital aspect of development is engineering the fibre/matrix interface. The surface chemistry of the activated fibres and their adhesion to the multifunctional matrix are, therefore, being investigated. It is also important to ensure that the constituent properties are carried through into the resulting composite. For example, the matrix's nanoscale structure must remain bi-continuously connected when activated carbon fibres are embedded within it.

The preliminary studies at Imperial have led to a prototype that demonstrates the concept but has poor electrical performance. The laminates being investigated (see image top) show improvements of several orders of magnitude over this and, with activated fibres and a second generation of multifunctional polymers, the electrical performance is starting to give effective energy densities.

System performance

In parallel with the constituent and composite development, there are a number of system issues that need to be addressed when using structural energy storage materials. For instance, the electrical connections need to be robust, although there is already considerable expertise in this field associated with lightning-strike protection of composites.

Conventional electrical devices need to be kept dry and exposed to a limited temperature range to function, and the same applies to structural energy storage materials, so there is a need for protective coatings. Finally, conventional composites must tolerate finishing operations, such as drilling and cutting. The concern is that machining structural energy storage composites could result in the electrodes being short-circuited. However, preliminary studies have suggested that panels can be finished without developing shorts.

In the longer term, when applications are developed for these novel materials, ownership issues will need to be addressed, including inspection, repair, damage tolerance and, ultimately, disposal and recycling.

Potential applications include unmanned aerial vehicles, as well as hybrid cars. Imperial has just completed a two-year programme, funded by the MoD, in collaboration with BAE Systems. This has culminated in production of a demonstrator sandwich structure, which is representative of an access panel on a UAV. The college is leading a 3.3m euro EU Seventh Framework research programme (STORAGE) on developing these materials for hybrid cars. The latter will culminate in Volvo replacing part of the steel structure of a car (such as the spare-wheel well, see image above left) with a multifunctional material that will provide electrical energy, giving a 15% weight saving.

Although the critical electrical and mechanical properties of these materials have been improving enormously, they are still behind those of conventional supercapacitors and structural composites respectively. However, it is not necessary to match simultaneously the best performance of each separate function. A suitable balance still gives a weight saving on the resulting component. In some situations, for example secondary structures, performance targets are relaxed. The benefits of structural energy storage composites in terms of weight savings will be considerable, particularly for applications such as electric road vehicles, mobile devices and aerospace structures.

Further information

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