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J. R. Soc. Interface 2007 **4**, 347-348

doi: 10.1098/rsif.2006.0205

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Introduction: self-healing polymers and composites

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Self-healing materials are inspired by biological systems in which damage triggers an autonomic healing response. This new paradigm in materials design has led several exciting interdisciplinary approaches involving chemistry, mechanics and materials processing to successfully incorporate self-healing functionality in polymers and composites. The first clear demonstration of self-healing in an engineered materials system occurred in early 2001 with the introduction of a microencapsulated healing agent and suspended catalyst phase in a polymer matrix. Since that time, rapid advancement has been made in the field following this conceptual approach, while alternative concepts have emerged in the scientific literature. From molecular-based reversible bonding schemes to macroscale structural approaches using hollow glass fibres, there currently exists a number of concepts at various stages of development for self-healing in polymers and composites.

Owing to the increasing interest and activity in the field of self-healing, we believe that it is an opportune time for a special issue of the *Journal of the Royal Society Interface*. This themed supplement draws together current research from eight leading research groups. The papers encompass a range of topics with the common aim of developing self-healing functionality.

Verberg *et al.* (2007) are seeking the implementation of ‘synthetic leucocytes’ via microchannel delivery networks and microcapsules capable of releasing nanomaterial repair agents. These active agents will not only sense the state of the walls of the vasculature, but also direct the vital components to the damaged sites. Once there, the diffusion of the nanoparticles out of the microcapsules and deposition at the damage site due to the enthalpic environment leads to an autonomic ‘repair and go’ function.

A means to ascertain instantaneous knowledge of a material’s structural integrity and, more importantly, when it has been compromised, remains a considerable challenge in current systems and materials. In order for the full potential of self-healing materials to be realized,

a sensory component is needed to determine in real time the formation (and healing) of internal microcracks. To address this challenge, Williams *et al.* (2007) report recent efforts towards the development of an electronically conductive material that is structurally dynamic and responds to various types of external stimuli.

Functional repair components stored inside hollow glass fibres (HGFs) impart self-repair (and visual enhancement) of impact damage by a bleeding action. Work by Trask *et al.* (2007) considers the placement of self-healing HGF layers within both glass fibre/epoxy and carbon fibre/epoxy composite laminates to mitigate damage and restore mechanical strength. Their study investigates the effect of embedded HGF on the host laminate’s mechanical properties and the resulting healing efficiency after quasi-static impact damage.

The paper by Kersey *et al.* (2007) addresses self-healing on a molecular level by incorporating load-bearing, reversible interactions onto surfaces (i.e. model ‘skeletons’) or into covalent polymer networks. Self-healing is governed either kinetically as in the generation of new material (typically by the failure-induced initiation of chemical reactions) that fills and adheres to cracks/failure sites or thermodynamically as in the regeneration of the initial state of the original molecular components (typically by annealing reversible interactions). To preserve a desired structural state, reversible interactions can be incorporated in a composite material with components that preserve a memory of the desired state, for example by encasement within an exoskeleton or tethering to an endoskeleton.

Jones *et al.* (2007b) discuss the healing response of damaged fibre-reinforced composites produced with a healing matrix resin. The system in question consists of a thermoplastic healing agent dissolved in a conventional thermosetting epoxy. Healing is accomplished by heating the fractured components. Upon repeated impact in the same location, the subsequent delamination area is reduced in comparison with the non-healing specimens.

Work by Mauldin *et al.* (2007) reports on recent advancements in a composite material that autonomically repairs crack damage by a healing process based on ring-opening metathesis chemistry to rebond the crack faces. Self-healing is initiated by the release of liquid dicyclopentadiene (DCPD) from fractured microcapsules that are embedded in a polymer matrix along with

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One contribution of 9 to a themed supplement ‘Self-healing polymers and composites’.

Grubbs' metathesis catalyst. While their original system used the commercially available *endo*-isomer, the *exo*-stereoisomer of DCPD is known to have much faster metathesis reaction kinetics. The group now reports on fracture toughness recovery as a function of healing time and compares the kinetics of damage repair for *endo*- and *exo*-DCPD and mixtures of the two isomers.

Fatigue and the associated slow accumulation of damage and deterioration in performance plague all materials. Jones *et al.* (2007a) demonstrate a material system which responds to fatigue loading by autonomic self-healing that leads to higher endurance limits and life extension, or even complete arrest of crack growth (infinite life). The system consists of a self-healing polymer that incorporates a microencapsulated healing agent and a solid chemical catalyst. Embedded microcapsules are ruptured by the crack growth and they release the healing agent into the crack plane through capillary action leading to the retardation or permanent arrest of further fatigue crack growth. It is shown that endurance training by periodic exposure to stress can lead to significant life extension and is governed by the interplay between the mechanical kinetics of crack propagation and the chemical kinetics of healing in the polymer.

A class of poly(ethylene-*co*-methacrylic acid) copolymers and ionomers has shown a unique ability to self-heal following projectile puncture. The healing process active in these materials appears to be significantly different in capability and mechanism than any of the other systems being studied elsewhere. Kalista & Ward (2007) examine thermal effects during self-healing and investigate the link to some of the behaviour observed in other self-healing systems. To effectively design materials that can take advantage of this capability, the mechanism by which these materials heal must still be determined. To provide further understanding of the self-healing capabilities, several new damage methods are considered, including sawing, cutting and puncture techniques.

The papers collected in this issue represent a reasonable survey of the current efforts across the

world in the development of self-healing materials. We know of several other groups currently making progress in the field and look forward to their contributions as they appear in the scientific literature. While the field is still quite young, we believe that a critical mass of scientific activities has been achieved throughout the world. The future of self-healing is quite strong and it holds great promise across a broad spectrum of technologies from transportation to manufacturing to biomedicine.

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