Self-healing on small length scales

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>>> Focus on sustainability, innovation and international
Outline

• Autonomous Materials @ Illinois

• Capsule Based Approaches
  – Interfacial healing with nanocapsules

• Molecular-Based Approaches
  – Mechanochemically active interfaces

• Conclusions
The Autonomous Materials Systems Group

Collaborators: Scott White, Jeff Moore, Paul Braun, Philippe Geubelle

Support: AFOSR, ARO, DHS, NASA, NSF, ONR + industry
Inspired by Biological Systems

Autonomic or Self-healing Functionality:
The ability to repair damage in an automatic and site specific fashion without manual intervention.
Three Approaches to Self-Healing

Capsule Based Self-Healing Materials

Compartmentalized, damaged triggered delivery of healing agents

(a) Capsule - Catalyst
(b) Multi-Capsule
(c) Latent Functionality
(d) Phase Separation

White et al., Nature (2001)
Jones, et al., JRS: Interface (2007)

= 90.3%
Vascular Based Self-Healing Systems

Continuous delivery of healing agents to damage site

Bioinspiration

Self-healing coating on a vascular substrate

Optimized networks & repeated healing

Biological Inspiration

Synthetic Concept

Vascularized woven fiber reinforced composite

Hansen et al., Adv. Mat. 2009

Esser-Kahn et al., Advanced Materials (2011)
Intrinsic Approaches to Self-Healing

Mechanochemically Active Polymers

1. Reversible bonding
2. Chain reentanglement
3. Noncovalent healing

Mechanophore-Linked Polymer Activation

mechanophore

stress

mechanochemical reaction prior to bond scission
Damage Length Scales

Laminated Composite

Microvascular

Microcapsules

Nanocapsules & molecular approaches
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Encapsulation of Healing Agents

*In situ* polymerization of urea and formaldehyde

**Sonication & chemical stabilization for smaller capsules**
Capsule Size Scales

- Nanocapsules: Stabilization
  - Blaiszik et al. Composite Science and Technology (2008)

- Sub-micron capsules: Miniemulsion / Sonication

- Microcapsules: Macroemulsion
Capsule Rupture and Release

Capsules induce crack pinning and crack deflection

Small capsules significantly increase epoxy fracture toughness
Self-Healing of Fiber/Matrix Interface

**Challenge:** Interfacial pullout, debonding and cracking in advanced composites

**Solution:** Interfacial Self-healing

High performance fibers functionalized with nanocapsules for self-healing
Healing Assessment for Interfaces

Test Protocol: recovery of interfacial shear strength in single fiber specimens

Single fiber microbond test

Capsule functionalized glass fiber

Self-healing specimen

Fiber: APS sized 15 um dia glass
Epoxy Matrix: EPON 828/DETA
<1 um diameter capsules
Solvent-Based Healing Chemistry

Single Capsule System
- EPA resin + EPON 862 resin

1.5 µm solvent capsules via sonication

solvent nanocapsules via sonication + chemical stabilization

Single Fiber Debonding

Custom load frame

In situ imaging of debonding
Recovery of Interfacial Shear Strength

97% EPA: 3% EPON 862 healing chemistry

\[ \tau_{\text{Virgin}} = \frac{P_v}{\pi d l_e} \quad \tau_{\text{Healed}} = \frac{P_h}{\pi d l_e} \]

Self-healing

Control
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Mechanochemical Approach

Mechanophore linked polymers

Mechanical → Chemical

stress-induced crosslinking

σ
Color Changing Mechanophore

\[ T_g = 10^\circ C \]
\[ \dot{\varepsilon} \approx 10^{-2} s^{-1} \]
\[ \lambda_{threshold} \approx 8 \]

\[ \sigma_{threshold} = 15 \sigma_y \]

Davis et al., Nature (2009)
Conclusions

• Capsule-based healing strategies can be applied to a range of interfaces: fiber/matrix interface, adhesives, electronics, batteries.

• Self-healing of fiber/matrix interfacial fracture has been demonstrated with capsules as small as 500 nm.

• Mechanochemical approaches hold great promise for self-healing interfaces.
For more information

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http://autonomic.beckman.illinois.edu/
In case of further questions

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