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Crack healing in cross-ply composites observed by dynamic mechanical analysis

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ABSTRACT

Cross-ply composites with healable polymer matrices are characterized using dynamic mechanical analysis (DMA). The $[90,0]_s$ samples are prepared by embedding layers of unidirectional glass or carbon fibers in 2MEP4FS, a polymer with thermally reversible covalent cross-links, which has been shown to be capable of healing internal cracks and fully recovering fracture toughness when the crack surfaces are kept in contact. After fabrication, cracks in the composites' transverse plies are observed due to residual thermal stresses introduced during processing. Single cantilever bending DMA measurements show the samples exhibit periods of increasing storage moduli with increasing temperature. These results are accurately modeled as a one-dimensional composite, which captures the underlying physics of the phenomenon. The effect of cracks on the stiffness is accounted for by a shear-lag model. The predicted crack density of the glass fiber composite is shown to fall within a range observed from microscopy images. Crack healing occurs as a function of temperature, with chemistry and mechanics-based rationales given for the onset and conclusion of healing. The model captures the essential physics of the phenomenon and yields results in accord with experimental observations.

1. Introduction

Fiber-reinforced composite materials are popular in structural applications due to their strength and light weight. They are composed of strengthening fibers embedded in a matrix material that facilitates load sharing. Due to mechanical and thermal property mismatches, composite materials are notoriously susceptible to microcrack damage. Through cyclic loading, these microcracks will grow, coalesce into larger cracks, and ultimately lead to structural failure. Current technology relies on identifying cracks and manual repair or replacement of the composite. If the microcracks could instead be healed before they grow, the useful life of the composite could be extended. This would be particularly useful in applications where human intervention is difficult or impossible, and materials that may not be practical or cost-effective in ordinary applications are considered.

There are currently two general approaches to creating a composite material that is self-healing or healable via external stimuli. The first approach is to embed liquid healing agent that can bleed out into a crack or other damage and mitigate it. White et al. (2001) incorporated catalyst particles and microcapsules containing a healing agent into a polymer material

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Table 1
Composite constituent properties.

	Carbon fiber[a,b]	Glass fiber[c]	2MEP4FS[d,e]
	$x=f$	$x=f$	$x=m$
Mass density (ρ_x)	1.76 g/cm^3	2.488 g/cm^3	1.347 g/cm^3
Longitudinal Young's modulus (E_{xL})	230 GPa	93.8 GPa	3.046 GPa
Transverse Young's modulus (E_{xT})	22 GPa	93.8 GPa	3.046 GPa
Poisson's ratio (ν_x)	0.35	0.23	0.367
Shear modulus (G_x)	22 GPa	38.1 GPa	1.114 GPa
Longitudinal CTE (α_{xL})	− 1.3 μm/m/°C	1.6 μm/m/°C	41 μm/m/°C
Transverse CTE (α_{xT})	7.0 μm/m/°C	1.6 μm/m/°C	41 μm/m/°C

[a] Kaw, 2006.
[b] Toray Carbon Fibers America Inc., 2012.
[c] AGY, 2006.
[d] Plaisted, 2007.
[e] Nielsen, 2012.

which could serve as the matrix in a fibrous composite. Pang and Bond (2005) moved the healing agent out of the matrix and into hollow fibers. In these two approaches, once the healing agent bleeds out into the damaged region and hardens, there is no more available if new damage subsequently forms in the same location. To overcome this limitation, Toohey et al. (2007) investigated using embedded microvascular networks where healing agent can be pumped to the damage site in a biomimetic process. The second approach to creating a healable composite material is through the use of a polymer matrix which can re-form broken cross-linking bonds at the molecular level. This is a fundamentally different process than the flowing of polymer chains to heal damage in a thermoplastic material (Wool and O'Conner, 1981). Plaisted and Nemat-Nasser (2007) have demonstrated full recovery of fracture resistance after healing cracks in a neat polymer that uses thermally reversible Diels–Alder (DA) adducts as cross-linking bonds. They studied 2MEP4FS, a polymer formed from two monomers reacting in a Diels–Alder cycloaddition (Chen et al., 2002, 2003). The healing was performed at temperatures below where the DA adducts separate, and the process required the crack faces to remain matched and abutted. As the matrix material in a cross-ply composite, the fibers will hold crack surfaces together, facilitating healing.

Plaisted (2007) also demonstrated crack healing in 2MEP4FS reinforced with glass and carbon fibers. The composite samples were characterized using single cantilever bending dynamic mechanical analysis. After subsequently subjecting them to cold temperature treatments to introduce microcracks, the samples were recharacterized. They were healed using an elevated temperature thermal treatment and characterized a third time. The composite samples were found to recover a significant portion of the originally measured stiffness. Park et al. (2009) used a single component, DA-based polymer as the

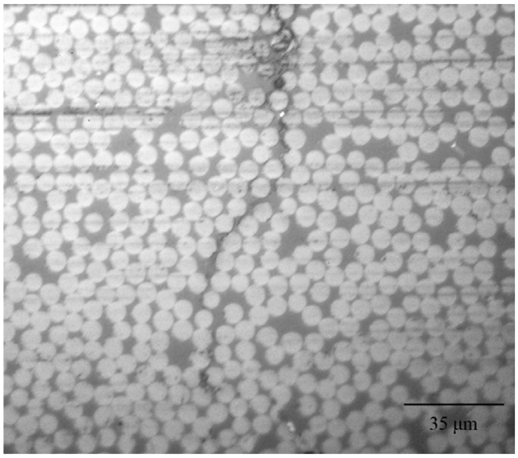

Fig. 1. Optical microscope image of a transverse ply crack in the carbon fiber composite sample. The crack runs from the top center to the bottom of the image.