PRESSURIZED VASCULAR SYSTEMS FOR HEALING CRACK DAMAGE AND MITIGATING FATIGUE CRACK PROPAGATION

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ABSTRACT

Synthetic materials with micron-sized vascular features mimic the ability of biological materials to distribute fluids throughout a material volume. These synthetic vascular materials are capable of responding to mechanical damage by delivering liquid healing agents to the regions of damage. In the case of small scale damage and an unimpeded flow path, capillary forces provide a passive means of healing agent delivery. However, this passive approach faces a number of limitations, including susceptibility to flow obstruction, the inability to control or direct flow, and a restriction upon the maximum healable damage volume. In this work, we overcome these limitations using pressurized vascular systems to deliver two liquid healing agents to regions of damage. In addition to addressing multiple events of quasi-static fracture damage, the propagation of fatigue cracks is mitigated using pressurized vascular systems to deliver rapidly-curing healing agents to actively growing cracks.

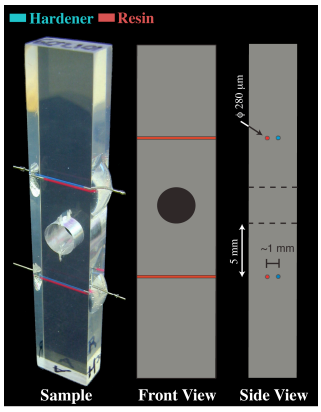

Figure 1: Image of a vascular DCDC fracture sample and schematics detailing microchannel position and contents.

The double cleavage drilled compression (DCDC) fracture sample geometry was employed to evaluate the recovery of fracture toughness. Two microchannels were positioned on each half of the epoxy specimens, as shown in Figure 1. On each half of the specimen, one microchannel was filled with a liquid resin and the other was filled with a liquid hardener. Pressurized reservoirs of the healing agents were connected to each microchannel via tubing and syringe tips inserted 1-2 mm into each microchannel. The application of static pressure heads to the healing agent reservoirs resulted in constant, nearly equal flow rates of each healing agent into the damaged region. Dynamic, out-of-phase flow rates were achieved using computer controlled pumps. These dynamic pumping protocols were intended to induce a higher degree of mixing of the two healing agents than static pressure and

subsequent diffusion alone. Healed samples were fractured and healing agents delivered through 15 cycles of damage and healing.

The healing efficiency (η) of a sample was defined as the ratio of the healed fracture toughness to the fracture toughness of the virgin sample. Average healing efficiencies resulting from pressurized vascular systems are presented in Figure 2 as a function of the healing cycle. The increased degree of mixing resulting from the dynamic pumping protocols translated into consistently higher healing efficiencies (red) as compared with the samples pumped using constant pressure (gray) or samples without pressurized vascular systems, in which capillary forces drove healing agent flow (blue).

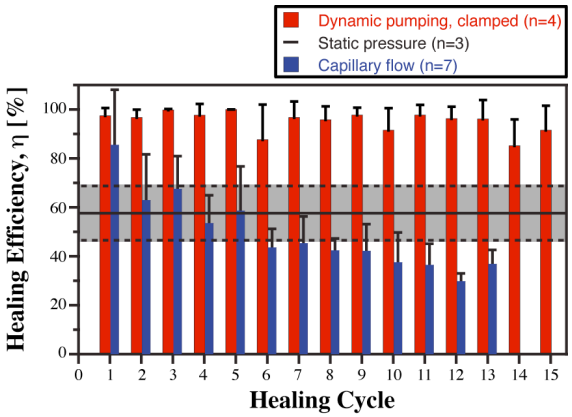

Figure 2: Comparison of average healing efficiencies in samples with dynamic pumping, static pumping, and capillary forces driving fluid flow.

In addition to quasi-static fracture tests, fatigue tests were conducted using the same specimen geometry (Figure 1), except each microchannel contained one component (Part A or Part B) of a commercially available two-part epoxy adhesive (ITW Devcon High Strength 5 Minute® Epoxy), which was selected for its rapid cure kinetics. After cracks propagated through the fluid-filled microchannels (at a crack length of 5 mm, in Figure 3), healing agents flowed into the crack plane and polymerized, causing a decrease in the rate of crack propagation.

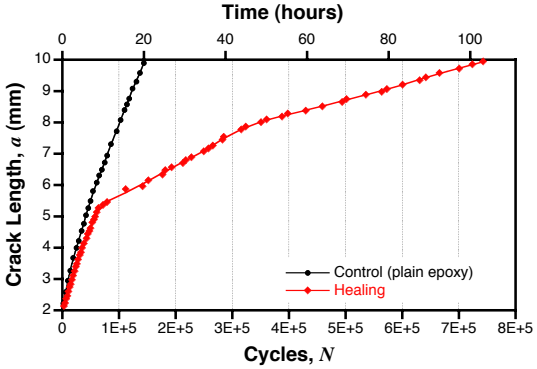

Figure 3: Crack extension as a function of time in specimens loaded in cyclic fatigue to $K_{max} = 0.73K_{IC} = 0.454$ MPa-m$^{1/2}$.

Using pressurized vascular systems, consistently higher recovery of fracture toughness was observed over more cycles of damage and healing as compared with unpressurized vascular samples where capillary forces drive the flow of healing agents. Furthermore, this higher degree of recovery was achieved using vascular systems that occupy 0.1% of the specimen by volume, compared with a volume fraction of 1.3% in unpressurized specimens with inferior healing performance. The rate of crack propagation under cyclic fatigue loading was significantly reduced using pressurized vascular systems to deliver rapidly-curing healing agents to actively growing cracks.