OPTICAL VOID FORMATION AND MOBILITY MEASUREMENTS IN CARBON FIBER REINFORCEMENTS

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Introduction

An experimental methodology to photograph bubbles in-situ during infusion of carbon reinforcements has been developed. A combination of transparent tooling, macro lens photography, UV-sensitive dye, and UV lamps allows clear imaging of inter-tow bubble morphology. The opacity of the tows makes intra-tow bubbles more difficult to characterize with this method. This presentation shows the preliminary results from analysis of the resulting images. Methodologies to extract void formation rates at the flow front are presented. Also shown are statistics on void morphology, and how this changes as the pressure gradient and flow front evolve. The development of void formation and void mobility models are dependent upon such experimentally-obtained data for a given fabric and fluid combination.

Background

Liquid composite molding (LCM) processes are becoming increasingly desirable for high-performance parts due to lower costs involved. Yet they produce higher void content than traditional prepreg methods due to bubble entrapment during infusion [1]. In light of this, characterizing void formation and mobility during infusion of composites continues to grow in importance [2,3], so as to allow optimization of LCM processing to narrow the gap between LCM and prepreg processing in resultant mechanical performance.

Voids are spaces of non-matrix, non-reinforcement material that are developed or trapped in a composite during molding and that reside after cure. Increased void content leads to a reduction of key mechanical properties of composites with matrix dominated properties being most affected [4]. Research has sought to find ways to reduce the void content in LCM processes by characterizing void formation *in situ*. For example, the relationship between flow front velocity and void formation rates for infusion processes has been proposed and studied [1,5]. Benefits of such modeling include process optimization for minimal void formation as well as anticipating where dry spots are likely to form based on RTM inlets, outlets, fiber layup, flow characteristics, and geometry [6].

Until now, *in situ* void formation characterization has mostly been done optically through transparent tooling, and such optical analysis was restricted exclusively to fiber glass composites due to their translucency. Capturing void flow in carbon fiber is challenging because of the limited visibility of voids against the opaque (black) carbon fiber background. Yet void characterization is even more important in carbon composites than fiberglass, due to the high-performance composites industry's dependence on the former for its superior mechanical properties. In order to characterize void behavior with carbon composites, researchers have commonly utilized microscopy to validate methods *ex situ*, or after processing. Yet *ex situ* microscopy can only give insights after the bubbles have moved and been entrapped, giving little information on bubble formation. Non-optical *in situ* methods for void characterization in carbon reinforcements include flowrate comparison, pressure sensors, electrical conductivity, thermal conductivity, x-ray scanning, ultrasound, and embedded electronics. These methods all require expensive, specialized equipment.

An optical methodology for photographing and examining *in situ* void flow and formation of carbon fiber laminates by use fluorescence has been developed. This methodology involves infusion with a test fluid (canola oil) mixed with an ultraviolet (UV)-sensitive dye, a UV lamp, transparent rigid tooling, and a macro lens with a digital camera. The lighting and camera settings were optimized for enhanced bubble clarity. Sample images of bubbles photographed with this method *in situ* during infusion are shown in Figure 1. One can see the dark outlines of the bubbles in each image. Two difficulties with this method are apparent: 1) dark spots are also generated by the opaque fibers pressing against the transparent tooling, making it difficult for image analysis to automatically detect bubbles by grey level thresholding, and 2) micro bubbles within the tows are difficult to discern because of the first difficulty.

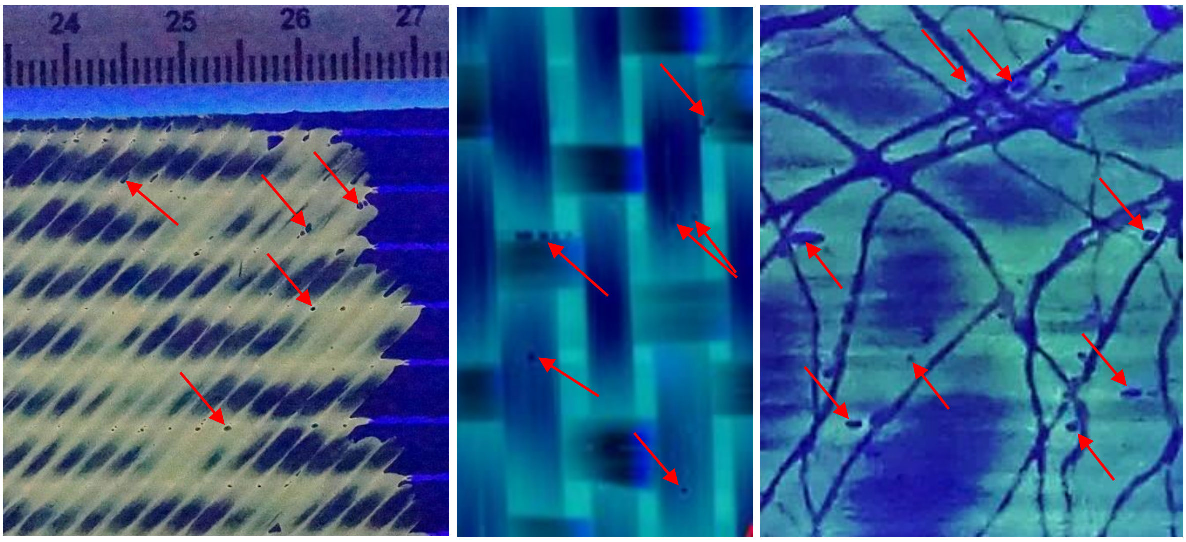

Figure 1: *Example void images with carbon reinforcements: (from left to right) biax non-crimped fabric, satin weave, spread-tow weave with binder beads on surface. Arrows mark example void locations.*

The bubble locations are fairly obvious in such images to the naked eye, allowing manual painting over these bubbles in an image analysis program for bubble analysis. But this process is tedious, and impractical for the statistical analysis needed for the many bubbles and many images captured during a single infusion. A script with various image analysis techniques has been developed, using shape, size, and darkness filters, to automate bubble identification in such images. This automated script is calibrated by comparing it against a manually identified voids image. The capabilities and difficulties will be presented at the conference. With this automated script, several analytics are available to a researcher including statistics on bubble morphology (size, aspect ratio, clustering), the concentration of bubbles near the flow front (which can be related to void formation rates at that local flow front velocity) and the location of bubbles in a series of photos (allowing bubble velocity to be calculated.

Another capability of this methodology is a comparison of void kinetics for various fabric architectures. For example, the spread tow weave shown to the right in Figure 1 has dark streaks on the surface which are beads of binder spread on the top of each ply. These binder beads are meant to disappear when infusing at high temperature. But this room temperature study at least shows proof of concept of observing bubble formation, mobility and entrapment with such a unique architecture. The binder beads traps voids, and cause preferential flow between the beads. Yet voids are still elongated with the fiber direction. These and other void analytics will be demonstrated in the conference presentation.

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