IMAGING OF COMPOSITE DEFECTS AND DAMAGE USING OPTICAL COHERENCE TOMOGRAPHY

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ABSTRACT

The Composites Group at the National Institute of Standards and Technology has found optical coherence tomography (OCT) to be a powerful tool for non-destructive characterization of polymer matrix composites. Composites can be made more cost competitive by improved composite design, process optimization, and quality control. OCT can help address all three of the aforementioned challenges. OCT is a very versatile technique that can be applied to a variety of problems in polymer composites, for example, defect detection and damage evaluation.

In this work, volumetric images of an epoxy/unidirectional E-glass reinforced composite are presented showing tow architecture and highly reflecting regions indicative of voids. Slicing of the volume at a particular depth reveals that point voids are actually channel-like voids that run in the direction of the fibers, as expected. The composite was then subjected to impact damage and a selected region of damage was analyzed. The damage was characteristic of a resin with some ductility indicating that the fiber-matrix interface was the weak component. The OCT images and laser scanning confocal microscopy results from the same sample are compared.

INTRODUCTION

For a properly designed composite, two of the most critical issues affecting performance are the defects introduced during processing and the damage that results from in-service exposure. How these features initiate and grow with time generally dictates performance and service life. The features themselves, however, are only part of the story since the microstructure in the sample, particularly the fiber arrangement, orientation, volume fraction, and interface bonding, plays a strong role in the initiation and growth of defects and damage.

There are many different kinds of processing induced defects. For example, voids can be formed when the resin does not properly penetrate into the fiber tows or inadequately wets the fiber surfaces. Such defects tend to follow the fibers, and this strongly influences their shape, size, and orientation. Other examples of defects include dry spots and resin rich regions. When the processing involves resin injection, such defects can result from improper flow patterns during molding. The position and shape of such defects often depend on how the fibers affect the flow so microstructure plays a crucial role. Once defects are generated, they can act as stress concentration points when the sample is loaded in service. If the local stresses are high enough, the defects will grow and can eventually cause failure. Although some information about defect initiation and growth can be gained by examining the failure surface, it is far more informative to monitor the events as they occur, particularly if the microstructure can also be seen.

Damage induced during service is also an important factor in performance. One common sources of damage is impact loading. When a composite is impacted with sufficient energy, cracks are generated in the polymer between the fibers and/or at the fiber-matrix interface. The number, size, shape, and location of the cracks are important since those which lead to delamination are usually more harmful that those that do not. Delamination reduces the load carrying capability of the composites, particularly the compression strength. In many aerospace applications, this is the most common failure mode. As a result, many studies focus on developing matrix resins and composite designs that are more resistant to impact and subsequent delamination (often called damage tolerant systems). Such studies have been hampered by the difficulty in quantifying impact damage and monitoring the role of microstructure non-destructively.

Both destructive and non-destructive techniques have been used to examine defects and damage. Destructive techniques such as microscopy on sectioned samples are sensitive to the small size scale that is required to examine microstructure as well as damage and defects. Because such techniques are destructive, however, they are not well suited to monitor how the situation evolves with time, and this is critical to study the initiation process and how defect or damage growth interacts with microstructure effects. Non-destructive techniques, like ultrasonics, are often used to characterize defects and can monitor the growth of defects and damage. Unfortunately, such techniques are not sensitive to the very small size scale that is appropriate for characterizing microstructure and its role in the initiation and growth process.

As a result, the capability to non-destructively measure microstructure, defects, and damage is very desirable. It is even more advantageous if these measurements are performed with a single technique because this eliminates the complications involved in combining data from different sources. A technique called optical coherence tomography (OCT) has the potential to address all of these issues for glass and Kevlar reinforced systems. Initially developed for biomedical imaging, OCT can non-destructively generate volumetric images with a resolution suitable for characterizing microstructure as well as defects and damage. The purpose of this paper is to demonstrate this potential through comparisons with other techniques: laser scanning confocal microscopy.

OCT is a confocal technique that is enhanced by interferometric rejection of out-of-plane image scattering. Briefly, OCT uses a low coherence source such as a superluminescent diode laser with a fiber optic based Michelson interferometer. In this configuration, the composite is the fixed arm of the interferometer and the fiber optic acts as the confocal aperture. Reflections from heterogeneities within the sample are mapped as a function of thickness for any one position by scanning the reference arm. Volumetric information is generated by translating the sample on a motorized stage in the plane perpendicular to the thickness. Quantitative information about the location and size of a feature within the composite is obtained. With real materials, OCT can image composites having a thickness of < 1 cm with a spatial resolution of 15 μm. OCT compares well to traditional composite NDE techniques such as ultrasonics and x-ray in terms of resolution, quantification, depth of penetration, speed and cost. This comparison is discussed in previous work.[1]

OCT also compares very favorably with less established composite NDE techniques such as laser scanning confocal microscopy (LSCM) which has been used extensively in the biomedical arena. LSCM utilizes variable pinholes to reject the image out-of-plane scatter. The size of the pinhole and the numerical aperture of the objective primarily determine the resolution in the thickness or axial direction. Generally, the smaller the holes, the higher the resolution but lower the intensity throughput. The ultimate axial resolution for OCT is solely determined by the bandwidth of the source and the numerical aperture of the focusing objective. For the same optical configuration, OCT has been shown to have substantially higher signal-to-noise and narrower point spread function than confocal microscopy. [2] Using OCT, the sample can be probed deeper with more image detail. For imaging features close to the surface, however, OCT does not have an advantage over LSCM. [2] Moreover, OCT is only performed in reflection mode while LSCM is amenable to either reflection or transmission. Also, sample birefringence can confound standard OCT images but is not an issue for LSCM.

In this work, imaging of composite damage and defects is demonstrated using OCT. Volumetric images of an epoxy/unidirectional E-glass reinforced composite are presented showing tow architecture and highly reflecting regions indicative of voids. Slicing of the volume at a particular depth reveals the point voids are actually channel-like voids that run in the direction of the fibers. The composite was then subjected to impact damage and a selected region of damage was analyzed. Results from OCT and LSCM are also compared.

EXPERIMENTAL

Details concerning the composite fabrication are provided in previous work. [1] To generate the damage, the composite was secured in a vise and impacted with a blunt object at various places with various loads. Details about OCT instrumentation, operation, and capabilities are provided elsewhere.[1] For the studies here, the image resolution is 40 μm along the x axis, 10 μm along the z axis, and 80 μm along the y axis. Axes references are shown in Figure 1.

For comparison, a Zeiss [3] laser scanning confocal microscope was used in reflection at 543 nm at 5 mW with a pinhole diameter of 99 μm. The confocal results are a collage of 12 individual, 12 bit images collected with a 10x/0.3 objective. The individual images consist of a 512 x 512 area of pixels. The collage represents an area of about 2 mm along the x axis and 1.9 mm along the y axis. The axial resolution is 15 μm.

RESULTS AND DISCUSSION

An undamaged e-glass composite was examined first. Figure 1 shows the volumetric OCT rendering of the sample. The composite cross-section is shown along the x-z plane. The image dimensions are 6.00 mm along the x axis, 1.48 mm along the z axis, and 3.85 mm axis the y axis. The gray ellipses are the fiber tows which are approximately 2 mm wide and 750 μm thick and consist of about two thousand, 10-20 μm diameter glass fibers. [4] The long axis of the tows is shown on the x-y plane. The polyester stitching that holds a single layer tow together before processing is indicated by the black arrows. These images show that the tows in this section of the composite reside in a nested configuration, whereas results from other sections of the composite show the layers aligned in a stacked configuration. Upon closer inspection, defects in the form of small dark areas are evident inside the fiber tows. These dark areas are high reflectivity regions indicative of the channel voids that can form inside the tows during resin injection, and can be better seen in Figure 2. Figure 2 displays a cross-section of the composite along the x-y plane at 740 μm from the top, and this plane bisects the middle row of tows in Figure 1. The black features of high reflectivity that are parallel to the x axis are the polyester (arrow 1). The black, elongated regions parallel to the z axis are thought to be voids (arrow 2).

After the composite shown in Figure 1 was subjected to impact loading, OCT x-z cross-sectional images were collected from a selected region of impact damage in the sample. These images were reconstructed into a volumetric representation and re-sliced along the x-y plane at two z positions of interest, 340 μm and 650 μm from the surface. The OCT images are 5.3 mm along the x axis (wide) and 6.0 mm along the y axis (long). The figures labeled "A" compare the OCT image to the corresponding LSCM image, labeled "B". All images are displayed as log(intensity).

The features seen by OCT are confirmed using LSCM. The OCT image in Figure 3A shows the tows (bracketed sections) perpendicular and the crack parallel to the x axis. The crack can be seen to run through 3 complete tow bundles (arrow 1). A smaller crack is also present. In-plane areas of damage are evident (arrow 2) as are the stitching. The dashed square shows the area of the composite captured by confocal microscopy in Figure 3B. The crack is still apparent (arrow 1) in Figure 3B. Only the highly reflecting damage regions appear (arrow 2) with poor differentiation of tows. Both the LSCM and higher resolution OCT suggest that the damage mechanism to be fiber de-bonding. The resin used here is relatively tough for an unmodified epoxy, and no special effort was made to optimize the fiber-matrix bonding. Consequently, it isn't surprising that the interface seems to be the weak component in the composites. The lower thickness resolution of the confocal is advantageous when features with diffuse boundaries are present, such as the damage region indicated by arrow 3. This feature is only partially seen in the OCT.

Figures 4A and 4B display the OCT (A) and confocal (B) images of the composite 650 μm from the surface. This distance corresponds to the bottom of the first layer of tows in both figures. In figure 4A, a larger de-bond region (arrow 1) can be seen in addition to the existing crack. The stitching is more readily visible (arrow 2). The dotted square defines the confocal region. Again, the damage in Figure 4B between the fiber tows is readily seen along with the fiber de-bonding and existing cracks in the confocal images. When depth of penetration is considered, OCT does substantially better than LSCM. Practically, features can be resolved down to 1 mm with LSCM. Using OCT, they can be seen down as far as 5 mm, the entire thickness of this sample.

CONCLUSIONS

OCT has been successfully used to image defects and damage in glass reinforced composites. Channel voids that could act as damage initiation sites were easily seen. The cracking, fiber de-bonding and microstructure detected using OCT have been confirmed using LSCM. The OCT images of the damage exhibited more detail and a higher depth of penetration than the LCSM. The LSCM performed better at detecting features with diffuse boundaries.

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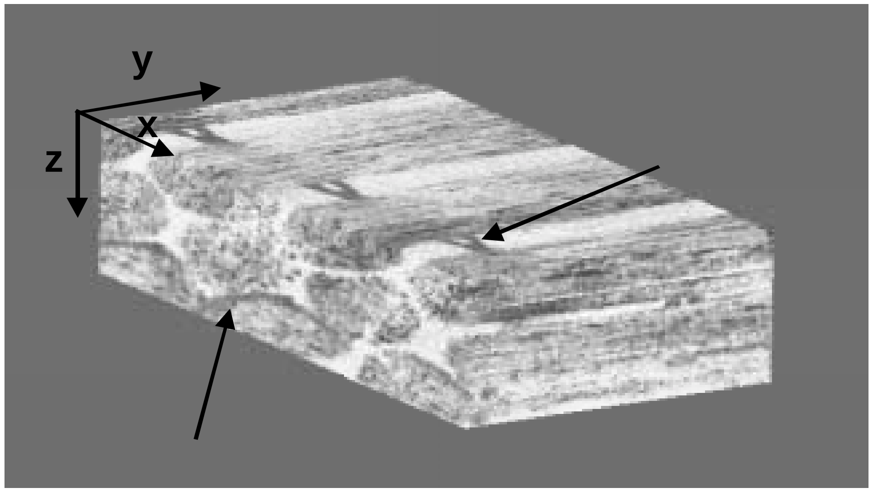


Figure 1: OCT volumetric reconstruction of an epoxy/unidirectional E-glass composite.

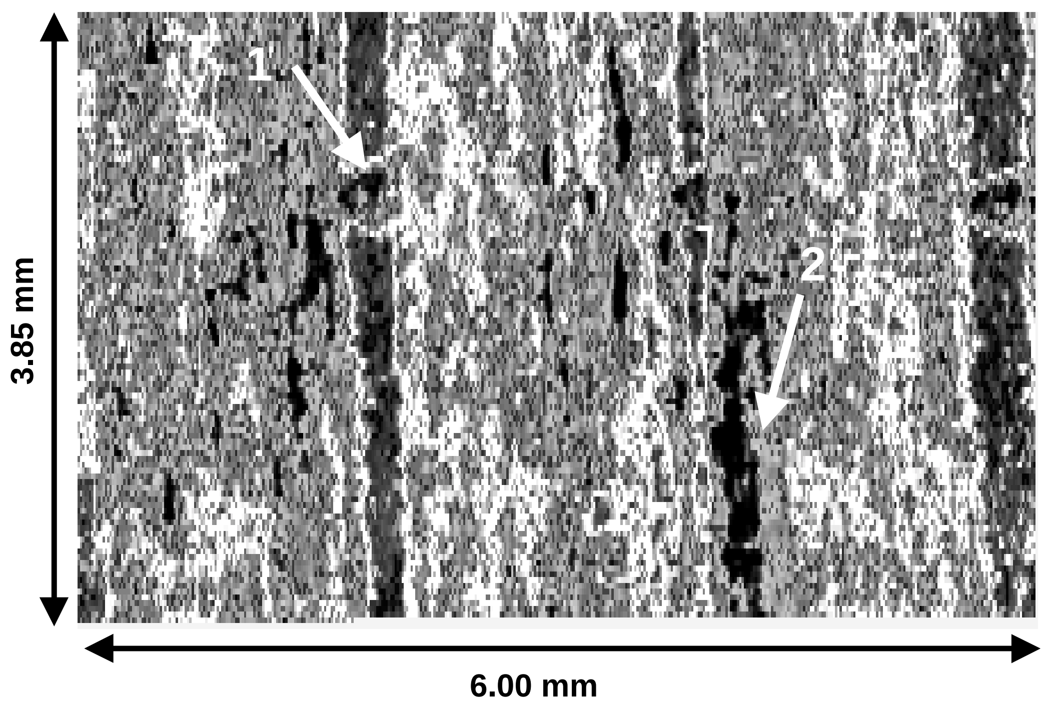


Figure 2: Cross-section of epoxy/unidirectional E-glass composite along the x-y plane at a depth of 740 μm. Arrow 1 shows the stitching that holds the individual layers together. Arrow 2 indicates an elongated void within the tow.

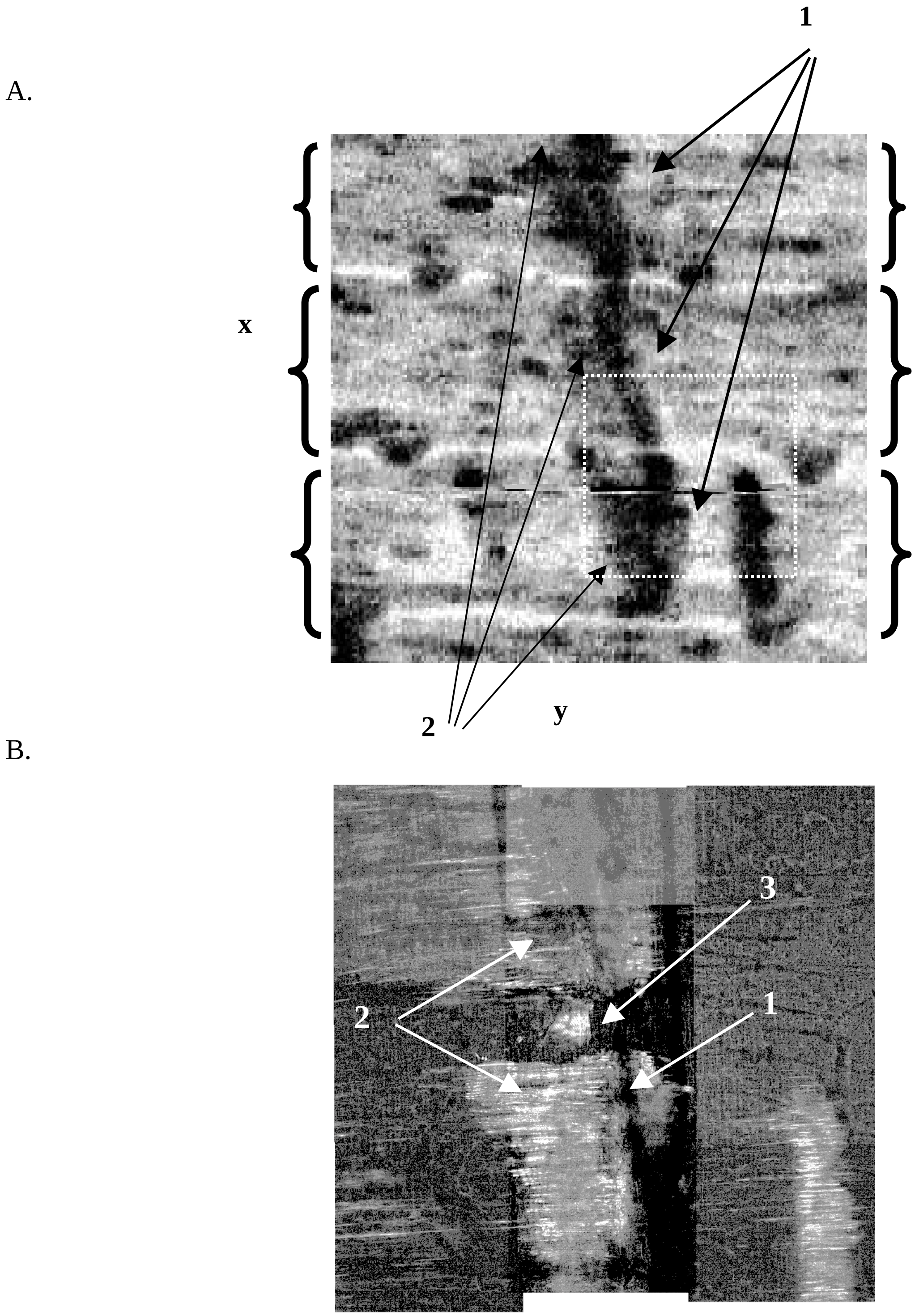
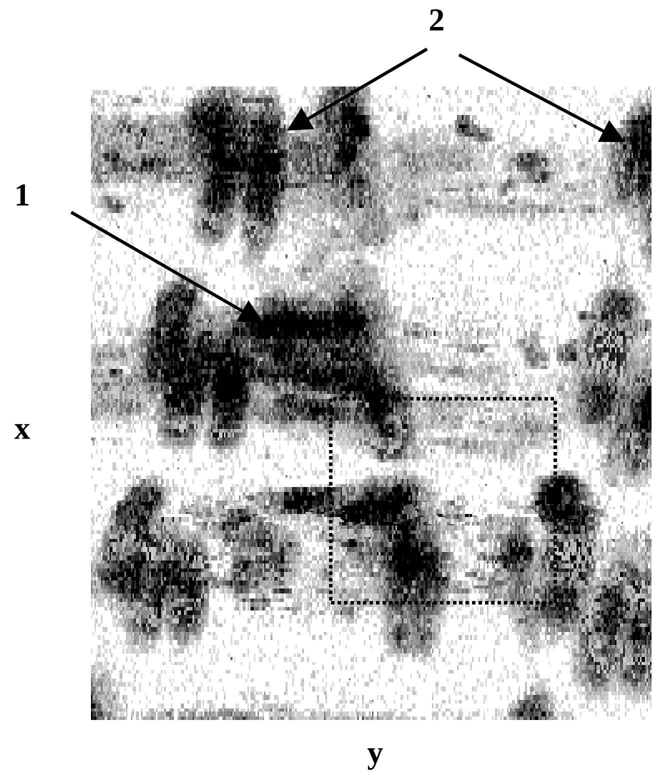


Figure 3: OCT (A.) and LSCM (B.) images 340 μm from top surface of composite**.**

A.



B.

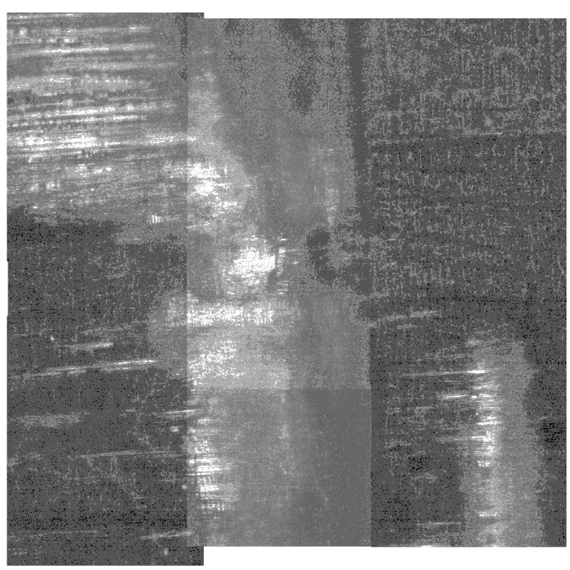


Figure 4: OCT (A.) and LSCM (B.) images 650 μm from top surface of composite**.**