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IMAGING OF IMPACT DAMAGE IN COMPOSITES USING OPTICAL COHERENCE TOMOGRAPHY

Joy P. Dunkers,[1] Daniel P. Sanders,[1]
Donald L. Hunston,[1] and Matthew J. Everett[2]

[1]Polymer Composites Group
National Institute of Standards and Technology
Gaithersburg, MD 20899

[2]Medical Technology Program
Lawrence Livermore National Laboratory
Livermore, CA 94551

INTRODUCTION

Resistance to impact damage is extremely important for most composites. Such damage can initiate delamination, one of the most common failure modes in composites. For example, impact damage tolerance is the basis for design in many aerospace applications since loss of compression strength via delamination is the dominant failure mode. When the impact energy is high enough, cracks are generated in the polymer matrix and 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. Because this is such an important failure mode, many studies have tried to develop matrix resins and composite designs that are more resistant to impact (often called damage tolerant systems). Such studies have been hampered by the difficulty in quantifying impact damage non-destructively. Optical coherence tomography (OCT) can address this issue for glass and Kevlar reinforced systems. One way to evaluate the success of any new technique is to compare it to an existing one. In this work, OCT will be compared to 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. Volume information is generated by translating the sample on a motorized stage. Quantitative information about the location and size of a feature within the composite is obtained. OCT can practically image composites having a thickness of <1 cm with a spatial resolution of 15 μm.

Laser scanning confocal microscopy (LSCM) 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[1]. Using OCT, the sample can be probed deeper with more image detail. OCT does not have an advantage over LSCM for imaging features close to the surface[1]. 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 does not pose an issue for LSCM.

Like LSCM, OCT was pioneered for use in biomedicine. OCT has been used extensively to image the human retina[2], skin and blood vessels[3], and the operating circulatory system of small live animals[4] with excellent clarity. Previous work has demonstrated the potential of imaging composite damage using OCT[5]. This work will focus on image interpretation and comparison to an analogous technique, LSCM.

EXPERIMENTAL

Details concerning the composite fabrication are provided in previous work[6]. To generate the damage, the composite was secured in a vice and impacted with a blunt object at various places with various loads.

Details about OCT instrumentation, operation, and capabilities are provided elsewhere[5]. In this work, 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.

A Zeiss[7] laser scanning confocal microscope was used in reflection at 543 nm at 5 mW with a pinhole diameter of 99 μm. The confocal images 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 image 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

OCT and LSCM were used to image an impact damaged epoxy and unidirectional E-glass composite. Figure 1 shows the volumetric reconstruction of the undamaged composite. 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[8]. The long axis of the tows is shown on the x-y plane. The polyester stitching that holds a single layer of tows together is indicated by the black arrows. Upon closer inspection, small dark areas are evident inside the fiber tows. These dark areas are high reflectivity regions indicative of individual voids.

OCT x-z cross-sectional images were collected from a selected region of impact damage from the composite shown in Figure 1. 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 2A 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 2B.

The crack is still apparent (arrow 1) in Figure 2B. Only the highly reflecting damage regions appear (arrow 2) with poor differentiation of tows. Both the LSCM and higher resolution OCT revealed the damage mechanism to be fiber de-bonding. The lower thickness resolution of the confocal is advantageous when features with diffuse boundaries are present, such as the cavitation region indicated by arrow 3. This cavitation is only partially seen in the OCT.

Figures 3A and 3B 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 3A, 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 cavitation in Figure 3B between the fiber tows is readily seen along with the fiber de-bonding and existing crack 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

The cracking, fiber de-bonding and microstructure detected using OCT has been confirmed using confocal microscopy. 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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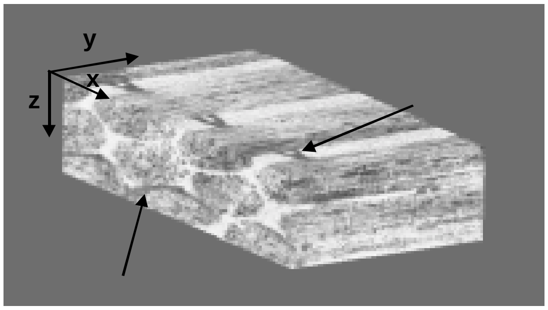
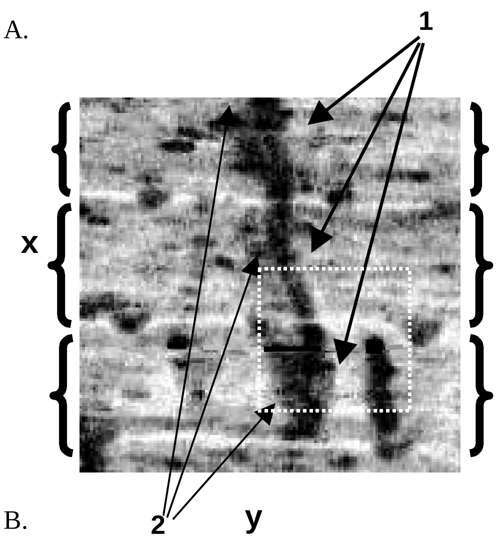


Figure 1: OCT volumetric reconstruction of an epoxy/unidirectional E-glass composite.

A.



B.

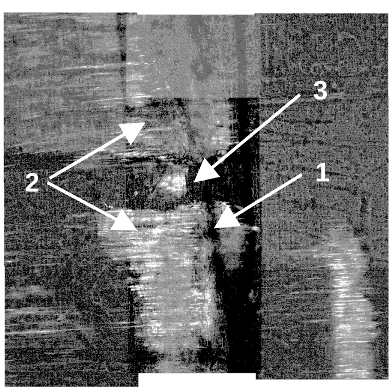
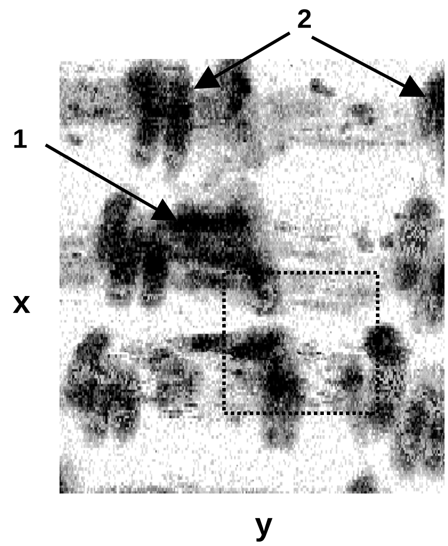


Figure 2: OCT (A.) and LSCM (B.) images 340 μm from top surface of composite.

A.



B.

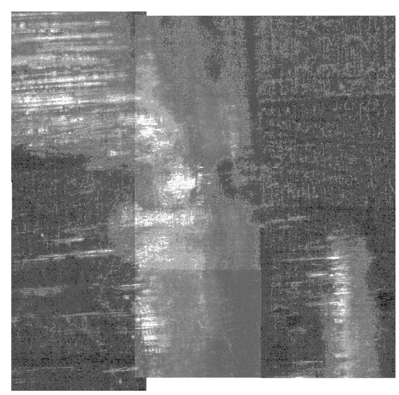


Figure 3: OCT (A.) and LSCM (B.) images 650 μm from top surface of composite.