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Imaging of porosity in fiber-reinforced composites with a fiber-optic pump–probe laser-ultrasound system

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ABSTRACT

Assessing material porosity in composites is critical because pores can greatly affect material strength and lifetime. Ultrasound (US) is one of the primarily methods to quantify porosity, usually based on the relationship between US speed/attenuation and void content. However, most US approaches require a sample with plane parallel and relatively smooth surfaces to correctly measure the attenuation and speed, but such conditions cannot always be fulfilled in practice. In addition, conventional US cannot directly image porosity as X-rays can. Here we present a non-contact US method to directly image porosity that can be easily integrated with US speed/attenuation measurements. The overall approach uses ultra wideband acoustic signals generated at the surface of a composite material with a laser pulse (i.e., pump), and non-contact, point-like detection of backscattered transients (i.e., probe) with spatial resolution better than 1 ply. US-assessed porosity is compared with that measured gravimetrically.

1. Introduction

Composites are widely used for many applications that can exploit their exceptional mechanical properties. For instance, the tensile strength of graphite–epoxy composites is comparable to that of metals at a few fold reduced weight [1,2]. In addition, many composites are not subjected to residual stress, a serious problem for metals [3,4]. However, because composite materials are multi-component, heterogeneities and material porosity often result in manufacturing. For example, a few percent of voids is normal in fiber-reinforced plastics. Multiple studies have shown that porosity is the main cause of reduced strength and lifetime of real composite parts [5–14]. Thus, robust methods for material porosity assessment are still in demand.

The porosity content can be evaluated by both nondestructive and destructive methods. Acid digestion [15,16] and materialography are usually employed as destructive methods. In the first case, gravimetry is used to measure the volume and mass of the whole sample and the mass of the fiber content alone. For accurate results, however, the material properties like epoxy and fiber density must be well known. Materialography in combination with (microscopic) analysis is time-consuming, expensive, and sometimes not accurate [17,18].

Various methods such as X-ray radiography, neutron-radiography, eddy currents, thermography, acoustic emission, and US methods have been proposed for non-destructive evaluation of porosity [19–21]. Active thermography and microwave testing [15,22] are still topics of research and their feasibility for practical applications in industry is not yet clear. X-ray computed tomography is an effective method for porosity imaging, but it is complicated, expensive and, most importantly, requires that samples be placed between the source and detector; i.e., it is not applicable to field testing of real components [23–25].

US appears to be the most practical tool proposed for porosity assessment. First, it is non-destructive, relatively inexpensive, portable, quite accurate and can be potentially employed not only in laboratories but for inspection of real parts in the field. The most common US methods for porosity assessment exploit the relationship between US speed/attenuation and void content. Both theoretical and experimental studies helping derive these relationships were performed in the 1970s and 1980s [5,9–11,15,17–21, 26–40]. From these studies it was clear that the frequency dependence of US attenuation is linear in the MHz range. This region lies between Rayleigh and stochastic scattering regimes and its boundaries can be estimated [29,33,35,37]. It was shown that this dependence remains linear for different material porosities. Thus, the slope of the attenuation over this frequency range

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is very robust for porosity evaluation if proper calibration is performed for a specific type of material (see, for example, [19,31,32]).

Attenuation-based methods for porosity assessment have been summarized in several patents [31,32]. The dependence of US phase speed on porosity can also be exploited although it is often less reliable due to the non-linear behavior of the speed dispersion curve at low frequencies.

The main drawback of US attenuation/speed methods is the requirement that samples have plane, parallel, and smooth surfaces because the back-wall US echo has to be recorded. Surface roughness can strongly influence the apparent attenuation curve and directivity pattern for the back reflected US signal and induce inaccuracies in porosity reconstruction. Moreover, this method does not work at all for samples with non flat geometry. There are also some physical limitations imposed on void geometry and spatial distribution: there is a rather good and more or less linear correlation between porosity and the attenuation coefficient, especially if the voids are spherical and homogeneously distributed. The ultrasonic attenuation coefficient is also affected by the size, shape and distribution of voids [11,15,17,18,39]. For some practical cases, the frequency dependence of US attenuation could not be considered as linear even in a limited frequency range [39].

A more robust way to assess porosity without using the back wall reflection is needed for US inspection of a much wider range of samples and parts, and especially for field inspection of critical components where it is often very difficult to ensure normal incidence to the back wall of a part. Back reflected "noise" US signals between front and back wall signals related to acoustic scattering from voids can be used for material porosity assessment [9,40–43]. Different algorithms to process this type of signal have been proposed. The premise of our work is that laser-generated US probe signals are preferred for quantitative backscatter measurements because they provide much better spatial resolution at the same characteristic frequency, and higher overall signal bandwidth, to simplify backscattered signal interpretation [40–42].

Another important issue for inspecting a wide range of samples and parts is US signal detection. Conventional US is a contact technique requiring acoustic coupling to the object under study. This makes it difficult for many potential applications where non-contact remote measurements are desirable or even necessary. Laser-ultrasonics, where light is employed both for laser generation and detection of US [44–58], provides a non-contact alternative. Laser-ultrasound (LU) methods have already been demonstrated for defect visualization as well as for porosity assessment in composites using US attenuation [30,59]. Thus, LU seems well suited to porosity assessment given its large signal bandwidth and non-contact nature. However, a serious disadvantage is the low sensitivity of optical detection compared with conventional contact transducers, which is especially true for composites [45]. In addition, most optical detection systems are also cumbersome, expensive, strongly sensitive to environmental noise and surface roughness, and very slow in operation.

Recently, we showed that the sensitivity, stability and robustness of optical detection can be dramatically improved with a new type of fiber optic interferometer [60–63]. As shown in [62,63], a compact, inexpensive LU system can operate at more than 1 kHz A-scan rates. The system also provides 1–10 MHz detection bandwidth, which can be used to resolve every ply in graphite–epoxy composites and visualize even small defects. This system is detailed in [60,63]. Recently we also reported that the sensitivity of laser-ultrasound detection can be greatly improved [62,63]. The system used in the studies reported below has an overall system noise figure of 8.3 dB (i.e., the noise power exceeds the Nyquist noise power limit by only 8.3 dB). Such a low noise figure enables sensitive detection of US signals backscattered from voids at high signal-to-noise ratio (SNR) in a single shot regime (i.e., no signal averaging required).

The paper is not primarily aimed at correcting or improving US speed/attenuation methods for porosity assessment. The goal is to show that porosity can be imaged with LU methods and that signal fluctuations in high-resolution US images (B-scans) correlate with porosity estimates derived from US speed and/or attenuation measurements and confirmed independently by sample weighing. We believe that LU imaging can provide information on material porosity similar to that produced by X-ray tomography, but can be done in echo-mode (i.e. with one-sided access to a sample under study), without any requirements on plane-parallelism of samples (i.e. without recording the US reflection from the back wall).

2. Materials and method

2.1. Samples of fiber reinforced composites with different void content

Six samples of fiber reinforced graphite–epoxy composites with different void content were manufactured at Boeing Research and Technology. All samples were 25 mm in diameter. Their thicknesses and weights were measured. To determine density, the volume of all samples was measured and the mass was normalized by the measured volume. The density of this particular composite structure with zero void content is assumed to be $\rho_0 = 1.613\ \mathrm{g/cm^3}$ (by information from manufacturer). Because material porosity is determined by the ratio of volume void content to whole sample volume, the porosity P can be determined simply as:

$$P = 1 - \rho/\rho_0. \tag{1}$$

Composite samples were not transparent for both pump and probe light. The composite surface was not specially prepared prior to measurement; thus, optical detection was performed from the actual sample surface.

2.2. Fast scanning pump–probe LU system

The LU system contains a few main components: a pump nanosecond laser to generate probe US (LU) signals at the surface of composite samples; a fiber-optic modified Sagnac interferometer for non-contact detection of backscattered ultrasound; an XY translation platform to perform scanning; an analog to digital converter (ADC) and computer (PC) for signal capture, processing, and image display.

The system is described briefly below; detailed information on interferometer design can be found in [60,61] and its block diagram and fast (at least 1000 A-scan per second) scanning performance is detailed in [63].

A custom designed 2D XY translation platform (Aerotech, aerotech.com) is employed with the pump–probe system. The composite sample is fixed on the translation platform, which can be moved at a linear translation speed of 100 mm/s with a peak acceleration of 10 $\mathrm{m/s^2}$ in both lateral directions. A position synchronized output of the translation platform is used as a trigger for lasing. Thus, all laser firings are triggered based on the coordinate (see Fig. 1), i.e. based on the spatial, not time, interval between firings. The scan step was kept constant even for acceleration/deceleration regions. A-scan stepping accuracy is better than 1 μm over the whole scanning length, including acceleration/deceleration regions. Immediately after triggering, the laser (Laser Export Co. Ltd., Model Tech 1053 Advanced, laser-export.com) fires and sends a trigger signal to the ADC (GaGe, Model Razor Compuscope RZE-002-300, gage-applied.com) to start data acquisition. Laser firing fully synchronized with fast sample translation enables