Polymer Testing 56 (2016) 379–386

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Test Method

Application of air-coupled ultrasonics for the characterization of polymer and polymer-matrix composite samples

Juerg Neuenschwander*, Roman Furrer, Arno Roemmeler

Empa, Swiss Federal Laboratories for Materials Science and Technology, Ueberlandstrasse 129, CH-8600 Duebendorf, Switzerland

A R T I C L E I N F O

Article history:
Received 23 September 2016
Accepted 1 November 2016
Available online 2 November 2016

Keywords:
Air-coupling
Ultrasonics
Nondestructive testing
Lamb-waves

A B S T R A C T

This study investigates the application of air-coupled ultrasonics for nondestructive, non-contact characterization of polymer and polymer-matrix composite samples. A lot of progress has been made with this technique which does not require any liquid couplant, hence water sensitive samples can be studied without deterioration. We demonstrate the power of highly focused transducers for topography imaging of structured polymer surfaces such as a craquelure, fingerprint or an acoustic lens with a lateral resolution up to 0.1 mm and an elevation resolution of 2 μm. With a further technique, transmission resonance, the thickness of plates can be imaged with a resolution of 3 μm. Air-coupling is also used for checking the integrity of a polymer-matrix composite plate, revealing invisible internal impact damage. Finally, a single-sided Lamb-wave technique is used to detect sub-wavelength artificial defects such as notches and through-holes in plates.

1. Introduction

Ultrasonics is a well-accepted method for nondestructive integrity testing of polymers and polymer-matrix composites. A drawback can be the use of liquid couplants. However, recent developments allow the application of air-coupling. This contribution shows the power of this technique in the field of polymer and polymer-matrix composite samples. Methodologies such as surface topography, transmission and Lamb-wave defect inspection are presented and discussed.

In a recent book chapter [1] a large number of nondestructive testing methods applied to polymers and polymer-matrix composites have been reviewed, such as mechanical, optical, radiation, electromagnetic, ultrasonic, thermal and analytical techniques. This contribution will focus on the ultrasonic method with emphasis on air-coupling. This is a relatively new non-contact testing technique that has the advantage to work without any liquid or gel couplant.

Pioneering work on air-coupled ultrasonics has been done by Hutchins et al. [2], including defect detection in normal transmission, frequency analysis for sound velocity measurement and also Lamb-wave detection. An overview on airborne transducers with focus on capacitive transducers is given by Hutchins et al. [3] and a review of air-coupled materials characterization is presented by Chimenti [4]. An interesting recent work proposes passive focusing techniques to enhance the lateral resolution of piezoelectric transducers [5].

Air-coupled ultrasonics allows the imaging of surfaces by measuring the reflected ultrasonic signals. The amplitude contains information about the topography since regions perpendicular to the sound beam are highly reflecting, whereas oblique incidence gives low reflectance [6], leading to an edge detection method. On the other hand, the time-of-flight (TOF) of the echo can be measured and converted with the sound velocity in air to a 2D elevation profile [7,8]. Depth resolutions down to 1 μm are possible [9].

A transmission inspection with separate transmitter and receiver on adjacent sides of the sample allows the examination of the internal structure of samples. Amplitude C-scans allow integrity diagnosis of e.g. composite laminates and honeycomb structures used in aerospace industry [10], and impact damage detection and degradation monitoring of wet glass fibre reinforced polymers [11]. Spectral methods permit the use of thickness resonances for sound velocity or thickness measurements [7,12].

Air-coupled ultrasonics is widely used to generate and detect Lamb-waves in plates, pipes or more complicated thin-walled structures. The transmission as a function of notch depth has been studied in steel plates [13] or in aluminium plates [14,15]. Experiments and simulation was done on through-holes in

* Corresponding author.
E-mail address: juerg.neuenschwander@empa.ch (J. Neuenschwander).

http://dx.doi.org/10.1016/j.polymertesting.2016.11.002
0142-9418/

aluminium plates, impact damage in glass polyester plates [16] and interface delamination in composite T-joints [17]. The curing process has been visualized by Lamb-wave propagation in carbon fibre reinforced polymers (CFRP) [18] and filament-wound composite pipes were investigated by Ref. [19]. The prepreg level of impregnation has been studied with a resolution better than 1 mm^2 [20].

For the sake of completeness, it should be mentioned that pitch-catch defect detection with bulk waves is reported for single-sided air-coupled arrangement for aluminium plates with through-holes parallel to the plate [21], and a slanted incidence method was applied to extruded polystyrene foam to detect step wedge saw cuts [22].

This work presents the application of air-coupled ultrasonics for the characterization of polymer and polymer-matrix composite samples. State of the art gas matrix piezoelectric composite transducers are used [23,24] for this recently developed non-contact technique. The surface topography is imaged both with amplitude and TOF scans of both smoothly and highly structured polymer samples. With resonance transmission the thickness variation of a polymer plate is inspected. Furthermore, transmission defect imaging is applied for integrity checking of a carbon-fibre reinforced polymer (CFRP) sample which was subjected to impact damage. Finally, the power of single-sided Lamb-wave defect imaging is shown on polymer samples with notches and through-holes.

2. Experimental

2.1. Surface topography

An air-coupled focalized 4 MHz transducer (NCT4-D6-P6, The Ultran Group Inc., State College PA, USA) was attached to a computer-controlled three-axis mechanical scanner in order to record 3D ultrasound datasets [25]. The transducer has an effective diameter of 6 mm and a −6 dB beam diameter of 0.1 mm at the focal distance of 6 mm. A pulser/receiver (5058PR, OlympusNDT Inc., Waltham, MA, USA) working in pulse/echo mode (band-width 5 MHz, energy 100 µJ) was used to excite the transducer and to amplify the received echo signals. All the measurements (also those in the following sections) were made at ambient laboratory conditions. Even at the high resolution scans (0.05 mm Pixel) no interference by normal turbulence of air was observed. The experimental setup is shown in Fig. 1: The probe points orthogonal towards the sample – in this case a craquelure – which is put onto a glass support.

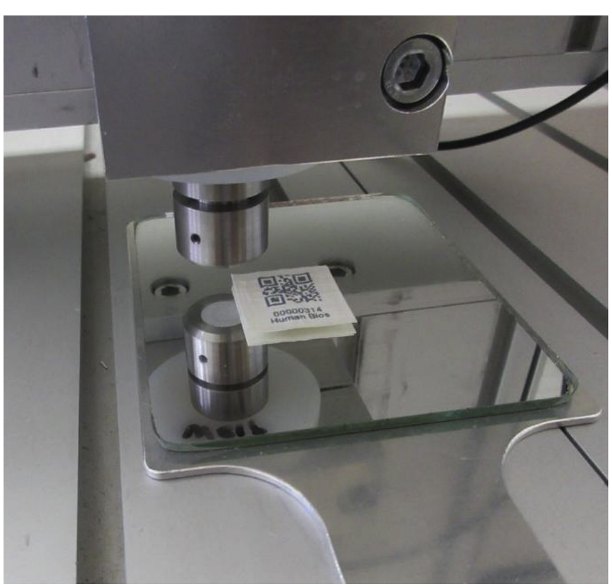

Fig. 1. Experimental setup of surface topography measurements: the ultrasonic probe points orthogonal towards the sample (craquelure) which is put onto a glass support.

Amplitude C-scans of the surface echo revealed the topography by edge detection: high amplitude at normal incidence and reduced amplitude at oblique incidence. The power of the method is revealed in Fig. 2 which shows the scan of a 1 Swiss Franc coin. The pixel size was 0.05 mm and the scanning time 15 min.

The time-of-flight (TOF) of the surface echo is linearly dependent on the distance of the probe to the surface of the sample. This is demonstrated in Fig. 3 where the TOF of the surface echo of a planar glass plate is measured as a function of the distance transducer-surface. The data follow closely the linear regression line with $R^2 = 0.9998$ and the slope gives the sound velocity in air of 346 m/s which is very near to the calculated value of 348 m/s (26 °C, 50%rH). A scan parallel to the surface gives a TOF D-scan. The TOF data may be converted to an elevation d via

$$d = 0.5ct$$

where c is the sound velocity in air and t the TOF value. The resolution is 2 µm and the mean error 0.03 mm.

2.2. Transmission inspection

A pair of air-coupled 200 kHz transducers (Ultran NCG200) were pointing towards each other, set at a fixed distance and moving parallel to the sample scanning the whole surface. The effective diameter of the transducers was 25 mm and 13 mm, respectively. A pulser/receiver (RPR4000, Ritec Inc, Warwick, RI, USA) together with a 40 dB preamplifier (5600C, Olympus NDT Inc, Waltham, MA, USA) working in transmission mode was used, as documented in Ref. [26]. The setup is shown in Fig. 4: Transmitter Tx and receiver Rx probes were situated on opposite sides of the sample – in this case the CFRP plate. The insonification was orthogonal.

Fig. 2. Amplitude C-scan of the surface of a 1 Swiss Franc coin.