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Non-destructive evaluation of puncture region in polyethylene composite by terahertz and X-ray radiation

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ABSTRACT

An ultra-high molecular weight polyethylene composite sample has been non-destructively imaged via X-ray and Terahertz waves. The sample stopped a projectile, which resulted in delaminations, a bulge, and a chamber. Although the X-ray computed tomography reliably showed all interesting internal features of the sample, the axial resolution was moderate and artefacts and deformations limited its performance. A terahertz time domain spectroscopy system was used both for transmission and reflection raster scanning of the sample. The propagation of the THz pulse through the sample was compared with a theoretical model. Transmission investigations roughly determined the distribution of delaminations and size of the chamber. The reflection scanning through the time-of-flight analysis and signal processing enabled a detailed 3D imaging of the sample. A very good agreement of X-ray and THz images was achieved. Both measurement methods were compared and discussed.

1. Introduction

The increasing amount of threats arising from firearms and explosives leads to the development of new fiber-reinforced composite materials for ballistic protection in helmets, bulletproof jackets and vehicles [2–4]. Composites made of ultra-strong aramid, carbon, glass, or ultra-high molecular weight polyethylene (UHMWPE) fibers are light, durable and resistant to environmental conditions [1–4]. Here, we report on examination of an UHMWPE composite, which acts like a system of nets gradually stopping a projectile [5–7]. This interaction results in delaminations whose positions and dimensions are important for better understanding of the process and helps in designing materials with higher level of protection.

Composites can be thoroughly analyzed using established non-destructive evaluation (NDE) methods, like X-ray, microwave, ultrasonic, acoustics or thermographic techniques [8–12], but alternative methods are sought to meet the demands of new materials. So far, the most common technique for puncture examination in UHMWPE composites has been X-ray computed tomography (X-ray CT) [7,12]. This method provides clear images of the internal features and enables deep penetration. However, this method uses ionizing radiation and the price of scanners is relatively high. THz radiation with a frequency between 0.1 THz and 3 THz can provide nonionizing and contactless examination of highly transparent and almost non-dispersive polyethylene [13]. Although UHMWPE composites are widely used for ballistic protection, only few THz results were already published [14–18].

Previously, we have demonstrated the application of reflection THz time domain spectroscopy (THz-TDS) [18] to investigate the internal structure of an UHMWPE composite plate that was totally punctured by a projectile. The TDS reflection method was selected from already available THz scanning techniques (like computed tomography [19] or a FMCW radar [20]) because it offers high resolution 3D imaging [21–26] through the time-of-flight analysis [21]. The signal processing was based on deconvolution and binarization. It indicated only two regions: polyethylene and air. The distribution of delaminations was properly imaged by THz-TDS which was compared with cross-sectional and frontal view obtained by waterjet cutting. The main drawback was the inability to

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measure the central part of the sample with the puncture because the tilted surfaces deflect the radiation.

Here, X-ray CT and THz-TDS techniques were used to image the internal structure of the UHMWPE sample which stopped a 5.56-mm-projectile. Although X-ray CT reliably showed all interesting internal features of the sample, the axial resolution was moderate and artefacts and deformations limit its performance. In relation to previous investigations [18], the THz measurements were extended by a transmission investigation of the sample, which can provide a rough distribution of delaminations and the size of the chamber. Moreover, the sample was also scanned from its back side in reflection configuration. The waveforms obtained from both sides of the sample were then binarized and merged, what enabled imaging of the entire sample. The X-ray and THz reflection images show very good conformity. Finally, the performance of both measurement methods was compared and discussed.

2. Characteristic of the sample

The investigated UHMWPE sample was manufactured from the HB26 tape from Dyneema [2]. This 270-μm thick tape consists of four 65-μm thick layers. Each layer is composed of 17-μm diameter SK 76 crystalline fibers. Fibers in subsequent layers are perpendicular to each other and altogether they are glued with polyurethane resin of about 17% of volume [2,7]. HB26 tapes were next stacked together and hot pressed to form a 250-mm-side squared sample having a thickness of 16 mm.

The sample was mounted in a holder and shot perpendicularly by a 5.56 × 45 mm projectile (NATO SS109) using a ballistic barrel. The bullet weighed 4 g and the velocity was 948 m/s according to the STANAG 4569 level 1. The projectile was stopped by the sample but it split into fragments, which entered the sample, freely moved inside the formed chamber and were removed from the sample. The small inhomogeneous and asymmetrical inlet bulge has a height of about 2 mm and a diameter of about 30 mm (Fig. 1a). The oval, uniform and symmetric back bulge is significantly bigger with a height of about 12 mm and diameter of about 100 mm (Fig. 1b). The inspection of the puncture with a thin elastic stick revealed an empty chamber with irregular shape (Fig. 1d). The thickness of the separated layer of the back bulge is around 7 mm.

Due to the dynamic interaction of the projectile with the sample, its back part was deflected and the formed bulge caused a contraction of the layers and their pullback of about 1–3 mm visible as steps in Fig. 1d. As a result at the points P, Q, R, T (red arrows in Fig. 1b), on the lateral surfaces of the sample (named with letters p, q, r, t) characteristic steps connected with delaminations (up to 100 mm-long) are visible (Fig. 1c). Fig. 1c shows the lateral surface p with an estimated depth of hardly visible delaminations marked with roman numerals (I–III). Thicknesses of the delaminations I–III at the point P, determined with a microscope, were equal to about 200 μm. A metallic 20-mm wide tape was glued to the back surface of the sample, which helped to determine the position of this surface in the THz reflection measurements carried out from the front side.

3. X-ray CT set-up and measurement results

The sample was investigated using the X-ray CT system – GE phoenix v/tome/x m with 300 kV tube and detector array (Fig. 2). Examinations were carried out under the following conditions: voltage 110 kV, current intensity 140 μA and timing 500 ms. The sample was located 150 mm from the radiation source, which determined the voxel size to be around 150 μm. The sample was mounted on a rotating holder at an angle of 30° in relation to the beam, which provided relatively uniform illumination. The rotation step was 0.5°. The image was reconstructed using a graphical station with Phoenix Datosx 2 programme. Next, VG Studio Max 2.2 software was used for processing and analysis of images.

B-scans for two cuttings along P-O-R and G-O-F axes are shown in Fig. 3. To improve the readability, the images have been expanded two times along the Z axis (in depth). Fig. 4 illustrates C-scans for different planes (marked in Fig. 3a with lines on the left)

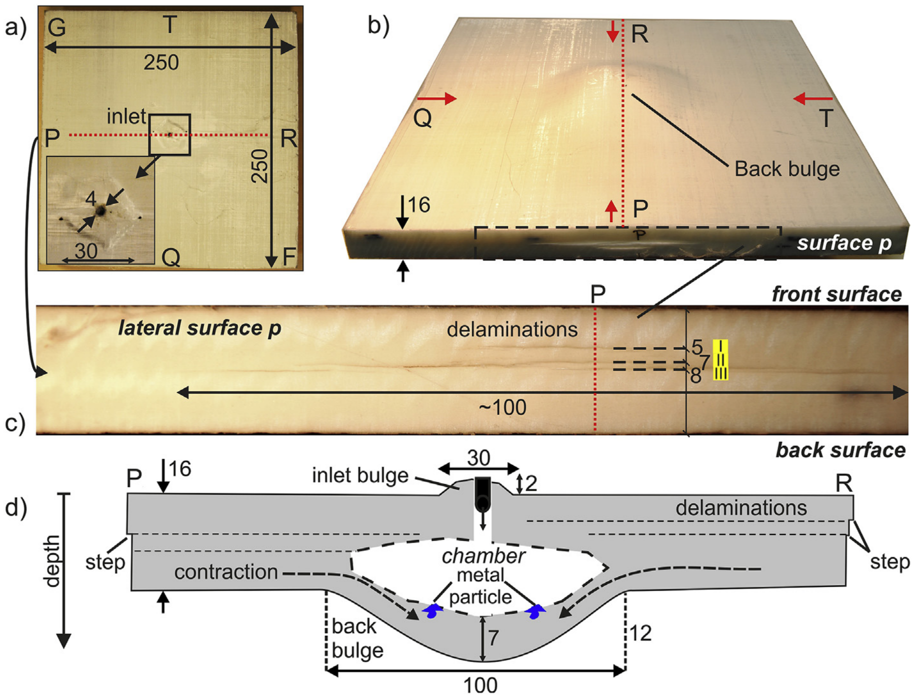

Fig. 1. Photographs of the sample: the front surface (a), the back surface (b), and the side view (c). The scheme of the cross-sectional view (d). All dimensions are in mm.