Nondestructive characterization of UHMWPE armor materials

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Nondestructive characterization of UHMWPE armor materials

Abstract
Ultra-high molecular weight polyethylene (UHMWPE) is a material increasingly used for fabricating helmet and body armor. In this work, plate specimens consolidated from thin fiber sheets in series 3124 and 3130 were examined with ultrasound, X-ray and terahertz radiation. Ultrasonic through-transmission scans using both air-coupled and immersion modes revealed that the 3130 series material generally had much lower attenuation than the 3124 series, and that certain 3124 plates had extremely high attenuation. Due to the relatively low inspection frequencies used, pulse-echo immersion ultrasonic testing could not detect distinct flaw echoes from the interior. To characterize the nature of the defective condition that was responsible for the high ultrasonic attenuation, terahertz radiation in the time-domain spectroscopy mode were used to image the flaws. Terahertz scan images obtained on the high attenuation samples clearly showed a distribution of a large number of defects, possibly small planar delaminations, throughout the volume of the interior. Their precise nature and morphology are to be verified by optical microscopy of the sectioned surface.

Keywords
delamination, flaw detection, inspection, optical microscopy, plates (structures), polymers, terahertz wave imaging, terahertz waves, ultrasonic materials testing, X-ray spectroscopy, nondestructive evaluation, QNDE

Disciplines
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Comments
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NONDESTRUCTIVE CHARACTERIZATION OF UHMWPE ARMOR MATERIALS

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ABSTRACT. Ultra-high molecular weight polyethylene (UHMWPE) is a material increasingly used for fabricating helmet and body armor. In this work, plate specimens consolidated from thin fiber sheets in series 3124 and 3130 were examined with ultrasound, X-ray and terahertz radiation. Ultrasonic through-transmission scans using both air-coupled and immersion modes revealed that the 3130 series material generally had much lower attenuation than the 3124 series, and that certain 3124 plates had extremely high attenuation. Due to the relatively low inspection frequencies used, pulse-echo immersion ultrasonic testing could not detect distinct flaw echoes from the interior. To characterize the nature of the defective condition that was responsible for the high ultrasonic attenuation, terahertz radiation in the time-domain spectroscopy mode were used to image the flaws. Terahertz scan images obtained on the high attenuation samples clearly showed a distribution of a large number of defects, possibly small planar delaminations, throughout the volume of the interior. Their precise nature and morphology are to be verified by optical microscopy of the sectioned surface.

Keywords: Ultra-High Molecular Weight Polyethylene, Material Characterization, Ultrasonics, Terahertz Radiation, X-ray

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INTRODUCTION

Ultra-high molecular-weight polyethylene (UHMWPE) is being increasingly used as an armor component. This material, consisting of very long molecules with a simple repeated atomic structure, has low density but high toughness. It can be spun into fibers that can then be laid into sheets. Four-ply-thick sheets of UHMWPE fiber plus resin are commercially available under two brand names: Spectra Shield® and Dyneema®. These thin sheets can be layered and compacted to form structures such as the helmet shown in Fig. 1a. The properties of UHMWPE structures depend in part on the details of the fabrication procedure such as the temperature and pressure used for consolidation. During this processing, however, inadvertent generation of defects can occur. Thus, it is desired to evaluate and select an optimal technique among the various NDE methods for inspecting and characterizing these UHMWPE materials. The eventual goal is to establish the correlations between fabrication parameters, NDE signatures and armor performance.

As the first step toward that goal, in this work we investigate the use of ultrasound (UT), X-ray and terahertz radiation (THz) as modalities for characterizing the uniformity of compacted UHMWPE plates. South Dakota School of Mines & Technology supplied 12 UHMWPE plates, fabricated at different consolidation pressures ranging from 1000 to 5000 psi (Fig. 1b). The consolidation temperature was 280°F in each case. Seven of the plates were made using thin sheets of Spectra Shield 3124 as the starting point. The remaining seven
were made using Spectra Shield® 3130. The latter is the newer Spectra Shield® product that uses a different resin. Each plate measured roughly 6” x 6” x 0.25”. To check fabrication reproducibility, duplicates of two of the 3124-series plates (4000 psi and 5000 psi) were made some months after the initial batch of plates were fabricated. Work began with the basic physical weight and density measurements, followed by air-coupled and immersion UT testing, X-ray imaging, and ended with THz examinations.

ULTRASONIC AND X-RAY INSPECTIONS

UT through-transmission (TT) measurements were made using the air-coupled and water-immersion setups pictured in Fig. 2. The nominal center frequency for the air-coupled system was 120 kHz, while that for water-immersion was 500 KHz. For the central 3” x 3” region of each plate, a TT C-scan image was made by displaying the peak amplitude of the earliest-arriving ultrasonic signal. Such C-scans are shown in Fig. 3 for five of the 3124-series plates. Significant variability in signal amplitude was found, both between plates and within a given plate. Although the air-coupled and immersion C-scans use different color palettes, the patterns of high and low amplitude for a given plate are seen to be fairly similar for the two techniques. Generally speaking, both plate-to-plate and intra-plate variabilities were smaller for the 3130-series plates as compared with the 3124 plates.

All of the UHMWPE plates float in water, and we can apply Archimedes principle to estimate the plate densities. Results are shown in Fig. 4a. For 3130 series, all densities were within a few tenths of a percent of unity, while for the 3124 series, densities ranged from about 0.95 to 0.98 gm/cc. The average UT response (from the central 3” x 3” region) was fairly well correlated with density, with TT amplitude decreasing as the density dropped. That is illustrated in Fig. 4c for the immersion inspections.

The average UT responses shown in Fig. 4b are broadband measures of the relative sonic transmissivities of the various plates. An absolute measure of attenuation-versus-frequency can be done, for example, by comparing the TT spectra at a location on the specimen to that seen in water only with the specimen removed. Fig. 4d shows attenuation curves deduced by that method for “high amplitude” regions of two of the plates, 3124-5000psi, and 3130-1000psi. The measured attenuations are seen to rise roughly linearly with frequency. At 500 kHz, the measured attenuation is about 10dB/inch for the 3130 plate, and about 45 dB/inch for the 3124 plates. Because the attenuation values are fairly high and rise with frequency, we have used 500 kHz transducers for our immersion measurements.
In addition to UT methods, limited X-ray examination was also performed. Fig. 5 shows the 40kVp X-ray TT image of plate 3124-3000psi, revealing a few small high-density inclusions and a ply wrinkle near one edge of the specimen. However, in the central 3” x 3” region of the specimen, there was no pattern of transmitted X-ray intensity that mirrored the transmissivity pattern seen in the UT inspection.

The 3124 plates are the most interesting in the sense that they show greater variability in UT transmissivity (or attenuation). There are three possible reasons why the variations are seen within a given plate, e.g. 3124-3000psi:

1. At one particular depth, there may be incomplete bonding between the two adjacent plies. If this were the case, one might expect to see evidence of internal reflection at that depth via pulse-echo ultrasound. Pulse-echo inspection at 500 kHz was performed, but revealed no clear evidence of clustered internal reflectors at one particular depth,

2. There may have been migration of material during fabrication with some regions becoming fiber rich, and others resin rich. If so, one might expect to see evidence via X-ray examination.
However, as mentioned above, none of the UT pattern was seen in the X-ray image. Apparently, this discrepancy requires further study, and may eventually be resolved by destructive analysis.

(3) There may be distributed porosity/delamination whose local density varies with position. It is expected that different plates can have different overall average densities, so perhaps the local density within a plate varies as well. If this is the case then one would expect to see a correlation between sound speed and attenuation. That is because the presence of porosity/delamination reduces elastic stiffness (hence reducing sound velocity), and raises the attenuation (due to scattering from the pores) [1].

Continuing on reason (3), further examination looked for a correspondence between sound speed and UT transmissivity in plate 3124-300psi. The result is summarized in Fig. 6. For a TT inspection of the central 3” x 3” region, both amplitude and time-of-flight (TOF) C-scans were made. For the former, the peak-to-peak amplitude of the early-arriving UT signal was used as the amplitude measure. For the latter, the TOF was taken to be the arrival time of a particular zero-crossing in the transmitted signal. One sees in Fig. 5a that regions with high peak-to-peak amplitude tend to correspond to regions with low TOF values. Thus high amplitude is associated with early arrival time or hence with increased sound speed. Going one step further, in Fig. 6b a pixel-by-pixel comparison of the two C-scan images is made, plotting TOF versus transmitted amplitude. One sees a fairly well-defined trend to the data of the type expected, if local porosity/delamination variations were the driving force behind the amplitude and TOF variations. Also note that the variation in arrival time within plate 3124-3000psi corresponds to about a 5% variation in sound speed with lateral position.

FIGURE 4. Summary of immersion UT results: a (top left) measured plate densities; b (top right) average TT amplitudes for the central 3” x 3” region of each plate; c (lower left) correlation between UT amplitude and density; d (lower right) measured attenuation-versus-frequency for selected regions on two of the plates.
FIGURE 5. 40kVp X-ray image of plate 3124-3000psi.

FIGURE 6. a (top row) Comparison of amplitude and TOF C-scans for TT immersion inspection of plate 3124 – 3000 psi. The drawing at right shows the waveform features used to measure amplitude and TOF; b (bottom) Correlation between amplitude and TOF for plate 3124 – 3000 psi.
THZ INSPECTION

As described in previous section, significant progress was made in UT inspection and the corresponding analyses. However, because the inspection frequencies were limited in the relatively low region, pulse-echo immersion UT testing could not detect distinct flaw echoes from the interior. To characterize the nature of the defective condition that was responsible for the high UT attenuation, THz time-domain spectroscopy (TDS) mode was used to image the flaws.

THz is an emerging electromagnetic technique applied to a variety of science and engineering fields [2]. Its application in NDE, particularly for inspecting and characterizing materials, is being explored actively (see, e.g. [3-4]). THz bears strong resemblance to UT. Both are governed by similar wave propagation laws such as Snell’s law, etc. Echo-dynamics such as time-of-flight, amplitude, phase, etc. and attenuation/material scattering are key quantities for both. THz TDS operates similarly to pulsed UT as both can have A-, B-, and C-scans acquired in both reflection and transmission modes. Still there are some basic differences between THz and UT. The most vital one to NDE practice is the “shadow effect”. THz’s electromagnetic energy can go through vacuum, while UT, as a mechanical wave, is hampered by the “shadowing” or blockage of the UT propagation by crack/void/delamination type of defects.

A typical THz inspection of the UHMWPE materials in reflection mode is shown in Fig. 7 where a larger 58-ply plate is raster scanned by a TDS system using a small-angle pitch-catch setup. All 12 UHMWPE plate specimens of this study were examined in the same setup. The entire plate area was covered at 1mm spatial resolution. The THz beam was focused at half depth (thickness) below the front entry surface with a focal length of 50mm in air. Waveform data (A-scan) were taken at each of the scan positions. Fig. 8 displays the resulting A-, B- and C-scan images of one of the high attenuation specimen 3124-4000psi #2. These images clearly show a distribution of a large number of defects, possibly small planar delaminations, throughout the volume of the interior. From the B-scan (Fig. 8b), it is observed that most of these planar delaminations/porosities are confined in the middle two-third of plate thickness. The orientation of these indications runs in parallel with the fiber direction, some are more than 20mm long. The B-scan also indicates the plate thickness is reduced towards the edge of the plate. In-between the front- and back-surface echoes, spikes of fairly large amplitude can also be seen in the A-scan (Fig. 8a)

Plates 3124-2000psi #1 and 3124-1000psi also show similar high amplitude patterns as that of 3124—4000psi #2 while plates 4000psi #1 and 3124-5000psi revealed some delaminations/porosities indications of much lesser severity.

FIGURE 7. THz TDS scan of a 58-ply Spectra 3PSF plate using a small-angle pitch-catch reflection setup.

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FIGURE 8. THz scan images of plate 3124-4000psi #2 a (top left) A-, b (top right) B-scans; c (bottom) C-scan.

SUMMARY

In summary, we found both air-coupled and immersion UT useful for inspecting layered UHMWPE plates. Either technique could discern plate-to-plate and intra-plate differences in UT transmissivity. Those differences are believed to arise from the presence of distributed porosities within the plates whose volume percentage (in the through-thickness direction) varies with position. The assumption that porosity/delamination is responsible for the variation is supported by immersion-UT data showing a correlation between transmitted amplitude and time-of-flight. However, due to the “shadowing” effect of the porosity/delamination, UT cannot provide direct evidence of the presence of the porosity/delamination. Fortunately, the electromagnetic THz is able to rectify this deficiency. As revealed in THz A-, B- and C–scan images, the geometric morphology of the distributed porosities/delaminations are clearly seen with exceptional resolutions in both longitudinal depth and lateral spatial extent. This result also demonstrates the complementary role of UT and THz examinations.

In the future, we hope to perform destructive analysis in selected regions in order to (1) verify the presence of porosity/delamination, (2) compare the size, shape and number density of
the pores with the THz data and (3) correlate the NDE data with the actual mechanical performance of these plates. By integrating all these results, we wish to ultimately establish the direct links between fabrication parameters, NDE inspection data and armor performance.

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