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Test Method

Characterization of ductile damage in polyethylene plate using ultrasonic testing

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ABSTRACT

An experimental study was conducted to explore the possibility of using ultrasound to quantify deformation-induced damage in polyethylene (PE) plate. Specimens of two gauge lengths were machined from PE plates with thickness in the range from 1.5 to 10 mm. The specimens were first stretched monotonically to various prestrain levels to vary the extent of damage introduced by the stretch. Ultrasonic testing in the through transmission mode was then conducted on the prestrained specimens to determine the time of flight, based on which ultrasonic velocity was determined. The results show that the ultrasonic velocity, normalized by the speed in the virgin plate of the same thickness, decreases with the increase of prestrain. The study also shows that, with the correction of density change by the prestrain, the normalized ultrasonic velocity can be used to determine the dependence of damage level on the prestrain which, for specimens with long gauge length, is consistent with the damage determined by mechanical testing. The study concludes that ultrasonic testing can be used as a non-destructive means to quantify deformation-induced damage evolution in PE plates.

1. Introduction

Semi-crystalline polymers are increasingly used in a wide range of applications, including aerospace, automobiles, nuclear power plants and pressure tubing for water and natural gas transportation. In the pressure tubing applications, statistics shows that over 90% of the newly installed gas pipeline systems are now made of PE [1]. Such an extensive usage is attributed to the combination of reliable thermal stability, excellent corrosion resistance, relatively low cost, light weight and good flexibility, to name a few, which provide easy installation and maintenance of PE pipelines. However, unexpected, catastrophic failures of PE pipes were still reported in the last decade [2–4], suggesting that new methodologies are needed to monitor PE's property deterioration in order to predict accurately their remaining service life. Furthermore, in spite of a lot of effort being devoted to the study of damage and failure mechanisms in PE [5–10], characterization of damage in PE is still a real challenge due to the possibility of damage generation in normal service conditions, such as squeeze-off process for repair and maintenance and variation in service loading histories. The problem is further aggravated by PE's complex deformation behavior.

Over the past decades, thanks to the rapid development of damage mechanics and experimental instrumentation, studies on the behavior of damaged materials have come up with various methods for the damage characterization. These methods can be broadly classified into two approaches based on (i) mechanics of porous media (MPM) and (ii) continuum damage mechanics (CDM). The former uses void volume fraction (i.e., porosity) as the damage indicator to describe property degradation of materials. In this approach, Gurson's damage model [11] is most widely used for quantifying ductile damage evolution, which is through the use of a porosity term to progressively down-scale the yield surface. This model has been successfully extended to account for coalescence and growth of voids [12–14]. Techniques based on this model use volume strain to quantify the porosity, which include scanning electron microscopy (SEM) [15–18], wide-angle X-ray scattering (WAXS) and small-angle X-ray scattering (SAXS) [19–24].

For the CDM-based approach, a macroscopic damage variable D is introduced to reflect a progressive deterioration of material properties, and is used to quantify the damage process. Based on

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the effective stress concept and strain- or energy-equivalent hypotheses, various methods have been developed to measure degradation of mechanical properties, such as elastic modulus, strength and hardness, based on which damage is quantified. In 1987, eight different direct and indirect experimental methods to characterize damage were discussed by Lemaitre and Dufailly [25]. The direct methods include digital microscopy to observe areas covered by voids or cracks and measurement of density variation. The indirect methods, on the other hand, are to measure changes in elastic modulus, ultrasonic velocity, micro-hardness or electrical potentials. One of the most widely used methods to characterize damage is to measure reduction of elastic modulus from cyclic loading-unloading tests [26–35]. However, most of the aforementioned works are to quantify damage development in metallic materials. Much less attention has been paid to characterize damage development in semi-crystalline polymers based on the concept of continuum damage mechanics (CDM).

Compared to the destructive methods that require preparation of n specimens to determine, for example, ratio of damaged area to the total surface area, density or elastic modulus, non-destructive evaluation (NDE) methods have the advantage of providing in-situ characterization of material properties or inspection of engineering structures such as pipelines. A number of NDE methods, such as acoustic emission [36–39], electrical methods [40–42], infrared thermography [43–46], vibration-based methods [47–49] and ultrasonic methods [50–54], have been proposed for non-destructive damage characterization. Among these methods, ultrasonic methods are considered to be one of the most feasible to evaluate change in mechanical properties because ultrasonic system is relatively low in cost, easy to operate and has the ability to reveal microscopic changes in the inspected materials. Since magnitude of ultrasonic velocity is related to density and stiffness of the material, measurement of the ultrasonic velocity can provide a non-destructive means to assess changes in mechanical properties of the material. Damage state and its evolution can then be determined by comparing the measured mechanical properties with the corresponding values of the virgin materials.

According to the definition of effective stress in CDM, ultrasonic velocity and damage variable D are suggested to follow the expression of $D \approx 1 - v_D^2/v_0^2$ [25], where v_D and v_0 are ultrasonic velocities of longitudinal waves in damaged and virgin materials, respectively. This expression enables people to use ultrasonic methods as an effective tool to characterize various types of damage in materials, such as damages by tensile loading [35,55], compressive loading [56–58], creep loading [59,60] and fatigue loading [52,61]. However, current use of ultrasonic methods for such damage characterization is mainly for concrete and metallic materials. To our knowledge, no work has been reported to use ultrasonic methods to quantitatively characterize damage in semi-crystalline polymers.

Although no work has been reported to use ultrasound to characterize damage in polymers, studies have shown that many factors affect ultrasonic wave propagation in polymers. For example, ultrasonic velocity and attenuation are known to be sensitive to polymer morphology [62–64], and vary markedly with the change of crystallinity and density. These studies also found that these quantities vary with the frequency of the ultrasonic transmitter used for the measurement. Furthermore, temperature and stress are known to affect ultrasonic velocity of longitudinal waves in polymers [65,66].

In view of in-service detection and monitoring of damage development being important to ensure safe operation of pipeline systems, we have explored the feasibility of using ultrasonic wave propagation as a NDE tool to assess damage development in PE pipes. This paper summarizes results from a preliminary study that uses ultrasonic wave in the through transmission mode to explore the possibility of developing an ultrasonic method to detect and quantify damage in PE, as a first step to evaluate its applicability to PE pipes.

2. Experimental details

2.1. Materials and specimens

PE plaques, provided by NOVA Chemicals, were used to prepare specimens for the testing. The PE plaques were compression-molded from pellets to nominal thickness of 1.5, 3, 6 and 10 mm with material characteristics shown in Table 1. Two types of PE specimen, designated “short” and “long” for ligament lengths of 3 and 10 mm, respectively, were used to provide two levels of stress triaxiality at which the damage is generated. The specimen dimensions are shown in Fig. 1. Because thickness of the specimens ranges from 1.5 to 10 mm, the constant 10 mm ligament width results in a change in aspect ratio (width/thickness) from 6.7 (for nominally 1.5 mm-thick specimens) to 1 (for nominally 10 mm-thick specimens). For simplicity, long specimens with nominal thicknesses of 1.5, 3, 6 and 10 mm are denoted by L-1.5, L-3, L-6 and L-10, while short specimens by S-1.5, S-3, S-6 and S-10 respectively.

2.2. Mechanical tests

All mechanical tests were conducted using a universal test machine (QUASAR 100) at room temperature. A two-stage test method, initially proposed by Jar [67,68], was adopted to investigate the effect of prestrain on the degradation of elastic modulus. At the first stage, prestrain is introduced to specimens at a constant crosshead speed of 1 mm/min. Then two months later at the second stage, elastic modulus is measured at the crosshead speed of 0.01 mm/min. The period of two months is to allow the specimens to recover from the viscoelastic deformation before the second-stage tests.

The procedure for the first-stage tests is similar to that used before [69]. That is, at the end of the loading phase, specimens were held at the displacement for a period of 3 h for stress relaxation before unloading. Note that changes in both ligament width and ligament thickness were recorded during the test, the former through a data acquisition portal of the test machine and the latter a digital oscilloscope. Since data recorded using the digital oscilloscope could be converted to thickness only after the test, prestrain introduced in the first-stage test was controlled using the recorded change of ligament width. This provided a similar prestrain range for long specimens of different thickness. For short specimens, however, as shown later, the prestrain range covered by the same width contraction varies significantly among specimens of different thickness. This is because contraction in the thickness direction shows a strong dependence on the specimen thickness. Nevertheless, results reported here are presented in terms of prestrain values introduced in the first-stage tests, calculated using the following expression.

Table 1
Material characteristics for HDPE used in this study.

M_w (g·mol^{-1})	M_n (g·mol^{-1})	M_w (g·mol^{-1})	Density, ρ (g·cm^{-3})	M_w/M_n
73,100	30,400	147,000	0.941	2.4

M_w, M_n and M_z stand for weight-average, number-average, and Z-average molecular weight respectively.