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Investigation on perforation mechanism of medium density polyethylene

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Abstract: In this article, the perforation mechanism(s) of polyethylene was investigated through experiments. Several polyethylene (PE) film samples were fabricated by compression molding technique. In order to examine the perforation mechanism of PE, perforation tests were conducted according to ASTM F 1306 Standard procedure. The damage and plastic zone areas around the perforated area in PE test samples under cross polarized light condition were studied using the optical microscope. The plastic zone area was measured using an image analysis technique. For further clarification of the perforation mechanism of medium density PE (MDPE) films, the micrographs obtained form scanning electron microscope were examined. SEM observation of the test specimens showed shear bands formed in the plastic zone around the perforated area. The shear bands were observed to be on 45° angle with respect to the direction of applied force.

Introduction

Polyethylene (PE) is commonly used in the plastics industry and especially for cable covering due to its abrasion resistance, flexibility, excellent electric insulation properties, low toxicity, and easy processing [1]. PE, like all plastics, is a polymer based material consisting of long chains of identical molecules. PE is classified into several different categories based mostly on its density and branching character. The mechanical properties of PE depend significantly on a number of variables including the extent and type of branching process, its crystal structure and molecular weight. Medium density polyethylene (MDPE) is a kind of PE defined by a density range of 0.926 - 0.940 g cm^{-3}. MDPE has good shock and drop resistance properties. It is also less notch sensitive than high density polyethylene (HDPE) and its stress cracking resistance is better than HDPE.

PE possesses a semi-crystalline structure which makes it a suitable choice for a variety of engineering plastics and particular applications. Crystallinity offers many desirable attributes such as stiffness, strength, obstructing gas (moisture and oxygen) transport, resistance to chemicals and dimensional stability. The non-crystalline segments impart such attributes as toughness and resistance to slow crack growth.

There have been many investigations in the past few years with the main focus on the mechanical, thermal and morphological properties of different types of PE materials with regard to their different applications. Several researchers have considered the effect of parameters such as crosslinking, crystallinity, the length of short chain branch and filler particles on the surface and mechanical (tensile, fatigue, and shock loading) properties of PE materials. The effect of crosslinking on properties of various types of PE has been extensively studied [2]. Crosslinking leads to an increase in the viscosity of the liquid polymer, increased tensile strength, improvement of creep properties and an increase in the resistance to environmental stress cracking [2]. It is well known that the degree of crystallinity has a strong influence on polymer's mechanical properties including Young's modulus, yield stress, strain hardening rate, work of fracture and ultimate tensile strength [3]. Truss et al. [4] have showed that the modulus of ultra high molecular weight PE (UHMWPE) varies as a function of cooling rate from the melt temperature (133 °C).

MDPE is typically used in gas pipes and fittings, sacks, shrink films, packaging films, carrier bags, and screw closures. Indeed in almost mentioned applications resistant against perforation and

tearing resistance is an important issue. Furthermore, Material's response to penetration varies with numerous factors such as film thickness, elastic modulus, rate of penetration, temperature, and the shape and type of probe used for testing. No significant investigations have been conducted before for evaluating the perforation behavior of medium density PE (MDPE). Thus the main goal of the current research is to elucidate role of nano size calcium carbonate on resistant against perforation of MDPE.

Experimental work

Materials and Sample preparation. In order to clarify the perforation mechanism(s) of polyethylene, MDPE films were produced. Medium Density PE (Eltex B4020) supplied by Solvay Polyolefins, Rosignano, Italy, was used for making the film specimens. Figure 1 shows the scanning electron micrograph of MDPE powder used in this investigation. Standard test samples were made using compression molding technique at process temperature of 140 °C.

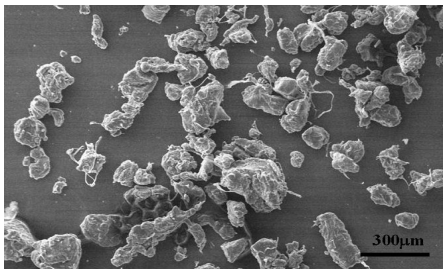

Figure 1. Scanning electron micrograph of medium density Polyethylene powder as the starting material.

Perforation test. As mentioned previously, penetration behavior is controlled by different parameters including the thickness of film specimen and its elastic modulus, the rate of penetration, test temperature, and the shape and type of probe used for the test. On this basis, perforation tests were conducted at room temperature according to ASTM F1306-90 procedure [5] using a Zwick Z250 tensile test machine with the cross-head speed of 10 mm/min. The tip angle of the indenter used for the experiments was around 30°.

Microscopic evaluation. A Carl Zeiss optical microscope was employed to examine the damage and plastic zone developed around the perforated area in polyethylene film specimens under the cross polarized light condition. A XL30 scanning electron microscope with tungsten filament and 20 kV accelerating voltage was utilized for electron microscopy examination. The test specimens were coated using a sputter coater (BAL-TEC SCDOOS) with a thin layer of gold prior to electron microscopy in order to avoid building up the electrical charge.

Image Analysis for measuring of plastic zone area. An image analysis technique was used for quantitative examination of the plastic zone area in test specimens using images taken from the optical microscope. The color images obtained from the optical microscope were first converted to grayscale images. A controlled threshold operation was then employed for image digitization since the plastic zone pixels were darker than those in remaining image, with the final effect of reduced intensity. The gray images consisted of 256 levels of gray intensity (0 = black and 255 = white). To identify the plastic zone, a threshold gray intensity value had to be chosen. The gray intensity measured for a given point was higher or lower than this specified threshold. Using the threshold value, the gray images were transformed to binary images of white (plastic zone) and black (remaining areas) colors. Finally, the pixels corresponding to the plastic zone areas were converted to square micrometer units.

Results and discussion.

Fig. 2 shows the perforation force–displacement curve for the investigated material. As can be observed in this Figure, there is a noticeable discontinuity in curve at the initial stages of the test representing a region (or a point) where the test indenter penetrates the sample. This point is defined as a point at which the specimen resistance against first penetration of the indenter has been

overcome. The load increases afterwards as the indenter penetrates further into the sample, until at a region where the applied load reaches its maximum value. The applied load then starts to decrease suggesting that the ultimate resistance of the specimen against tearing phenomenon has been already reached.

In order to determine the probe penetration (depth probe (mm) traveled in the film specimen from the initial probe in contact with the sample to the penetration at break.) and its relevant force, force to the final break point (peak force corresponding to the final break area), the variation of instantaneous slopes of the perforation force–displacement curve was plotted with the same perforation displacement as the x-axis.

A number of load drops were observed in the slope-displacement curve (Fig. 3). According to the criterion mentioned previously, the first significant drop in the applied load (Fig. 3) with the final value close to zero was considered to be the first fracture phenomenon occurred corresponding to the first penetration of the indenter into the test specimen. Finally, the unique point in the x-axis indicating its intersection with the slope curve was considered as the peak force, which was defined to be the last point for the test where the indenter penetrated entirely in the specimen.

According to ASTM F1306-90 procedure, the area underneath the force–displacement curve up to the peak force was assumed to be the energy (work) necessary to break the test specimen. The results of all the measurements and calculations mentioned above are summarized in Table 1.

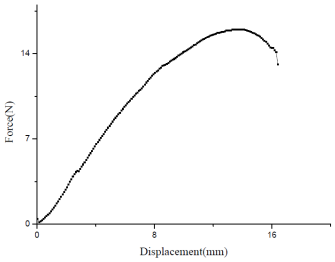

Fig. 2. Perforation force – displacement curve for the investigated material

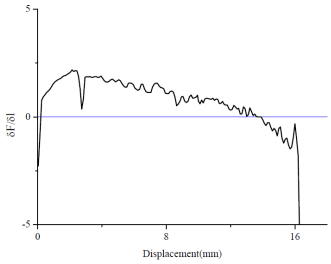

Fig. 3. Variation of $\partial F/\partial l$ with displacement for the investigated

Fig. 4 shows the optical micrograph of a polyethylene film specimen with the plastic zone around the perforated area and the digitized image obtained from the image analysis technique.

The scanning electron micrographs showing the damage zone around the perforated area in a PE test specimen can be seen in Fig. 5. Observation of the damage zone around the perforated area in this sample clearly shows the occurrence of shear yielding within the damage zone areas [6,7]. Deformation of matrix in this series of images suggests that a mechanism based on the matrix shear yielding has been the dominant toughening mechanism in this material during the perforation test.

Table 1. The experimental and calculated data for the test specimens.

Prob Penetration(mm)	Force at first break(N)	Peak Force(N)	Energy of Break(J)	plastic zone area(μm^2)
2.75	4.36	16	136.86	4128429.75

a b

Fig. 4. Optical micrograph of the plastic zone (a) and its digitized image (b) in a test specimen.

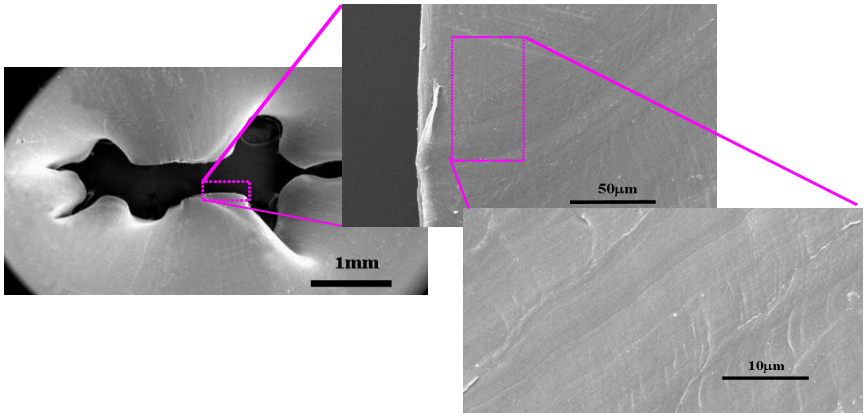

Fig. 5. SEM micrographs showing the damage zone around the perforated area in a PE test sample at different magnifications.

As clearly observed in SEM micrograph in Fig. 6, repeated tearing is occurred in test sample after perforation. It was finally concluded that deformation and perforation phenomena were followed by delamination since the test samples were clamped during the whole perforation tests.

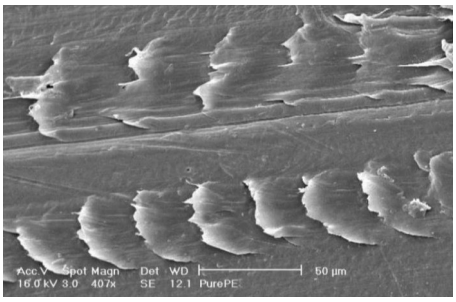

Fig. 6. SEM micrograph showing repeated tearing around the perforated area in a PE test sample.

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