SAND2007-1863C

Fracture Behavior of Polyurethane Foams

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ABSTRACT

Due to their high energy absorption capabilities, polyurethane (PU) foams have been widely used in many applications. The mechanical behavior of Polyurethane (PU) foams has been attracting the attention from engineers and researchers. But most of work was to study the compressive behavior of PU foams. Very little knowledge is available about the fracture behavior of the PU foams. In this paper, single edge notch bend (SENB) tests are conducted to study the mode-I fracture behavior of a rigid closed cell PU foam, PMDI 20, with a nominal density of 20 pcf (320 kg/m^3). The stress intensity factor K_{IC} is calculated from the loading curves. The displacement and strain field around the crack tip is obtained using digital image correlation (DIC) technique.

INTRODUCTION

Polyurethane (PU) foam can absorb energy by undergoing a large amount of compressive deformation. It has been widely used in packaging and cushioning to protect sensitive objectives. However, they have a tensile failure strain of a few percent or even less than one percent. In our previous uniaxial compression tests, it has been shown that both tensile and compressive strains are developed inside the foam specimens due to the inhomogeneous deformation of the foam specimens during compression and that there is large tensile strain concentration at the interface of foam specimen and the protected object. The tensile deformation causes the failure of the foam specimen by the propagation of the crack [1]. Therefore, it is very important to study the fracture behavior of the foam specimens in order to effectively protect sensitive objects.

Most rigid polymer foams are linear-elastic in tension. The fracture failure can thus be treated by the concept of linear-elastic fracture mechanisms [2]. The efforts of determining the fracture toughness of foam materials can be traced back to more than three decades ago. Fowlkes *et. al* determined the fracture toughness of a low density rigid PU foam using the center, double-edge notched, single-edge notched tension test and the double cantilever beam specimens [3]. McIntyre *et. al* studied the fracture properties of a rigid PU foam with a range of densities using the single edge notch test to find out the relation between the fracture toughness and the foam density [4]. Kabir *et. al* studied the tensile and fracture behavior of polymer foams using prismatic bar specimens and single edge notch bend specimens. Most of these studies focused on polymer foams with relatively low density, less than 12 pcf (192 kg/m^3). In this paper, the foam material of interests is a specific rigid closed-cell PU, PMDI (Polymeric Methylene Diphenyl Diisocyanate) foam, with a nominal density of 20 pcf (320 kg/m^3). Single edge notch specimens were tested under three point bending. The fracture toughness is obtained from the load versus displacement curves. The digital image correlation (DIC) technique is applied to calculate the displacement and strain distributions around the crack tip. The DIC technique is a full-field surface deformation measurement technique that mathematically compares a subset of a digital image from a reference configuration with a digital image from a deformed configuration. Researchers at the University of South Carolina [4-7] originally proposed and developed this technique, which has become an accepted method by the experimental mechanics community for measuring the surface displacement with subpixel resolution. The DIC technique has proven successful when applied to foam specimens for large deformation and strain concentration [8].

FOAM SPECIMEN PREPARATION

All the specimens were cut from the same foam billet. The density of each specimen was measured carefully, with variations among the specimens. The average cell size is about 150 μm as shown in the scanning microscopic image of the cross section perpendicular to the rise direction in *Fig. 1*.

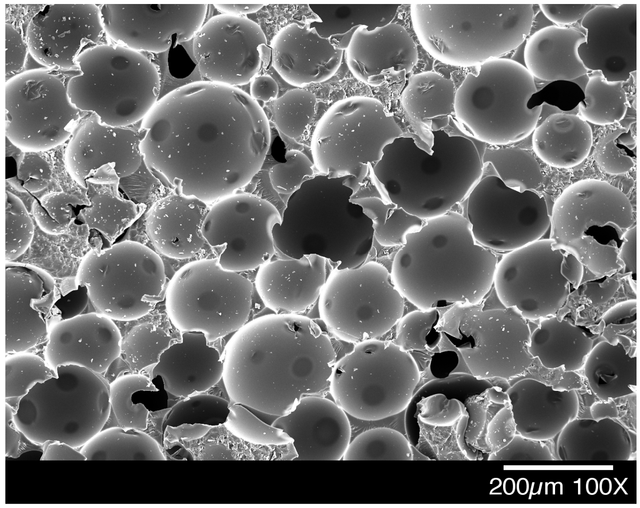


Fig. 1. SEM image of foam PMDI 20

The specimens were cut with the notch edge oriented along the foam rise direction as schematically shown in Fig. 2a. A sketch of the bending specimen is shown in Fig. 2b. The dimensions of the specimens are W (height) = 1" (25.4 mm), L (specimen length) = 5W = 5" (127mm), B (width) = 0.5W = 0.5" (12.7mm). The crack length a = 0.4W = 0.4" (10.2 mm). The initial edge crack of 0.3" deep (7.6mm) is produced by saw cut with cut width of 0.025" (0.63mm) and the sharp crack tip of 0.1" deep (2.54mm) is produced by a sharp thin razor blade.

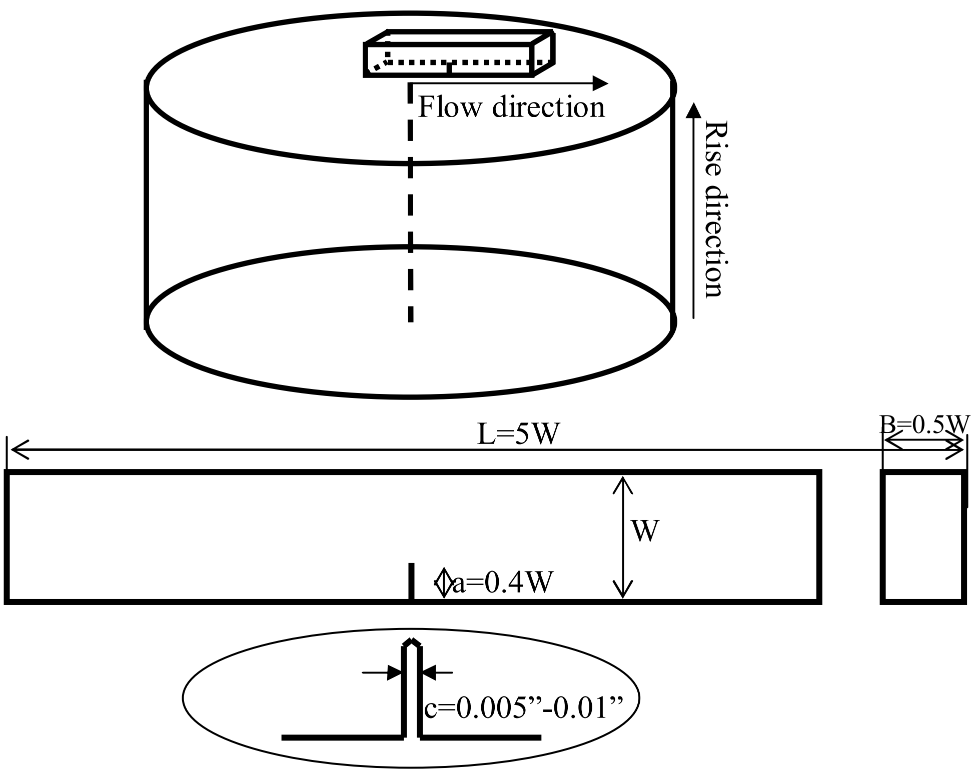


Fig. 2, (a). Schematic of specimen orientation, (b). Drawing of SENB specimen

To generate the random speckle patterns for the purpose of the DIC technique, normally a flat thin layer of white paint was first applied to the surface of specimens. When the base layer was dry, a black speckle pattern was sprayed randomly on top of the white layer. But in these foam fracture tests, random black speckle patterns were sprayed directly onto the foam specimen surface to avoid the effect of the layer of white paint to the crack opening and propagating. A digital image of the random speckle pattern from a 1-inch foam specimen is shown in *Fig. 3*.

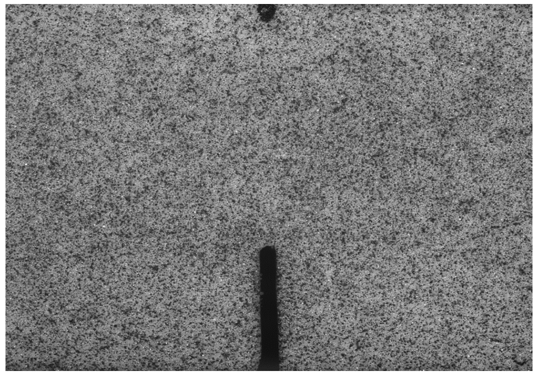
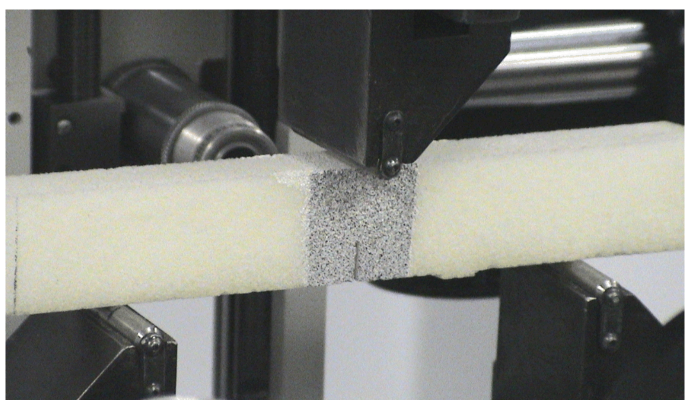


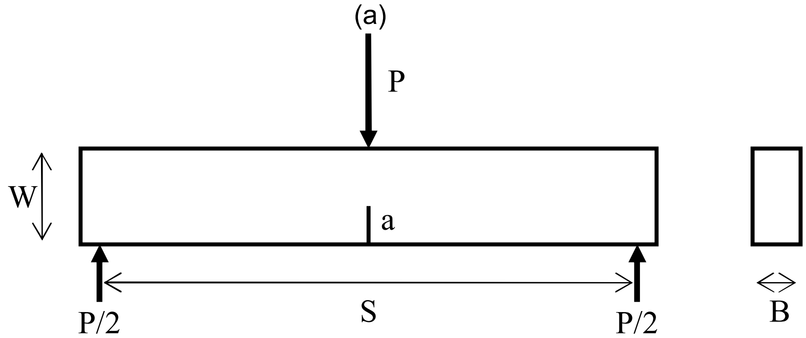
Fig. 3. Digital image of foam specimen patterns for the DIC technique

QUASI-STATIC FRACTURE TEST

The fracture tests were conducted under three-point bending load under displacement control, with a rate of 0.001"/s (0.025mm/s). The fracture tests were carried out on an MTS 858 Mini Bionix Axial-Torsional System with TestStar-IIM controller. The axial load and deflection were recorded during the test. Fig.4a. shows the experimental setup and Fig. 4b shows the schematic of the loading configuration for SENB test.



(a)



(b)

Fig. 4. (a) Experimental set-up of fracture test, (b). Schematic of the loading configuration for the SENB test.

The load versus deflection curves are plotted in Fig. 5 for two PMDI foam specimens with slightly different density. PMDI_01 has a density of 20.8 pcf (332.8 kg/m^3) and PMDI_03 has a density of 21.0 pcf (336 kg/m^3). The fracture toughness K_I is calculated from the critical load and the shape function using the linear elastic fracture mechanics.

$$\sigma = \frac{6M}{BW^2} = \frac{3}{2}\frac{PS}{BW^2} \quad \left(M = \frac{PS}{4}\right)$$

$$K_I = \sigma\sqrt{\pi a}\,F(a/W)$$

For $S/W = 4$:

$$F(a/W) = 1.090 - 1.735(a/W) + 8.20(a/W)^2 - 14.18(a/W)^3 + 14.57(a/W)^4$$

Where a is the crack length, B is the specimen width, W is the specimen height, S is the span and $F(a/W)$ is the geometric shape factor. PMDI_01 has K_I of 0.21 ksi√in (229.6E+3 Pa√m). PMDI_03 has K_I of 0.20 ksi√in (215.1E+3 Pa√m).

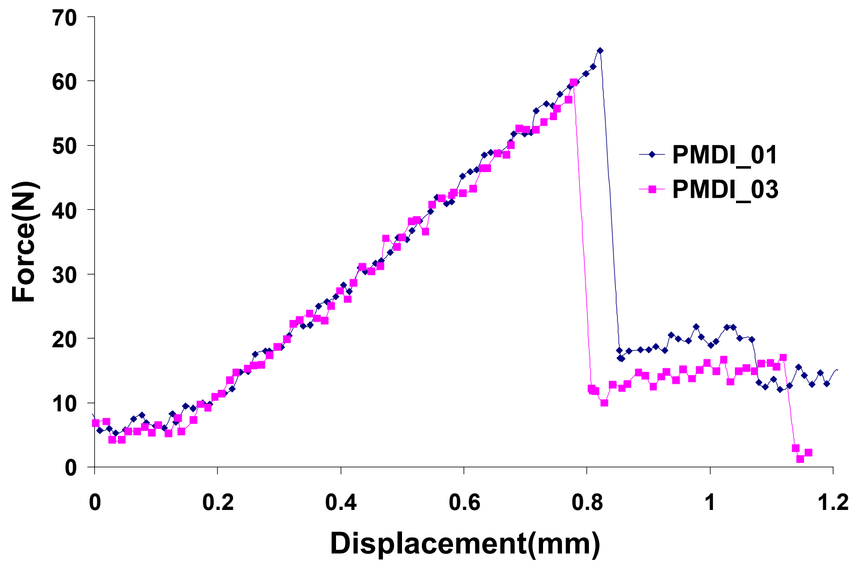


Fig. 5. Load versus deflection for SENB

FULL-FIELD DISPLACEMENT AND STRAIN MEASUREMENT

The digital images of specimens were acquired during the fracture tests. In these fracture tests, the foam specimen only undergoes small amount of deformation before failure and the out-of-plane deformation is negligible. The tests are considered as 2-D. Therefore, only single camera is used to record the images. The frame rate used in these experiments is 2 fps because the test is quasi-static, about 0.001 in/s (0.025mm/s).

Fig. 6 shows the area of interest for DIC over the foam specimen. The AOI is about 18mm x 20mm. The spatial resolution is 0.016mm/pixel. DIC is applied to AOI to calculate the displacement and strain field. Fig. 7(a) shows the displacement field Dy and Fig 7(b) shows the strain contour E_{yy} around the crack before the crack propagates.

SUMMARY

SENB tests are conducted to study the mode-I fracture behavior of a rigid closed cell PU foam, PMDI 20. The stress intensity factor K_{IC} is calculated from the loading curves. The K_{IC} is about 0.20 ksi√in (215.1E+3 Pa√m), with slight variation with density. The displacement and strain field around the crack tip is obtained using the digital image correlation (DIC) technique. In future work, the effects of various parameters, such as foam density, loading rate, crack length, specimen size and crack orientation will be examined.

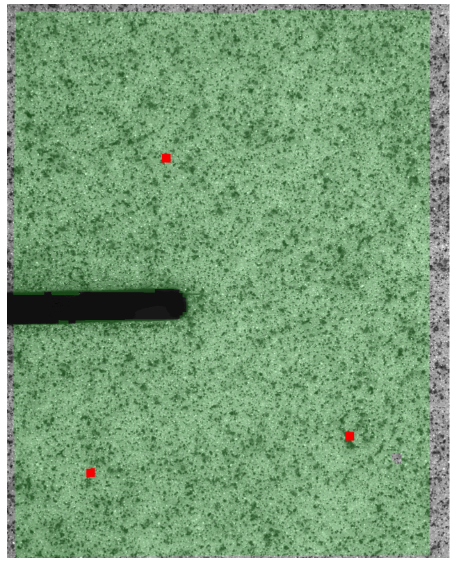


Fig. 6: AOI for DIC on foam specimen

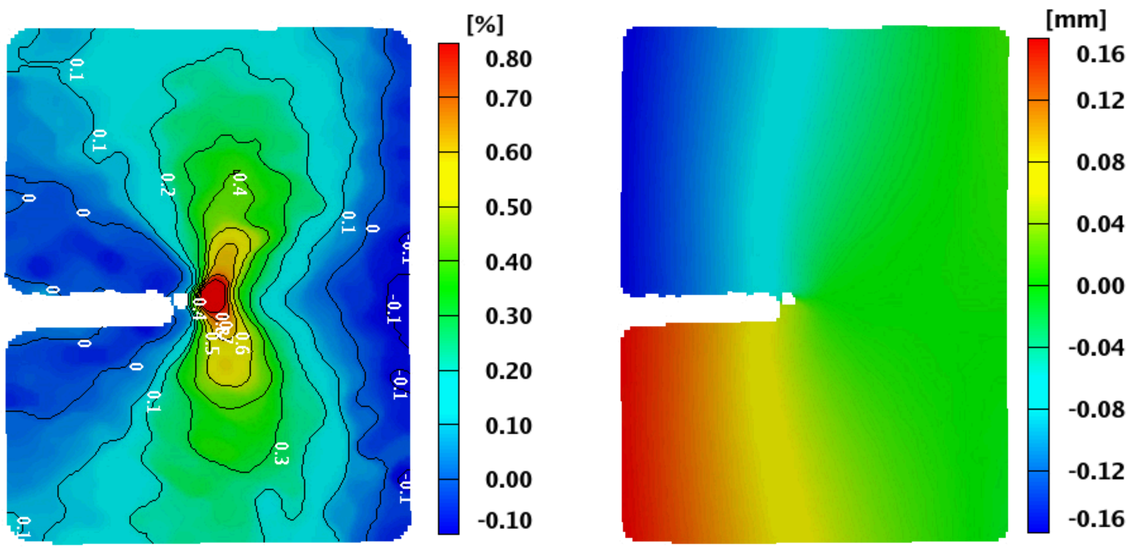


Fig. 7: (a) Displacement field Dy and (b) strain field Eyy for the foam specimen before crack propagation

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