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In situ analysis of fatigue crack propagation in polymer foams

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1. Introduction

Polymer foams are widely used as core materials in the sandwich structures of pleasure boats, naval surface vessels and wind turbine blades. It is, however, recognized that low density foams typically are weak and susceptible to fracture, especially under cyclic loading which tends to limit the service lifetime of sandwich structures [1–4]. Fatigue life is composed of the time required for a dominant flaw to initiate to measurable dimensions and the time required for stable propagation of the flaw. A fundamental equation describing the growth of cracks is the Paris law expressing the rate of crack growth in terms of the cyclic stress intensity factor [5]. This law has been found valid for both solid polymers [5], polymer foams [1–3], as well as metal foams [4].

Crack propagation in foams on a micro-scale has been analyzed by Maiti et al. [6], see also the text by Gibson and Ashby [7]. Maiti et al. [6] developed a model for fracture of a 2D open cell foam (Fig. 1) where the crack propagates when a strut ahead of the crack tip fails in bending. Fatigue of foams may be modeled using an extension of the static fracture model by Maiti et al. [6], see Gibson and Ashby [7]. According to this model, the cell wall just ahead of the crack, Fig. 1, is loaded cyclically in bending until it breaks. The crack then advances by an amount equal to the cell size.

Motz and Pippin [8] conducted an in situ fracture analysis on pre-cracked closed-cell ductile aluminum alloy foam specimens in a scanning electron microscope (SEM). They found that crack growth was controlled by stretching of the cell walls and edges. The crack propagated through the thinnest section of the cell edges by a tearing mechanism. Motz et al. [9] also conducted an in situ fatigue analysis on the same aluminum foam materials. They found that crack growth through the cells

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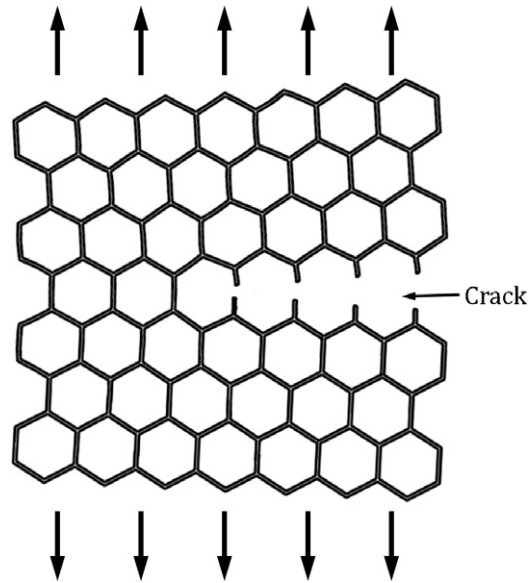


Fig. 1. Crack propagation in 2D open cell foam.

was governed by the cyclic stress intensity factor. Near the fatigue threshold, a single crack propagated through the cell structure. Larger stress intensity factors lead to a more complex fracture process zone due to plastic yielding of the material and micro-cracks in the vicinity of the crack tip. Crack propagation occurred predominantly through the center of the cells by an extensional deformation process.

The present authors recently examined the in situ static fracture behavior of PVC and PES polymer foams [10]. Similar to the findings on aluminum foams by Motz and Pippan [8], the cell structure in both foams failed in an extensional mode of deformation. However, the crack in the relatively brittle PVC foam propagated in the intercellular region consisting of an agglomerate of very small cells between large cells. Furthermore, a damage zone in the form of damaged cells was observed above and below the main crack in the brittle PVC foam. Investigation of the fracture process in the more ductile PES foam revealed blunting of the initial sharp crack tip. Craze-like deformation bands were observed in the cell wall material in front of the blunted crack tip. Fracture occurred predominantly by failure of highly stretched cell edges and walls in the center of the cells.

The objective of this paper is to examine the mechanisms of cyclic crack propagation under low cycle fatigue loading of two PVC and PES foams. In situ SEM observations of failure mechanisms in the cellular structure at the crack tip during the extension of the fatigue crack will be presented and discussed.

2. Experimental

2.1. Materials

Two types of polymeric foams were examined in this study, viz. polyvinyl chloride (PVC) foam and polyether sulfone (PES) foam, both obtained from DIAB. Material properties of solid PVC and PES are listed in Table 1 [7,12,13]. Both base polymers are amorphous, ductile thermoplastics. The PVC foam is designated “H60” of nominal density of 60 kg/m^3 . During foaming, the PVC polymer becomes slightly cross-linked, which increases the modulus and strength, but reduces the ductility of the material [11]. The mechanical properties of solid PVC listed in Table 1 are therefore not representative for the solid material in the cell edges and walls in PVC foams. The PES foam, designated “F90”, has a nominal density of 90 kg/m^3 . The solid constituent of the PES foam remains unmodified during the foaming process. Hence, the material properties of solid PES listed in Table 1 should be representative for the solid polymer in the PES foam although the very small dimensions of the cell edges and small wall thickness may alter the response. Fig. 2 displays tensile stress–strain curves for the foams [14]. It is

Table 1
Material properties of solid PVC and PES [7,12,13].

Material	ρ (Mg/m ³)	E (GPa)	σ_{ys} (MPa)	G_{IC} (kJ/m ²)
PVC	1.40	2.70	55.0	2.02
PES	1.37	2.70	90.0	2.60

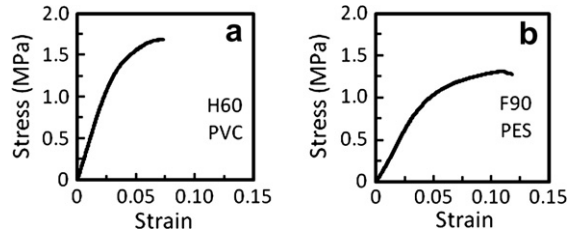


Fig. 2. Tensile stress–strain curves of foams: (a) H60 PVC foam and (b) F90 PES foam [16].

readily observed that the PVC foam is stiffer and stronger than the PES foam although the density is less. This is apparently due to the enhancement of the mechanical properties by the cross-linking of the PVC polymer during the foaming process.

2.2. In situ fatigue crack propagation testing of foam specimens

A microtester accessory, manufactured by DEBEN, was used to perform in situ SEM cyclic loading of PVC and PES foam specimens. A small tensile tester accessory, see Fig. 3, was fitted into a Quanta 200 SEM, equipped with a 200 N capacity load cell and an electric motor driven lead screw. The tester has a user operated control for loading the specimen.

Small single edge notch (SEN) crack specimens shown in Fig. 4 having dimensions of $30 L \times 12.7 W$ and $2.4 H$ (mm) were prepared.

The SEN specimens were extracted from a foam panel as shown in Fig. 5 using a razor blade. A razor blade was also used to cut the initial crack to a nominal length (a_0) of 2 mm.

Each test specimen was mounted in the microtester fixture and clamped with bolts tightened just enough to hold the specimen in place and prevent slipping during load application. The electron voltage was set between 10 and 15 kV and a small vacuum of 0.14 torr was used (higher vacuum lead to foam cell collapsing). In situ testing of the foams was conducted

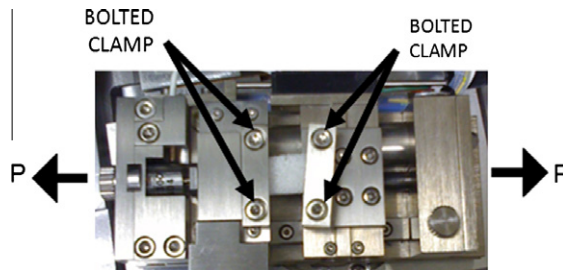


Fig. 3. Microtester with a cracked foam specimen (not clamped).

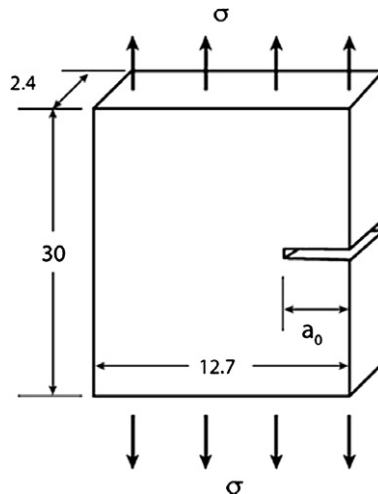


Fig. 4. Single edge notch tensile specimen dimensions ($a_0 \approx 2$ mm). All dimensions are in mm.

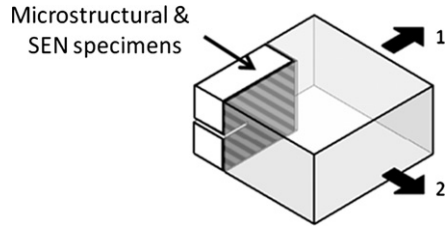


Fig. 5. Illustration of extraction of in situ fatigue specimens from foam panel. The directions 1 and 2 are in the plane of the foam panels.

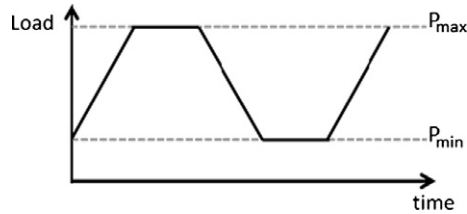


Fig. 6. Schematic cyclic loading program. P_{max} and P_{min} are the maximum and minimum loads applied.

at high and low magnifications. At high magnifications, $200\times$ for PVC and $100\times$ for PES, it was possible to examine the details of the crack propagation in the foam. An overall, macroscopic view of the crack propagation was obtained at a lower magnification, between $50\times$ and $100\times$. The test program involved two replicate specimens of each foam.

Fig. 6 schematically illustrates the cyclic loading imposed on the SEN foam specimens. The loading and unloading parts of the cycle were conducted at a rate of 1 mm/min for both the PVC and PES foams. The maximum and minimum loads for the PVC specimens were about 5 and 2 N, whereas the corresponding loads for the PES specimens were about 9 and 2 N. The maximum load was approximately 70–85% of the static critical load to ensure that crack propagation occurred after a small number of cycles. In order to allow enough time for a scan of the foams with sufficient resolution, the maximum and minimum loading positions were held for two seconds as indicated by the constant horizontal loads in Fig. 6. This provided a loading frequency ranging from 0.03 to 0.07 Hz. The maximum load was increased when no apparent crack growth was observed after about 20 cycles. This was done when the specimen was at the minimum load. Similarly, the maximum load was reduced if the rate of crack propagation increased. This procedure is not in agreement with traditional fatigue crack growth testing procedures, where the maximum load is kept constant over a large number of fatigue cycles [15]. But the manually controlled loading procedure used here did not allow for a high-cycle fatigue study. Service loading of foam core sandwich structures typically involves variable loads, but at very small cyclic strain levels as requirement for achieving long life. It is possible that the failure mechanisms of the foams considered here under low cycle fatigue loading conditions are different under high cycle fatigue loading conditions. Further studies are clearly warranted.

3. Results and discussion

3.1. Cyclic crack propagation in the PVC foam

Figs. 7–9 show micrographs of the crack tip region in fatigue loaded PVC foam SEN specimens. The figure captions list the cycle number and the maximum and minimum cyclic loads [max/min], (in N) Fig. 7a shows the initial razor sharpened pre-crack tip after 15 loading cycles. No crack propagation was observed. At cycle #21, Fig. 7b, some blunting and slight extension of the tip was observed. For the next loading cycle, the load was increased from 5 to 7 N. Fig. 7c shows that the crack propagated through the cell to new positions as marked by the filled arrow. The unfilled arrow indicates formation of a new crack or branching of the main crack running perpendicular through the center of a cell wall below the initial crack. The filled arrow points towards the extension of the pre-crack between two cells.

The maximum load was then reduced from 7 to 5 N. Observation of the crack tip region, Fig. 8a, revealed a small extent of crack growth from the position marked by the filled arrow in Fig. 8a after 33 loading cycles. No additional damage and crack growth occurred in the area below the main horizontal crack as marked by the unfilled arrow in Figs. 7c and 8a. The load was then increased to 7 N for another 12 cycles where the crack jumped from the configuration shown in Fig. 8a to location marked by the unfilled arrow in Fig. 8b. During this increment of crack extension, Fig. 8b reveals a broken edge and propagation between two cells below the main crack in Fig. 8a.

The maximum load was then reduced from 7 to 6 N for another 10 cycles where the specimen failed completely, see Fig. 9. Similar to the static fracture of this foam [10], cyclic crack propagation occurred predominately in the region between two cells (intercellular), although broken vertical cell edges are also present, see Fig. 9.

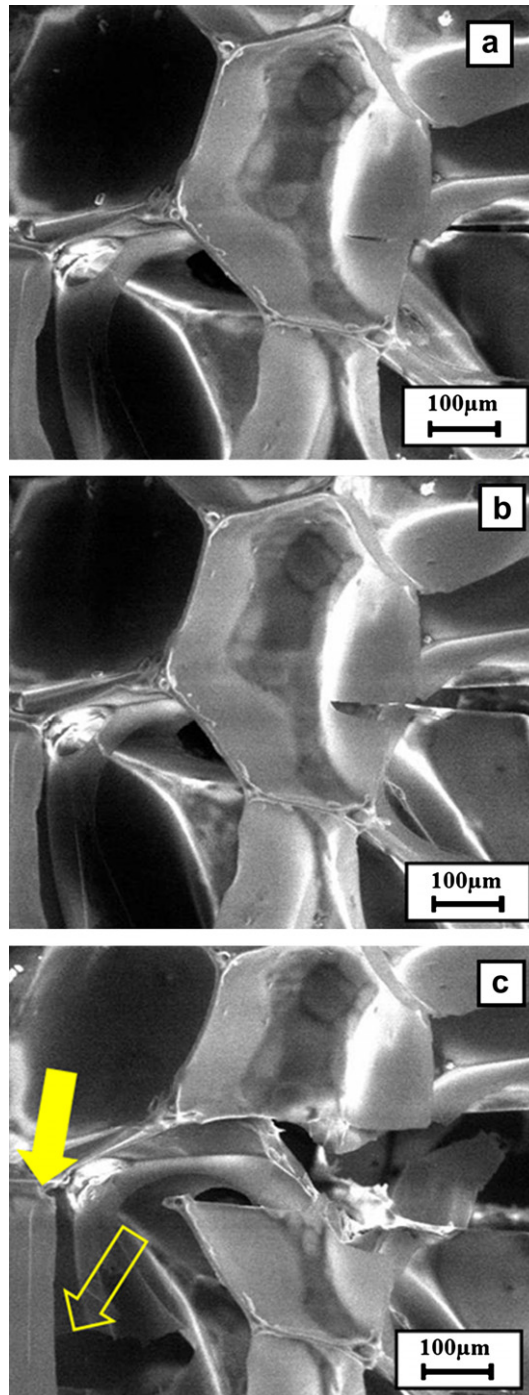


Fig. 7. Fatigue crack growth in PVC foam. (a) cycle #15 [5/1 N], (b) cycle #21 [5/1 N], (c) cycle #22 [7/1 N]. The filled arrow indicates the main crack front, while the unfilled arrow marks a secondary crack.

3.2. Cyclic crack propagation in the PES foam

Similar to the micrographs for the PVC foam, the Figure captions for the SEM micrographs of the PES foams (Figs. 10–14) contain the number of fatigue cycles and load range. Fig. 10a shows the initial razor sharpened crack tip, marked by an unfilled arrow, in an unloaded PES foam specimen. Fig. 10b shows slight extension of the crack tip through the adjacent cell after 21 cycles at a maximum load of 13 N. The crack stopped at a vertical cell edge. After 25 loading cycles, Fig. 11a shows

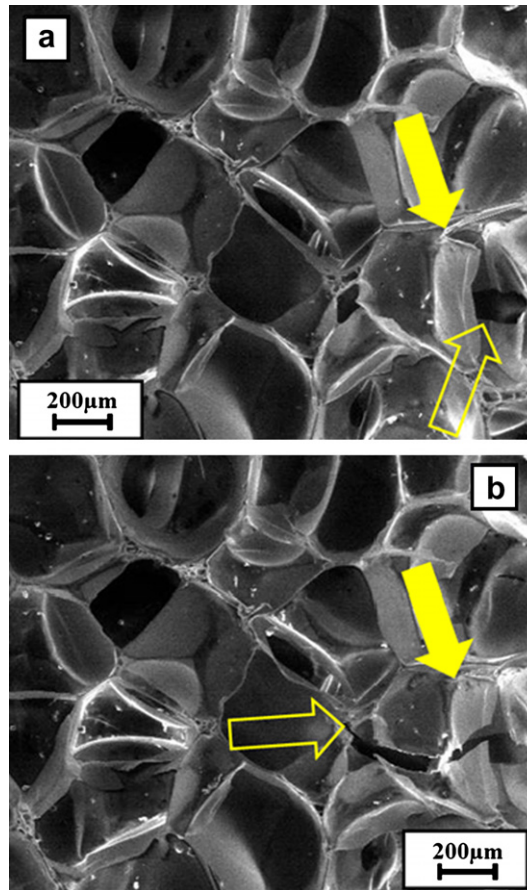


Fig. 8. Crack growth in PVC foam: (a) cycle #33 [5/1 N] and (b) cycle #45 [7/2 N]. The unfilled arrow indicates the crack front, while the filled arrow marks a secondary crack.

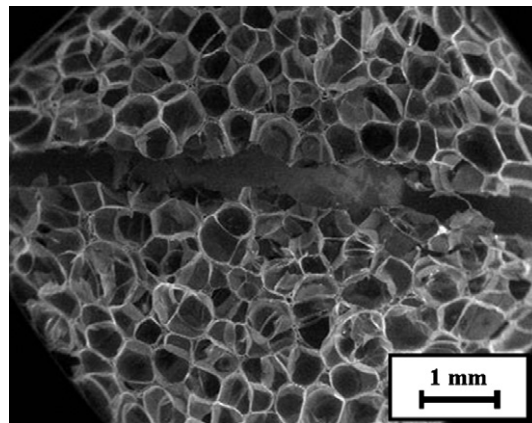


Fig. 9. Final fracture of PVC foam.

that a small secondary crack formed in a cell edge above the crack tip, as indicated by the filled arrow. After 27 loading cycles, the secondary crack extended both forwards and backwards and eventually bridged the initial crack see Fig. 11b through a region of highly shear deformed and fractured cells. Further crack jumping and bridging occurred during propagation of the crack during the following three cycles, see Fig. 12.

Fig. 13a shows the crack tip position shown earlier in Fig. 12 as indicated by an arrow. After 34 loading cycles, a region of extensive whitening of the cell edge at the tip of the crack tip was observed as shown in Fig. 13b. Ward [16] attributed the

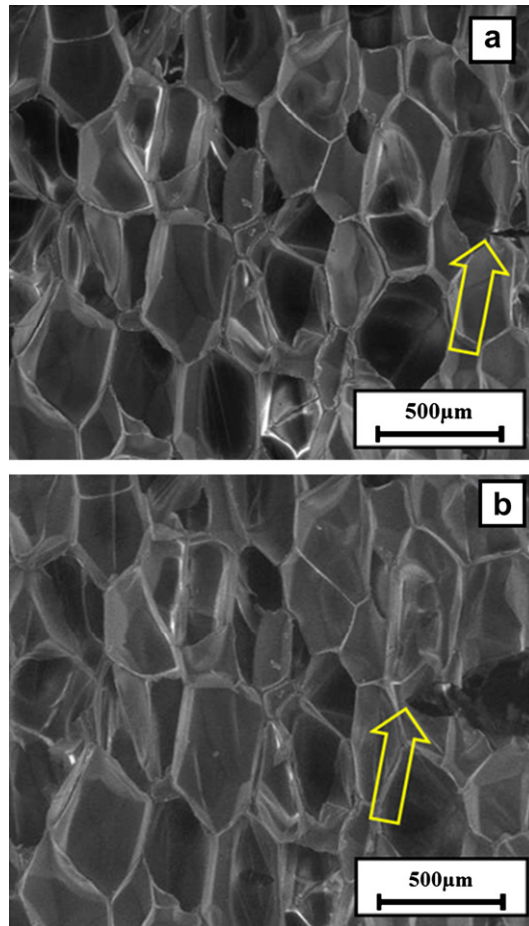


Fig. 10. Initial razor sharpened crack tip in PES foam: (a) no applied cycles and (b) cycle #21 [13/2 N]. The unfilled arrow indicates the crack front.

whitening of a polymer as a change in its refractive index due to formation of light scattering microvoids from crazes. Crazes were observed in front of the crack tip during static fracture testing of the PES foam [10]. Also in cyclic loading, damage of the polymer cell edge leads to whitening as detected in the SEM. After a few additional loading cycles, Fig. 13c shows failure of the whitened vertical cell edge corresponding to crack extension. Fig. 14 shows a highly magnified SEM micrograph of a failed PES foam specimen where the crack predominantly propagated through the center of cells.

Similar to what was observed in the static SEM study of the PES foam [10], cyclic crack propagation in the PES foam predominantly occurred through the center of the cells involving tensile failure of highly stretched vertical cell edges. In the PVC foam, fatigue crack propagation occurred predominantly in the intercellular region at the horizontal cell boundaries. Crack jumping, which involves a highly localized shear deformation and failure of the cells bridging the main and secondary cracks formed above or below the main crack, was observed in both foams.

At a maximum load of 13 N, the PES foam required a total of 25 cycles to extend the initial razor sharpened crack tip whereas a total of 21 cycles at a maximum load of 5 N resulted in crack extension for the PVC SEN foam specimen. This shows that the F90 PES foam requires higher load amplitudes than the H60 foam to extend the crack. As a reference, the static initiation fracture toughness values of the H60 PVC and F90 PES foams measured using a sandwich DCB specimen [14] are $G_{Ic} = 0.38$ and 0.72 kJ/m^2 , respectively. It is widely known that cross-linking of a polymer restricts the internal mobility of the polymer chains, making the material brittle as measured by tensile elongation to failure and fracture toughness (K_{Ic} and G_{Ic}).

When a polymer containing a crack is loaded in remote tension, the experiments conducted here, as well as micromechanical models of foams [6], show that propagation of a crack occurs by tensile or flexural failure of cell edges in front of the crack tip. Experimental data presented by Hertzberg and Manson [5] on cyclic crack propagation rate (da/dN) for PMMA, cross-linked to various degrees revealed that increased cross-linking led to higher crack propagation rates at a given stress intensity factor range (ΔK). A reduction in fracture toughness was also observed. It is thus expected that the higher ductility of the thermoplastic PES polymer would promote a higher resistance to cyclic growth of the PES foam, as compared to the partially cross-linked PVC polymer foam.

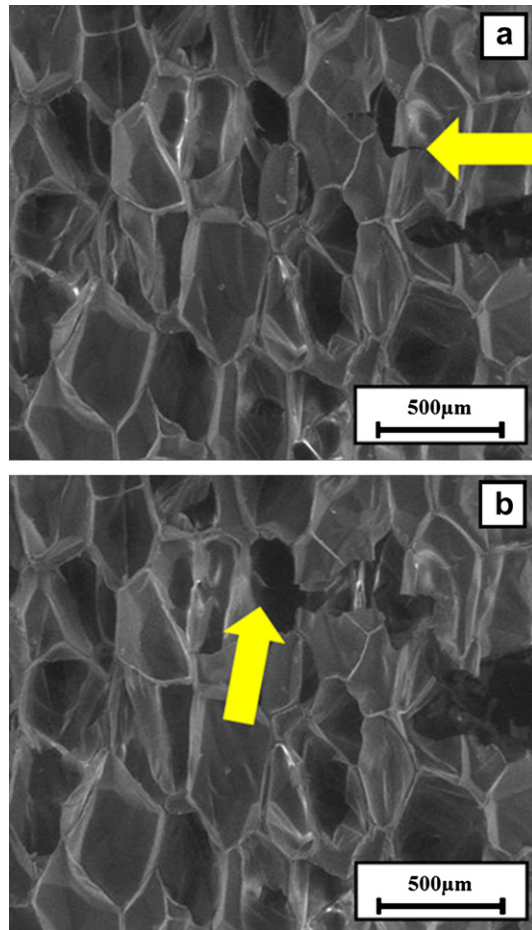


Fig. 11. Crack growth in PES foam: (a) cycle #25 [13/2 N] and (b) cycle#27 [13/2 N].

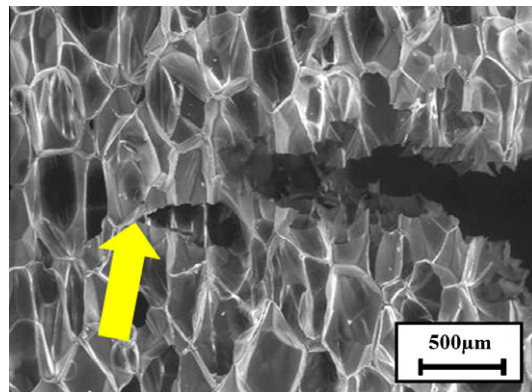


Fig. 12. Crack growth in PES foam at cycle #30 [13/2 N].

Static in situ fracture studies presented earlier [10] and the in situ cyclic crack propagation results presented here point to the importance of the extensional mode of deformation of the cell edges. Micromodels of fracture of foams highlight the bending mode of failure of the cell edges, which may be appropriate for brittle foams that fracture at very small strains. A micromechanical model of fracture of the ductile PES foam may require a geometrically nonlinear analysis to determine the stress in the highly stretched edges. It is also possible that nonlinear material response should be incorporated in such a model.

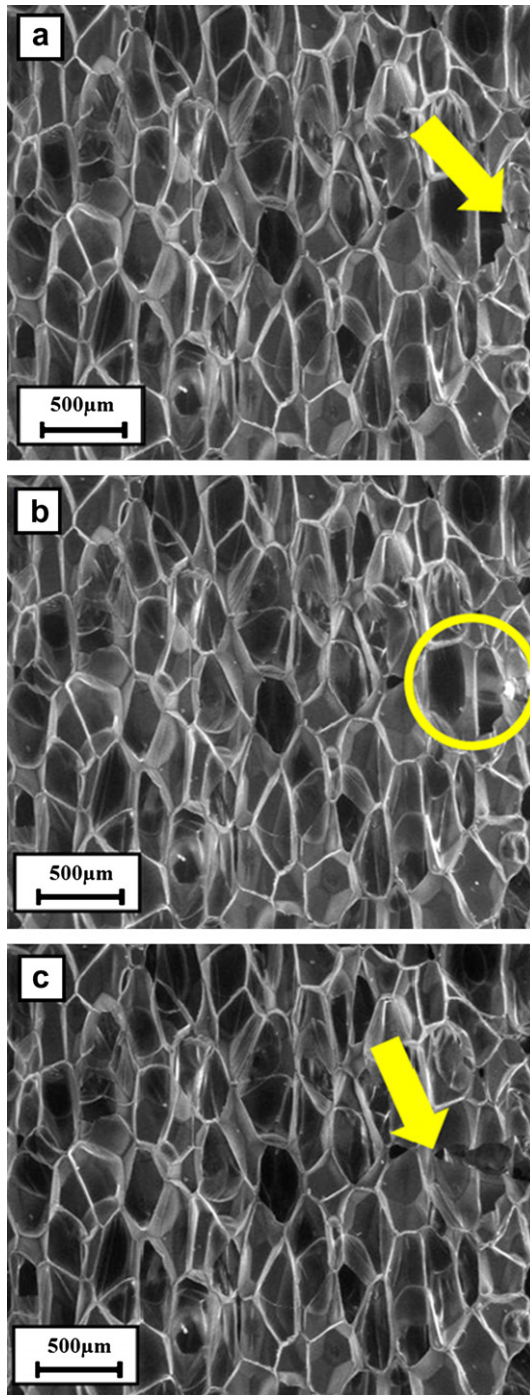


Fig. 13. Fatigue crack growth in PES foam: (a) cycle #30, (b) cycle #34, (c) cycle #37. All [9/2 N].

Technically, it is important to improve the fatigue life of cyclically loaded sandwich structures, such as elements of wind turbine blades. The use of foams with improved ductility should be an important step towards such a goal, at least for cases where the foam core is identified as the weak link.

It should be pointed out that the study presented herein focuses on the low cycle fatigue failure of PVC and PES foams. Sandwich structures in commercial use are typically designed to last for several million of cycles, i.e. high cycle fatigue and are loaded at small cyclic strains. The fatigue failure mechanisms involved in high cycle fatigue failure of the PVC and PES foams may be different from those identified here. Further experimental studies are definitely needed.

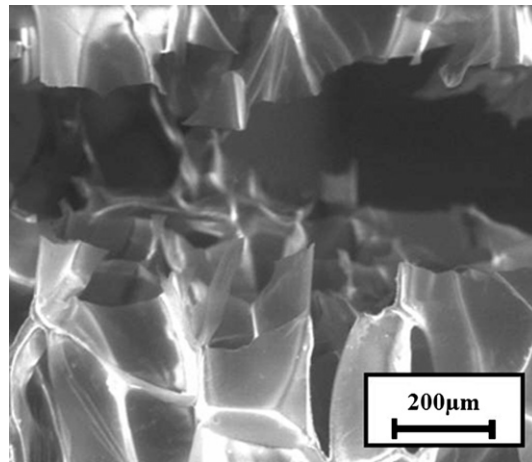


Fig. 14. Fracture surface of PES foam.

4. Conclusions

The in situ SEM study of crack extension and damage growth in low cycle fatigue loading of PVC and PES foams has revealed several important micro-mechanisms. It was found that the overall failure during mode I loading of the cell structure in both foams is dominated by an extensional mode of deformation of cell edges and walls ahead of the crack tip. Crack propagation in the PVC foam occurred predominantly by successive failure of the interface region between two adjacent cells ahead of the crack tip. The crack sometimes jumped to other cell boundaries in non-self similar growth. For the PES foam, cyclic crack propagation occurred predominantly by fatigue failure of tensile loaded vertical cell edges, although multiple crack formation and crack jumping was occasionally observed. Stress whitening of the tensile loaded vertical cell edge in front of the crack tip indicates that the energy dissipated at the crack tip caused by localized damage of the polymer. Higher load amplitudes were required to extend the crack in the more ductile PES foam than for the PVC foam. It is possible that the failure mechanism involved in low cycle fatigue failure of the PVC and PES foams identified here are different from those that occur under high cycle fatigue loading conditions. Further studies are clearly warranted.

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