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THE INFLUENCE OF CRACK-LIKE DEFECTS ON THE TENSILE STRENGTH OF AN OPEN-CELL ALUMINUM FOAM

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Introduction

Metallic foams have relatively large cells (typically 3–5mm) and may be used in applications where there is an insufficient number of cells to consider the foam as a continuum. For instance, aluminum foam core sandwich panels being considered for automotive applications are typically about 10mm thick, giving 2–3 cells through the thickness of the core. In practice, applications using metallic foams may not satisfy the specimen size requirements for the direct application of continuum fracture mechanics concepts. Since some components may have only a few cells spanning their dimensions and may have defects spanning only a few cells, the appropriate methodology to interpret the effect of these defects is not clear. This was the motivation for the present study. This paper describes a set of experiments designed to study the fracture behavior of open-cell foams in the presence of notch-like defects.

Double edge notches were cut to various depths in standard dogbone tensile specimens. Images of the notched region were recorded at various stages during loading to observe the nature of the deformation in the notched region. The load-displacement response was measured, and unloading measurements were made at various points. It was found that the net tensile strength of the foam, defined as the peak stress divided by the net cross-sectional area, increased with increasing crack length, indicating a notch-strengthening effect. A simple model, accounting for tensile yield in the ligament between the notches and shearing adjacent to the notches, gives a good description of the tensile strength data.

Experimental Procedure

A commercially available open-cell aluminum alloy (6101-T6) foam (trade name Duocel, ERG, Oakland, CA) with a nominal cell size of 40 pores per inch and a nominal relative density in the range 7–8% was used in this study. Because of its uniformity in cell size and orientation it is often thought of as almost an ideal foam and has been used in several studies to assess the validity of models for elastic modulus, compressive strength and multiaxial yield behavior [1–3]. The cells of the foam are elliptical in shape with major and minor axes of approximately 2.5 mm and 1.5 mm, respectively. The anisotropy in the cell shape gives rise to anisotropic mechanical properties. In this study, all the specimens were tested with the major axis of the cells parallel to the direction of the applied load.

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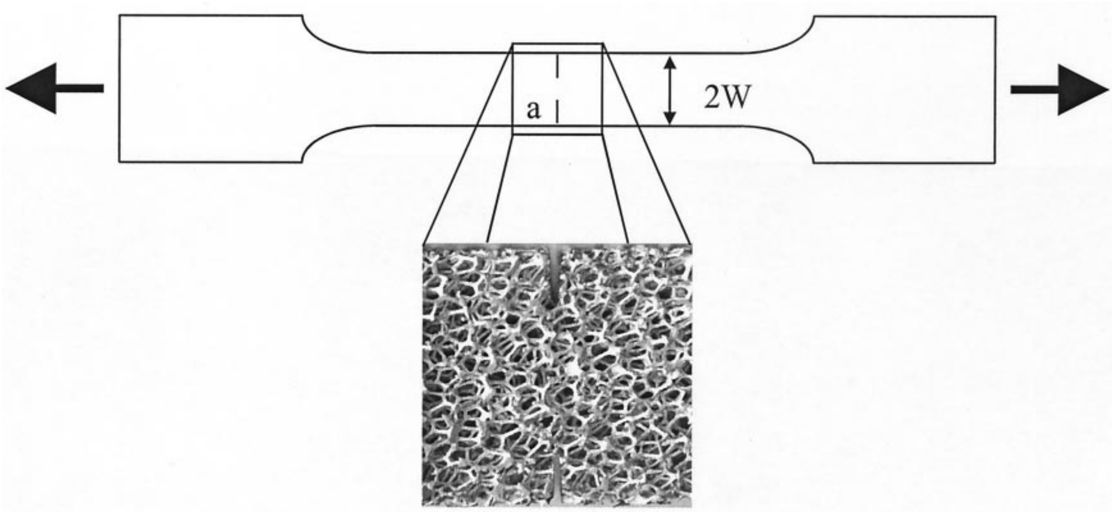

Figure 1. Schematic of specimen geometry and image of the notch region.

Dogbone shaped specimens for tensile testing were machined by the manufacturer using proprietary machining techniques. The length of the specimens was 220mm, with a 120mm gauge length; within the gauge length the cross section had a width 2W of 20mm and a thickness B of 20mm. Double-edge notches were cut in the samples using a low speed diamond blade to minimize damage to the specimen. The blade thickness was 0.35 mm, well below the cell size, giving a sharp crack. The depth of the notches varied from 2.6 mm to 7.4 mm. A schematic of the specimen geometry and an image of the gauge section, showing the microstructure of the foam and the notches, are given in **Fig. 1**.

The tensile tests were run in displacement control, with the loading rate set to give a nominal strain rate of 10^{-4} sec^{-1}. An extensometer with a gauge length of 25.4 mm was attached to the specimen to measure the local displacement around the notched region of the gauge section. Each test was stopped at several points during the test, with the displacement held fixed, to allow an image of the specimen to be recorded. The images were taken using a 1K $\times$ 1K pixel array CCD camera (Pulnix), with a telecentric lens. After the image was recorded, the crosshead was reversed to unload the specimen. Before the specimen was completely unloaded (to zero load), the crosshead was stopped and immediately reversed to continue loading the specimen.

Results and Discussion

A typical result for the net section stress (load divided by unnotched area) versus strain (recorded by the extensometer) is shown in **Fig. 2**. The test was stopped and an unloading measurement made and an image recorded at the points indicated. There was no stable crack growth: at the peak load sudden failure occurred across the entire section. Some struts may still have been attached, but a near complete failure occurred across the section so that the unloading measurements, which were mainly intended to assess crack growth, were not needed. The images of the specimen at points 1, 2, 3, and 4 on **Fig. 2** are shown in **Fig. 3**.

To assess the role of notches on the strength of the foam, a plot was made of the peak net section stress normalized by the uniaxial strength of the foam, $\sigma_{peak}/\sigma^*_{pl}$ vs. notch depth normalized by the specien half width, a/W (**Fig. 4**). The peak stress *increases* with increasing notch size, indicating a notch strengthening effect. We explain this effect as follows.

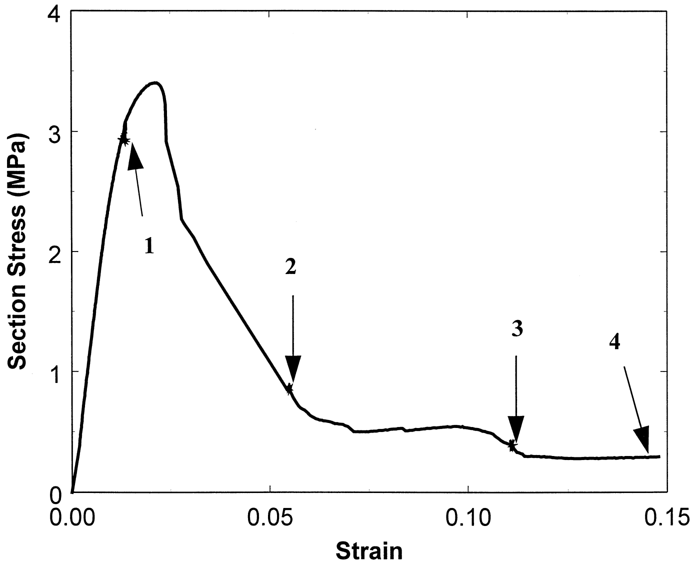

Figure 2. Net section stress vs. strain. The test was stopped and an image recorded at the points indicated.

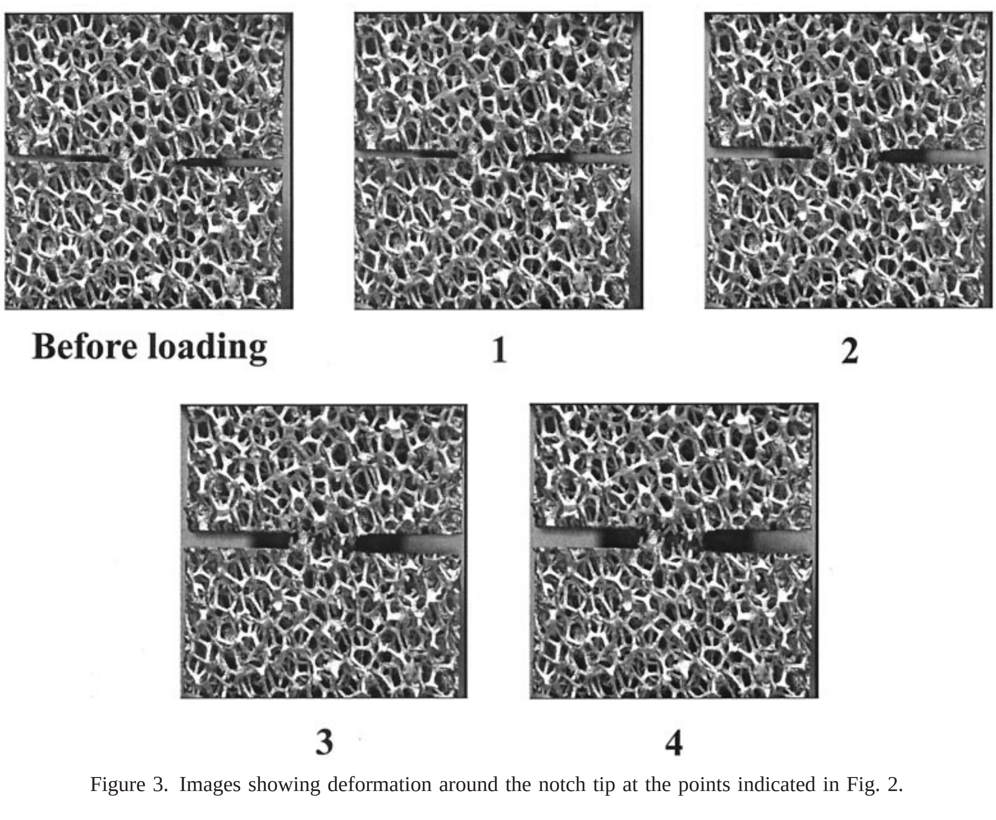

Figure 3. Images showing deformation around the notch tip at the points indicated in Fig. 2.

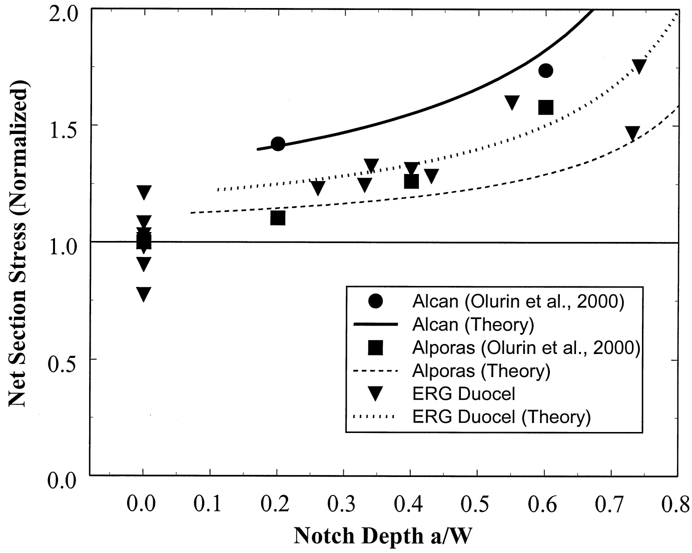

Figure 4. Normalized net section strength, $\sigma_{peak}/\sigma^*_{\mathrm{pl}}$ plotted against normalized notch, a/W, depth showing a notch strengthening effect.

The deformation of the specimen is considered to be plastic yielding over the uncracked ligament with localized shear at the notch tips (**Fig. 5a**). We note that this mode of deformation is similar to that observed in flat punch indentation, (**Fig. 5b**) [4]. As in the case of indentation, the peak load, F_{peak}, has two components, corresponding to the yielding of the ligament and shearing at the boundary of the notch:

$$F_{peak} = 2\sigma^*_{pl}(W - a)\,B + 2\tau^*_{pl}B\delta \tag{1}$$

where σ^*_{pl} and τ^*_{pl} are the uniaxial and shear strengths of the foam and δ is the depth to which the shearing takes place. Dividing by the area of the uncracked ligament, 2(W-a)B, to obtain the peak net section stress, σ_{peak}:

$$\sigma_{peak} = \sigma^*_{pl} + \tau^*_{pl}\left(\frac{\delta}{d}\right)\left(\frac{d}{W}\right)\left(\frac{1}{1 - a/W}\right) \tag{2}$$

where d is the cell size of the foam. If we assume that $\tau^*_{pl} \approx \sigma^*_{pl}$ and $\delta \sim$d (i.e. the shearing takes place over a depth of approximately one cell) we may write that:

$$\frac{\sigma_{peak}}{\sigma^*_{pl}} = 1 + \left(\frac{d}{W}\right)\left(\frac{1}{1 - a/W}\right) \tag{3}$$

Thus the net section strength is enhanced above σ^*_{pl} by the factor involving the notch depth, specimen width and cell size. This suggests that for samples with dimensions that are very large compared to the cell size (i.e. d/W $\sim$ 0) the strength of a notched sample will be simply the foam strength times the area of the uncracked ligament; no notch strengthening should be observed. A similar phenomenon is observed in flat punch indentation of foams; if the punch is very large compared to the cell size the peak indentation stress is simply the compressive strength of the foam. The experimental results for the ERG foam (from the present study), as well as those for two closed cell aluminum foams (Alcan and Alporas), reported by Olurin et al. [5], are compared with eqn (3) in **Fig. 4**: the theory gives a reasonable

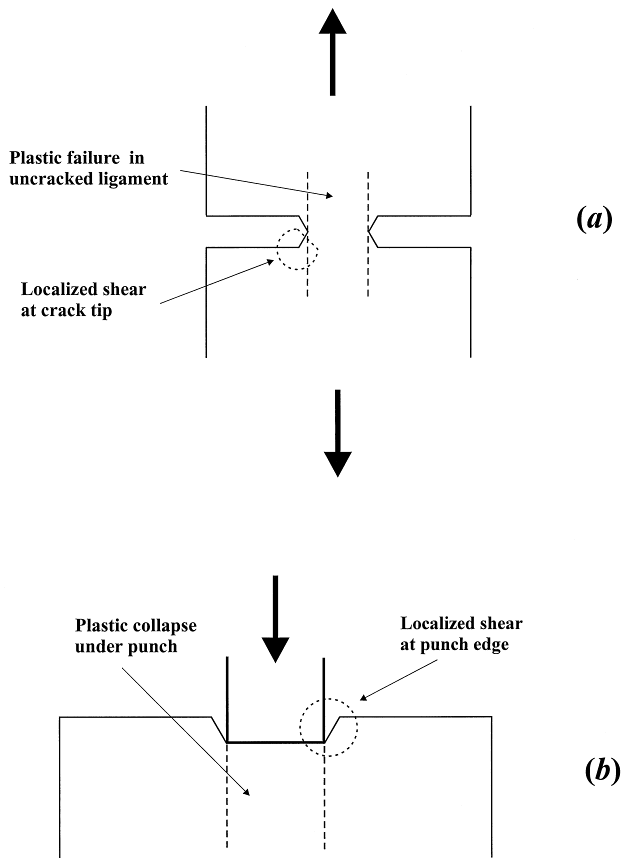

Figure 5. (a) Schematic depicting assumed mode of deformation. (b) Analogous mode of deformation for flat punch indentation.

description of the observed trends. This simple theory also predicts that under these conditions the Alcan foam should show the stongest degree of notch sensitivity, in agreement with the experimental results. Note that the analysis is invalid in the limit $a/W = 0$; the plots start from a value of a/W corresponding to $a = d/2$. To prepare these plots we have used the following cell sizes: ERG Duocel foam, $d = 2.0$ mm; Alporas foam, $d = 3.5$ mm; and Alcan foams $d = 10$ mm [5]; for the Alcan and Alporas foams, $W = 30$ mm [5].

The strengthening effect observed here is in contrast to the weakening effect predicted by fracture mechanics and the constant section strength observed for a closed-cell aluminum foam in the presence of circular holes [6].

Conclusions

The results of experiments assessing the role of notch-like defects on the strength of an open-cell aluminum foam have been presented. No stable crack growth was observed; the entire uncracked section failed when a peak load was reached. The net section stress increased with increasing notch size, indicating a notch strengthening effect. A simple model, accounting for tensile yield in the ligament between the notches and shearing adjacent to the notches, gives a good description of the tensile strength data. These results are important for analyzing defects in cellular solids in which the specimen dimensions are not large enough to apply continuum fracture mechanics concepts.

Acknowledgments

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