MULTI-SCALE MECHANICAL BEHAVIOR OF METALLIC FOAMS: FROM STRUTS TO FOAMS

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ABSTRACT
This paper reports the results of studies on mechanical behavior of open cell aluminum foams. The multi-scale nature of compressive deformation is examined from individual struts to overall foam deformation. Stress-strain curves of individual struts were investigated using micro-tensile testing. The localization (slip bands) in individual struts is discussed along with evidence of deformation bands at the macro-scale. The onset and propagation of deformation localization bands are elucidated via *in-situ* imaging and digital image correlation (DIC) techniques that provide continuous mapping of strain fields across sample section. A simple unit cell model is then used to estimate the dependence of foam strength and stiffness on relative density and strut properties.

1 INTRODUCTION

An increasing number of studies have been carried out to study deformation in open cell metallic foams [1]. Most of these studies were aimed at investigating foam mechanical responses to applied loads. Since foam structures are constructed by individual struts, their mechanical behavior may be determined by microstructure and mechanical properties of individual struts [2,3] However, no direct measurements were carried out to investigate the mechanical properties of individual struts in open cell foams. The mechanical properties of corresponding alloys are usually used to model foam mechanical behaviors. We used micros-tensile testing to measure the stress-strain curves for individual struts, and found that the strut behavior was significantly different from those of the corresponding bulk alloy. The mechanical behaviors of foams and individual struts under compression were studied using digital image correlation (DIC) technique, in conjunction with *ex-situ* scanning electron microscopy (SEM). Then a four-strut model is proposed to link the mechanical properties in strut scales and foam scales. It was found that the model predicts the upper and lower bounds of the measured foam strengths under compression.

2 MATERIALS

Duocel® open cell aluminum foams were used in this study. They were fabricated by ERG, Oakland, CA, using a casting technique similar to investment casting, which was described in details by Ashby et al. [3]. After fabrication, foam blocks were either strengthened or annealed with heat treatment schedules introduced in a previous study [4]. Then foam blocks were sandwiched by attaching two aluminum face sheets using epoxy. A front view of a foam sandwich sample is shown in Figure 1a, in which the arrows indicate how compressive load is applied in monotonic compression test. Typical foam morphology is shown in Figure 1b, in which the pore density of this foam is 10 pores per inch (PPI), corresponding to 4 pores per centimeter. Duocel® foams were fabricated from 6101 aluminum alloy. The chemical composition of the foams was measured using ICP-atomic emission technique [4].

3 EXPERIMENTAL METHODS

Micro-tensile testing was used to measure stress-strain curves of individual struts that were extracted from foam blocks in three heat treatment conditions: as-received (F), annealed (O) and T6-strengthened (T6). Two samples were tested for each heat treatment condition. Micro-tensile testing setup and procedure were introduced elsewhere [5]. To investigate micro-scale plastic deformation in struts, small samples with dimensions of ~ 10 (L) × 10 (W) × 10 (W) mm was progressively loaded and unloaded in compression. After unloading from each cycle, the samples were examined using an *ex-situ* SEM technique. This was done to reveal: the initiation of plastic deformation in each strut, and the subsequent propagation of plastic deformation across the struts as the strain increase; the structure change in the foam block. The small sample dimensions make it possible to examine and trace the initiation and propagation of micro-scale plastic deformation in each strut in SEM. In all cases, the onset of plasticity was identified by the presence of fine dislocation slip bands, which were revealed using SEM. Monotonic compression tests were also carried out on foam sandwiches with dimensions of ~ 71.1 (L) × 58.4 (W) × 75.0 (H) mm to measure foam stress-strain curves and investigate their deformation mechanisms. An *in-situ* digital camera was set up to record the morphology changes with increasing strain, and the digital images were then analyzed using digital image analyses (DIC) technique [5] to show the deformation localization and distribution during monotonic compression tests.

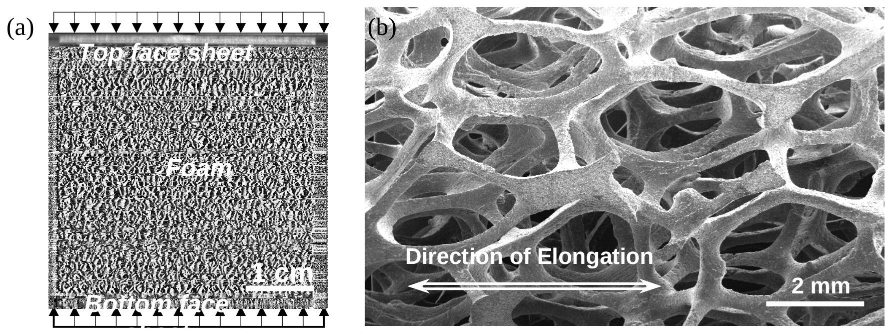

Figure 1: Front view of a foam sandwich (a) and typical morphology of open cell foams (b).

4 RESULTS AND DISCUSSION

4.1 Stress-strain curves of individual struts

The measured strut stress-strain curves are displayed in Figure 2a. Annealing reduces strut strength, but improves strut ductility. It also results in nearly elastic-perfectly plastic stress-strain behavior. In the case of the T6-strengthened struts, the measured UTS values increase, but strengthening is not associated with degradation in strut ductility. Furthermore, all struts exhibit excellent ductility with final failure occurs from 40 to 60%. Since selected struts for micro-tensile testing may have different initial curvatures, slight variation in stress-strain behavior was observed for struts in the same heat treat conditions. For a comparison, stress-strain curves obtained from corresponding bulk alloy subjected to the same heat treatment schedule are also shown in Figure 2b. Strut yield strengths are significantly higher than the corresponding bulk alloy. Furthermore, F and T6 struts are also more ductile than their corresponding bulk counterparts.

4.2 Foam stress-strain behavior under monotonic compression

Typical stress-strain curves measured from foam sandwich samples are presented in Figure 3a. Fore the as-received and T6-strengthened foams, a peak stress level was reached right after yielding. The peak stress level was followed by a stress drop, prior to a gradual increase in stress with increasing strain. Upper strength (σ_{upper}) and lower strength (σ_{lower}) are used to denote the peak stress level and valley stress level, respectively (Figure 3a). Since upper strengths and lower strengths are significantly different, both of them are plotted in Figure 3b, as a function of foam density. For the annealed foams, a stress plateau was reached right after yielding. The corresponding plateau stresses are, therefore, defined as foam strengths [6]. They are also plotted in Figure 3b. It is clear that foam strength increases with increasing foam density. These suggest that annealing and strengthening significantly change the foam mechanical behavior, and heat treatment can be used to engineering foam mechanical properties to satisfy application requirements.

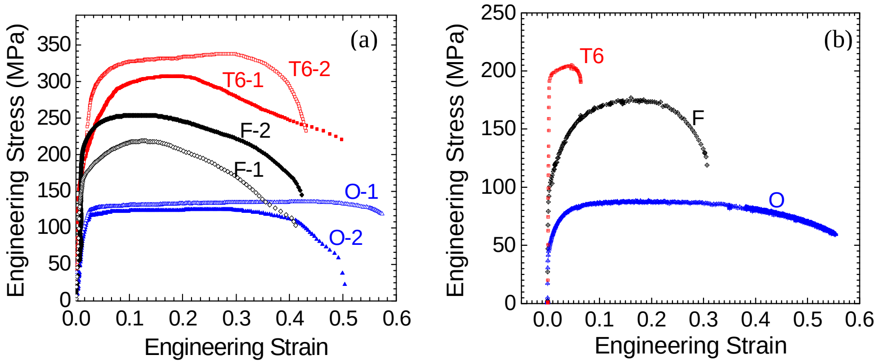

Figure 2: Measured stress-strain curves of struts (a) and corresponding bulk alloy (b).

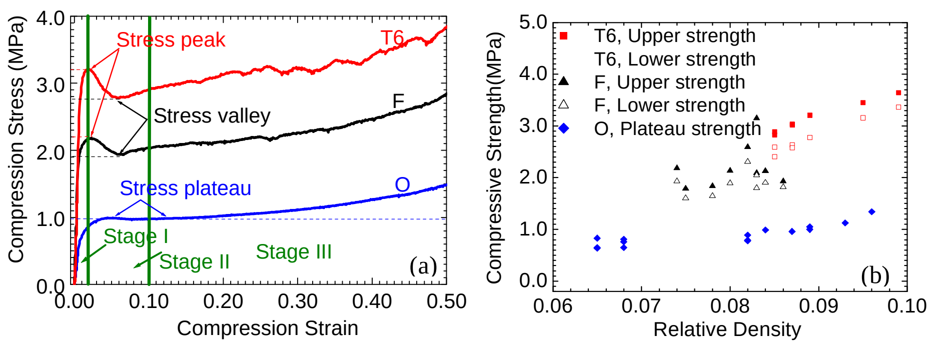

Figure 3: Measured foam stress-strain behavior (a) and compressive foam strengths.

4.3 Micro-scale deformation in struts under monotonic compression

It was found that both plastic bending and plastic buckling were strut deformation mechanisms, and the occurrence of the two deformation mechanisms depend on boundary conditions [7]. These are shown in Figures 4a and 4b, with the applied compression load along directions indicated by double arrows. Both figures consist of four sub-images. Each following sub-image presents the details of the central part of the former sub-image at higher magnification. Figure 4a displays deformation in a strut that was plastically bended. Dislocation slip bands were observed to form in the strut at two regions close to the vertices. For plastic buckling, dislocation slip bands are located in the central part of the strut and two regions close to the vertices (Figure 4b). It should be noted that both images were obtained before the peak stress point. Since plastic buckling requires more strict boundary conditions for it to occur, it rarely takes place. Therefore, plastic bending is the dominant deformation mechanics.

4.4 Macro-scale deformation of struts under monotonic compression

Mechanical deformation was studied to understand occurring events corresponding to different stages in the measured stress-strain curves. A foam sandwich without deformation is shown in Figure 1a, and the results of DIC analyses are presented in Figures 4a and 4b for the annealed (O) and T6-strengthened foams, respectively. Deformation mechanisms of the as-received foams are similar to the T6-strenthened foams, thus are not repeated here. Figures $4a_1$-$4a_3$ are three sub-figures. They are DIC results corresponding to global strain levels of 0.043, 0.054 and 0.097, respectively. Strain level of 0.043 corresponds to deformation right after peak stress point (Figure 3a). Compressive plastic deformation occurred through the overall as-fabricated specimen. Deformation localization developed in regions A – C at strain levels of 0.054. These regions then expended and merged to form a deformation band crossing through foam width at strain level of 0.097. Further deformation was observed to be limited within the deformation band and struts adjacent to the band [7]. This corresponds to deformation after the valley stress point (Figure 3a). More uniform deformation was observed in the annealed foams. This is shown in Figures $4b_1$-$4b_3$ corresponding to strain levels of 0.043, 0.054 and 0.097, respectively. Deformation localization was distributed in multiple regions across foam section. The following deformation carried out through the expansion of these regions simultaneously (at strain of 0.054), resulting a homogenously distributed plastic deformation at higher strain level (0.097).

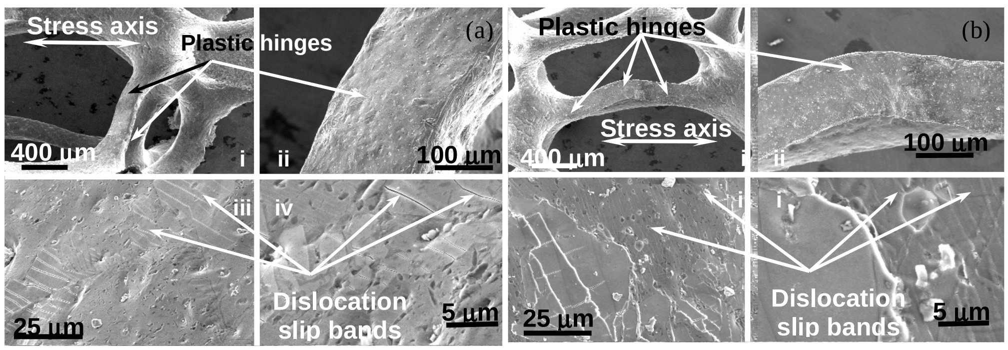

Figure 4: Microscale deformation mechanism in struts: (a) plastic bending and (b) plastic buckling.

4.4 Foam stiffness and strength and model prediction

Since the mechanical properties of individual struts are significantly different from the corresponding bulk alloy that were subjected to the same heat treatment schedules (Figure 2). It is, therefore, not correct to model foam mechanical behavior using the mechanical properties of the corresponding bulk alloy. Furthermore, we found that both plastic buckling and bending were the possible deformation mechanisms. Therefore, it is important to develop a new model to predict foam properties. This model should incorporate the observed strut deformation mechanisms, and use the exact strut properties to study the foam mechanical behavior. A four-strut unit structure model has been found to represent the deformation of real foam structure [8]. Analysis showed that foam strength, σ_{pl}^{cl} , is a range determined by a function of both strut properties and foam structural parameters: $0.31\,\sigma_{YS}\left(\frac{\rho_f}{\rho_s}\right)^{3/2} \le \sigma_{pl}^{cl} \le 0.44\,\sigma_{YS}\left(\frac{\rho_f}{\rho_s}\right)^{3/2}$, in which ρ_f and ρ_s are the densities of a foam block and struts, and the constants account for foam structural parameters. A comparison between model predictions and the measured foam strengths (Figures 6a-c) indicates that the bounds estimated using the four-strut unit structure model provide very close estimates for foam strengths. The four-strut model can also be used to model compressive foam stiffness, E_f , using equation $E_f = 0.784\,E_s(\frac{\rho_f}{\rho_s})^2$, where E_s is the strut Young's modulus. Similarly, constant 0.784 accounts for foam structural parameters [9]. Model predicted foam stiffnesses were found to be consistent with the experimental measurements. This further indicates that the four-strut unit structure model is a reliable one to model foam properties using strut properties.

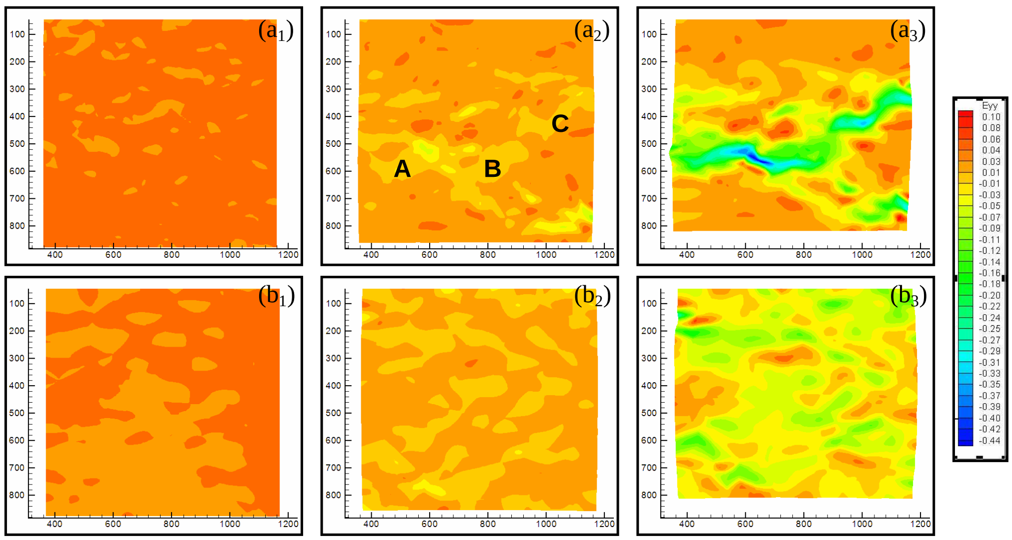

Figure 5: Macro-scale deformation localization for the T6-strengthened (a) and annealed (b) foams.

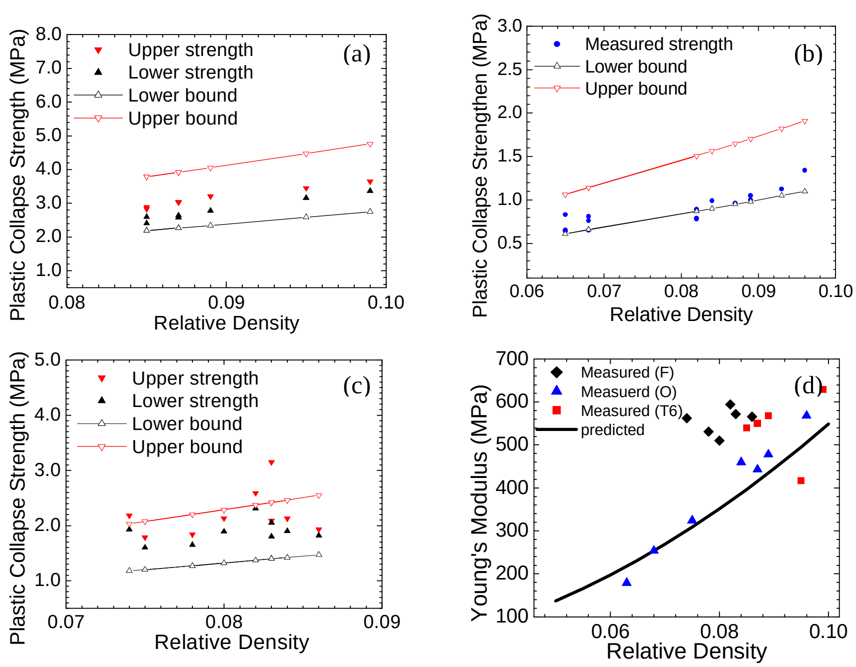

Figure 6: Comparisons between model predictions and measured data for the strengths of T6 foams (a), the strengths of O foams (a), the strengths of F foams (a), and the compressive foam stiffnesses.

5 SUMMARY AND CONCLUSION REMARKS

This paper examines the plastic deformation in an open cell Al foam. It has been found that the individual foam struts are typically stronger and more ductile than the corresponding bulk alloy subjected to the same heat treatment schedules. The onset of micro-scale plastic deformation in individual struts occurred far before the peak stress point in stress-strain curve. Plastic bending and plastic buckling are the two possible deformation mechanisms. Beyond the peak stress point, macro-scale plastic deformation occurred via the formation of several localized deformation regions that are discrete. A four-strut unit structure model was found to provide good predictions for the foam behavior under compression, when the real strut properties were used in the model.

6 ACKNOWLEDGEMENTS

This research has been supported by the Office of Naval Research (ONR) and The National Science Foundation (NSF). The authors would like to thank the ONR Program Manager, Dr. Julie Christodolous, and the NSF Program Manager, Dr. Carmen Huber for their encouragement and support. Grateful thanks are extended to Mr. Bryan Leyda of ERG for his assistance with foam processing and heat treatment. Finally, the authors would like to thank Dr. George Yoder for his assistance in the initiation of this work.

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