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DYNAMIC COMPRESSIVE BEHAVIOR OF CLOSED-CELL ALUMINUM FOAMS*

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ABSTRACT

Compression experiments were conducted on a closed-cell aluminum foam at strain rates ranging from $10^{-5}s^{-1}$ to 2000 s^{-1}. The materials demonstrated a strain-rate effect over the range of strain rates investigated; in particular, a marked strength increase at high strain rates is attributed to the stabilizing influence of the gas (i.e., air) pressure within the closed-cell structure. This was confirmed by testing samples with holes drilled through their cell walls to permit intercellular gas flow. An ultrahigh speed imaging system was used to capture the damage development sequence at high strain rates. Evaluation of sectioned microstructures following interrupted testing at a series of strains provided further insight on the deformation mechanism. The strain-rate sensitivity of the foam material appears to be related to sequential (time dependent) rupture of the cell walls that control the exit of cell-wall stabilizing gas from the structure. This conclusion was supported by the results of identical experiments involving a similar foam with very small pre-existing cell wall flaws.

INTRODUCTION

The contributions of intrinsic strength and relevant material properties to quasistatic deformation resistance of foam metals has been modeled by various authors [1-3]. Further theoretical analysis [4,5] suggests that cell wall imperfections (waviness; variation in wall thickness; non-uniform cell shape) probably are significant factors in local (initial) foam deformation. Experiments have shown [6] that such deformation proceeds by the formation of macroscopic deformation bands that initiate well below the steady-state flow stress.

Recently, several investigators have reported [7-10] strain-rate strengthening of Alporas closed-cell Al foam. Several mechanisms have been proposed to explain such behavior, including microinertial cell wall effects [11] on the kinetics of gas flow through broken cell walls [9]. The work reported here was aimed at defining the specific factors that control the strength-strain rate dependence of closed-cell metal foams.

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EXPERIMENTAL PROCEDURES

Two nominally closed-cell Al foams were investigated: (1) Alporas; relative density 0.15; cell size 2-3 mm; (2) Fraunhofer; relative density 0.24; cell size 1-2 mm. Cylindrical test samples (2.54 cm long x 2.36 cm diameter) were EDM-sectioned from blocks of each material. High strain rate ($\dot{\varepsilon}$ = 400 s^{-1} to 2000 s^{-1}) tests were conducted using a split Hopkinson pressure bar system, while low strain rate (10^{-5} s^{-1} to 1 s^{-1}) tests were achieved using a servo-controlled hydraulic test machine.

In some of the Alporas samples, 300 μm holes were drilled through the sample in order to produce interconnected cells. The spacing between the holes (4 mm) ensured that virtually all cells were thus penetrated.

A high-speed camera was utilized to capture the deformation sequence for the Alporas foam during SHPB testing at high strain rates. Strain levels were determined within the sample using the recorded images and the Southwest Research Institute (SwRI™) displacement mapping (DISMAP) system. This automated stereo-imaging technique, developed at SwRI, measures material deformation by mapping the displacements within the material [12].

Some high strain-rate compression tests were stopped at predetermined strain levels to allow evaluation of the deformed microstructures at a series of increasing strains; this was accomplished using metal spacers to limit the strain response. Samples were evaluated prior to testing, and after high strain-rate compression to approximately 3-4% and 9-10% strain. The 3-4% strain level was chosen since it represents a region on the stress-strain curve below the onset of the plateau region, while the 9-10% strain level is more representative of deformation throughout the plateau region.

Following high strain-rate testing, samples of both foams were longitudinally sectioned by EDM for optical and scanning electron microscopy evaluation. Compressed samples were evaluated to determine the extent of cell wall deformation and the associated damage modes.

RESULTS

Both foams display a strain-rate dependence, examples of which are shown as stress-strain plots in Figures 1 and 2. For the Alporas, a significant increase in both yield and flow (plateau) stress ($\varepsilon \cong 5\%$) is evident at high strain rates; for example, at $\dot{\varepsilon}$ = 700 s^{-1} (Figure 1). Under the same test conditions, the Fraunhofer material behaves differently (Figure 2). In this case, the material responds to the high strain-rate loading ($\dot{\varepsilon}$ = 700 s^{-1}, Figure 2) by experiencing a high stress pulse, which quickly drops to a plateau level that lies within the data band for quasistatic ($10^{-5}\ s^{-1} \leq \dot{\varepsilon} \leq 1\ s^{-1}$) experiments. Such peaks were never observed in any quasistatic tests, but were always present in high rate tests of Fraunhofer foam.

For Alporas samples with EDM-interconnected cells, no high strain-rate sensitivity was observed (Figure 3). Moreover, comparison of Figure 3 with Figure 1 shows that apart from the typical high strain rate closed-cell test at $\dot{\varepsilon}$ = 700 s^{-1}, all of the data lie within essentially the same scatterband.

The results of multiple tests at several strain rates are shown in Figures 4 and 5 for both foams, with strength plotted versus strain rate. For Alporas Al, the plateau strength for closed-cell samples clearly is strain-rate dependent at high loading rates (Figure 4), but it is essentially strain-rate independent for the drilled (interconnected cells) state. For the Fraunhofer material (Figure 5), strength enhancement at high loading rates is observed only if the height of the transient pulse is taken as the measure of strength. On the other hand, if the post-pulse (plateau) flow stress is plotted, it is found to be essentially strain-rate independent (Figure 5).

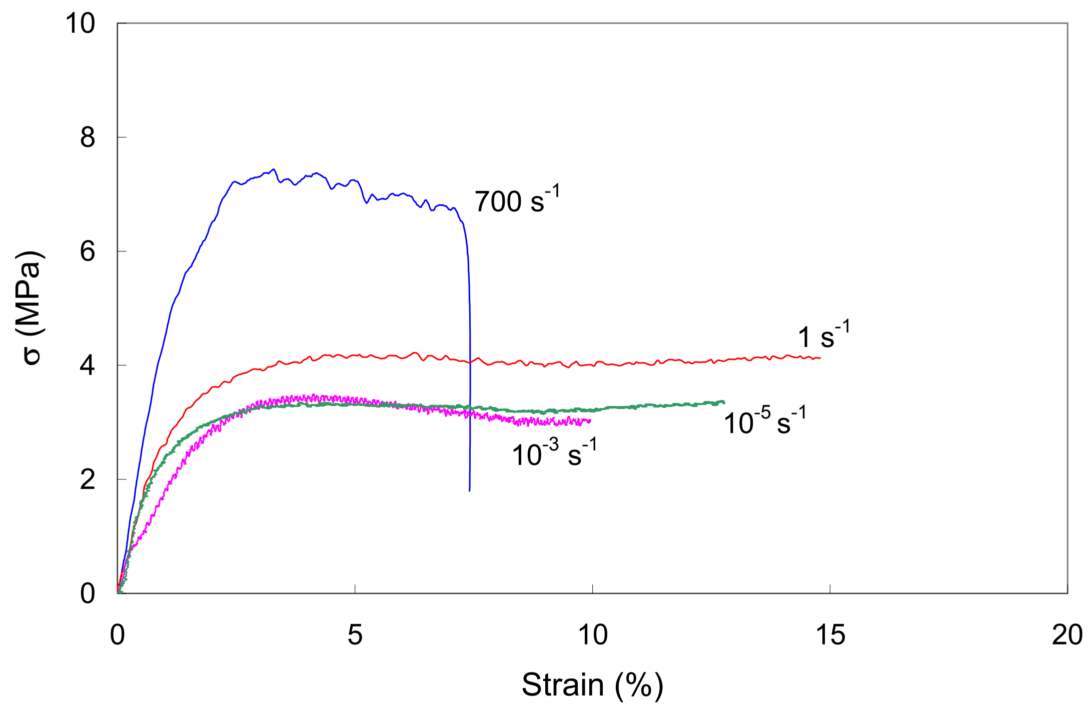

Figure 1: Stress-strain response of Alporas foam, showing marked increase in flow stress at a strain rate of 700 s^{-1} versus lower strain rates.

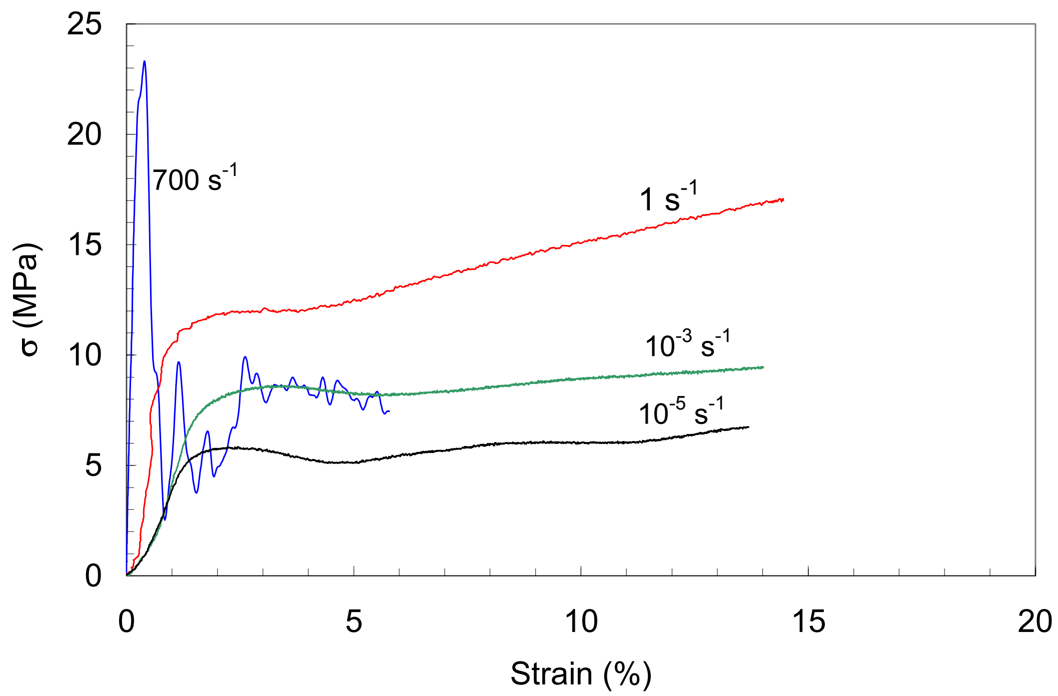

Figure 2: Stress-strain response of Fraunhofer foam, showing transient increase in strength at a strain rate of 700 s^{-1}.

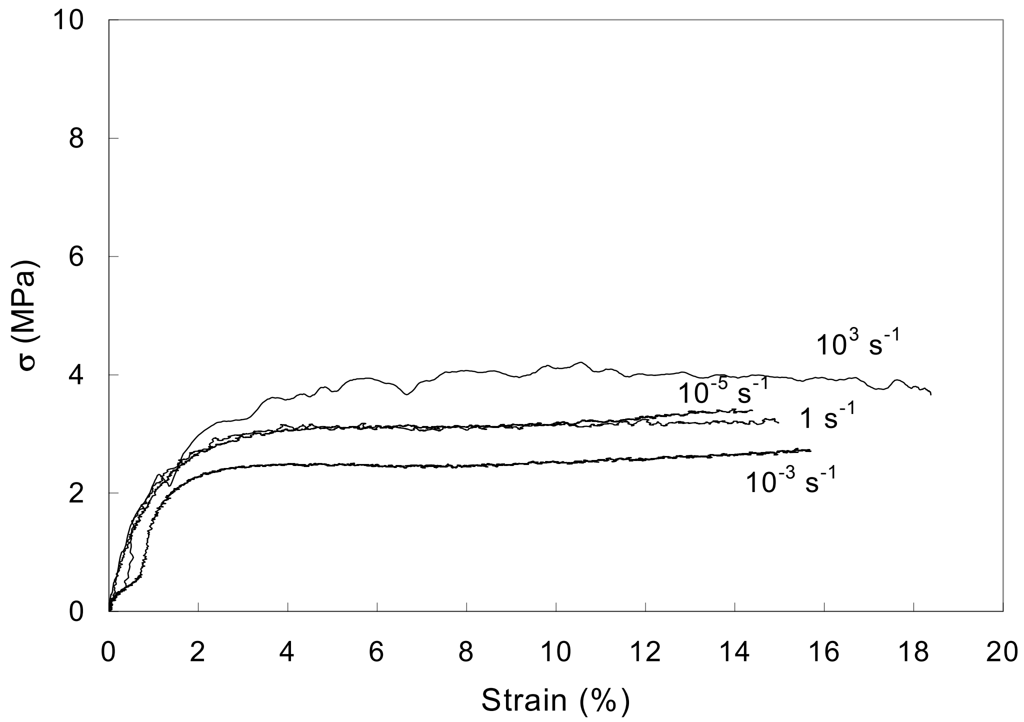

Figure 3: Stress-strain response of Alporas foam with EDM holes (interconnected cells).

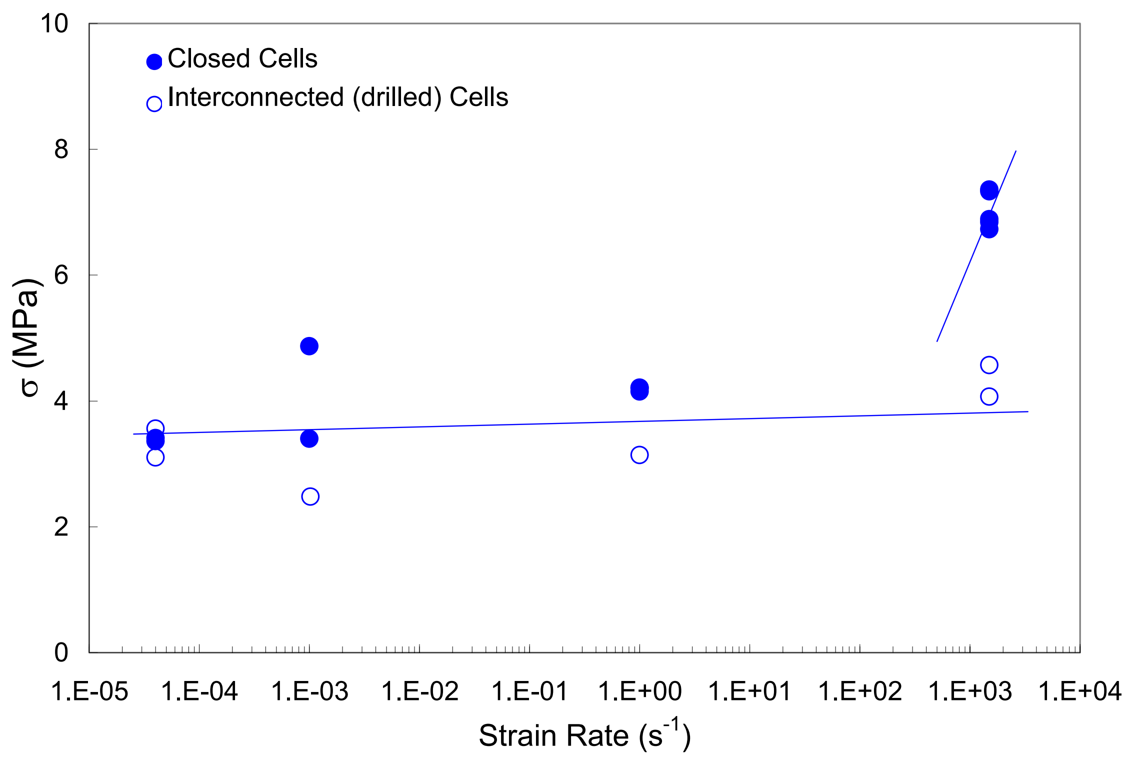

Figure 4: Flow stress (ε = 5%) versus strain rate for Alporas foam in the closed and interconnected cellular states. Lines are drawn to indicate trends.

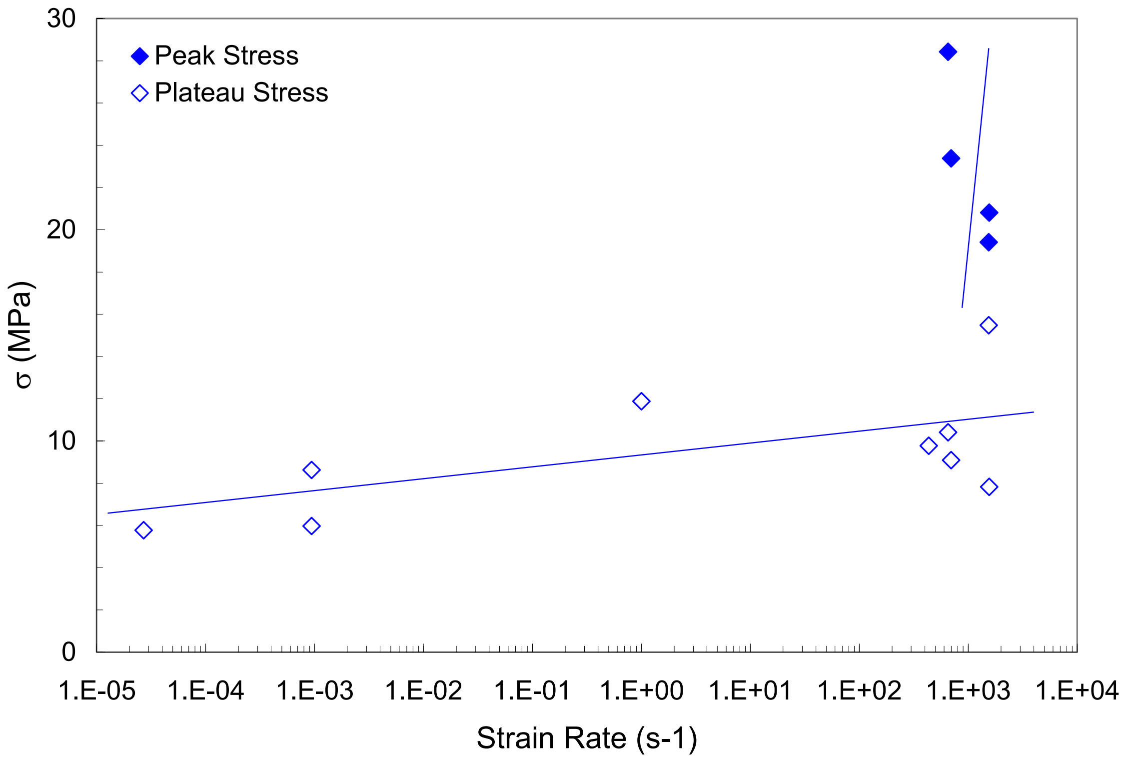

Figure 5: Flow stress ($\varepsilon = 5\%$) and initial peak stress versus strain rate for Fraunhofer foam. Lines are drawn to indicate trends.

Analysis of high-speed photos of SHPB tests [12] showed that, as for quasistatic tests [6], isolated deformation/damage bands nucleate early in Alporas foam, at stress levels well below the plateau flow stress. Local strains in these bands approached 50%, and lead to flexing, kinking, and buckling of cell walls. Within the local buckled zones, explosive rupture ("blowout") of the cells was observed for samples tested at high ($\dot{\varepsilon} > 400\ s^{-1}$) strain rates, versus more stable tearing at lower strain rates.

Microstructural investigations demonstrated that Fraunhofer foam also fails via discrete deformation bands, which likewise form under both quasistatic and dynamic loading conditions. However, local failure at high strain rate generally seems to be a consequence of the growth (tearing) of pre-existing cell wall flaws, rather than through cellular "blowout." Microscopic examination of untested specimens appeared to reveal tiny (~ 10 μm) holes, whose existence was verified by flotation experiments. Identical samples of Alporas and Fraunhofer foam were immersed in water; the former floated for days, while the latter sank irreversibly in less than 30 minutes.

DISCUSSION

The implication of the Alporas results is that buildup of gas pressure within cells eventually causes some of the cell walls to rupture. Specimen collapse occurs when there are no longer sufficient cell walls intact to support the compressive load.

This view is supported by the absence of strain rate strengthening (other than what is probably a mild intrinsic material contribution) in the drilled versus the closed-cell specimens tested in the SHPB. Clearly, it is not the rate of gas flow that is paramount since the average strength of drilled samples essentially coincides with that of closed-cell ones. Thus, the fact that the cell walls must rupture sequentially in order to permit the internal gas to exit the structure must account for the strain-rate sensitivity of the closed-cell structure. Such a surface-to-interior rupture sequence obviously is not required for the collapse of the drilled foam metal.

In the case of Fraunhofer foam, it appears that at high loading rates, all of the cells must be able to release pressure as the load increases. This controlled release forestalls to a much higher overall stress level the formation of the first unstable deformation band, whose presence then drops the stress to that (flow stress) needed to continue its propagation/expansion. The instability point may be related to the pressure-driven growth of the natural flaws, an intrinsically rate-dependent process.

This behavior contrasts with that of the artificially interconnected (drilled) Alporas foam. Evidently 300 μm holes are sufficient to permit virtually unimpeded (rate-insensitive) egress of internal gas, while the more than order-of-magnitude smaller natural flaws in the Fraunhofer foam require rate-dependent growth before gas loss is sufficient to destabilize the foam structure.

It should be noted that the two foams are fabricated via entirely different processes, i.e., Alporas through foaming an alloy melt by adding a foaming agent (TiH_2), and Fraunhofer through the powder-metallurgical mixing of alloy powder with a metal hydride foaming agent, followed by compaction heating of the precursor material. Hence, it is reasonable that the relative porosities of their respective cell walls might differ, and that Alporas foam could be more truly closed-cell than the Fraunhofer material.

REFERENCES

1. Gibson, L. J. and Ashby, M. F. (1997). *Cellular Solids: Structure and Properties*, 2nd edition, Pergamon Press, Oxford.

2. Sugimara, Y., Meyer, J., He, M.Y., Bart-Smith, H., Grenestedt, J. and Evans, A. G. (1997). *Acta Mater*. 45, 5245.

3. Banhart, J. and Baumeister, J. (1998). *J. of Mat. Sci*. 33, 1.

4. Simone, A. E. and Gibson, L. J. (1998). *Acta Mater*. 46, 11, 3929.

5. Grenestedt, J. L. (1998). In *Porous and Cellular Materials for Structural Applications*, pp. 3-13, Schwartz, D. S., Shih, D. S., Evans, A. G., Wadley, H. N. G. (Eds.). Materials Research Society Symposium Proceedings, Vol. 521.

6. Bart-Smith, H., Bastawros, A. F., Mumm, D. R., Evans, A. G., Sypeck, D. J., Wadley, H. N. G. (1998). *Acta Mater*. 46, 3583.

7. Mukai, T., Kanahashi, H., Miyoshi, T., Mabuchi, M., Nieh, T. G. and Higashi, K. (1999). *Scripta Met.* 40, 921.

8. Paul, A. and Ramamurty, U. (2000). *Mat. Sci. & Engr.* A281, 1.

9. Dannemann, K. A. and Lankford, J., Jr. (2000). *Mat. Sci. and Engr*. A293, 157.

10. Dannemann, K. A., Lankford, J., Jr. and Nicholls, A. E. (2000, in press). "The Effect of High Strain Rate Compression on Closed-Cell Aluminum Foams." In *Proc. of Mtls. Conf. on Fundamental Issues and Applications of Shock Wave and High-Strain-Rate Phenomena,* Explomet™ 2000, Albuquerque, NM.

11. Park, C. and Nutt, S. R. (in press). *Mat. Sci. & Engr.*

12. Davidson, D. L., Chan, K. S. and Page, R. A. (1989). AMD-Vol. 102, *Micromechanics: Experimental Techniques,* Sharpe, W. N., Jr. (Ed.) Book No. H00539.