Deformation Energy Absorption of Metal Foams at High Strain Rates

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Abstract

The attractive properties of metal foams include a high specific stiffness and a non-linear deformation behavior. For applications involving crush-energy absorption, the compression characteristics of metal foams at high strain rate are of particular interest. This paper reports on the high strain rate deformation characteristics of aluminum foams. Quasi-static and high strain rate tests including the Split-Hopkinson Pressure Bar tests and the ballistic target shooting are conducted. Metallographic examination indicated that the compression deformation of aluminum foam occurs by progressive cell wall shearing and tearing. This type of deformation mechanism is responsible for dissipating deformation energy while containing rearward deformation (such as spalling). Thus it provides added protection to equipment and personnel.

1. Objective

The objective of this study is to examine the deformation behavior of aluminum foams at high strain rates. Currently, only few data are available for foam structures at high strain rates. To better understand the foam material's deformation behavior as a function of strain rate, a series of experiments were designed and conducted including quasi-static testing, Split Hopkinson Pressure Bar as well as ballistic target shooting.

2. Fabrication of Metal Foam Samples

For all of the experiments conducted in this study, Al6061 foam samples with porosities ranging from 70% to 90% were fabricated (no subsequent heat treatment). These aluminum foams were made using aluminum 6061 alloy powder and TiH_2 as the foaming agent. Four different nominal densities of aluminum 6061 foams were produced for these tests. The foams were fabricated as rectangular plates approximately 13x150x150mm and had a typical closed cell structure [1].

3. Experiments

Quasi-static compression tests were conducted using a displacement-controlled Instron testing machine at a strain rate of $1.5\times10^{-3}\ s^{-1}$. High strain rate tests were conducted using a compression-type Split Hopkinson Pressure Bar (SHPB). Figure 1 is a schematic of the testing apparatus. Briefly, in this technique a cylindrical specimen is mounted between two long bars, referred to as the incident and transmitter bars, while a third bar, the striker bar, is used to impact to the end of the incident bar. This impact creates a compressive pulse which travels down the incident bar and into the specimen, which then deforms as it is sandwiched between incident and transmitter bars. The strains measured by strain gages on the incident and transmitter bars are then used to determine strain rate, strain, and stress in the specimen using one-dimensional elastic wave analysis on the bars. Details of the SHPB test technique and the corresponding data analysis are given elsewhere [2].

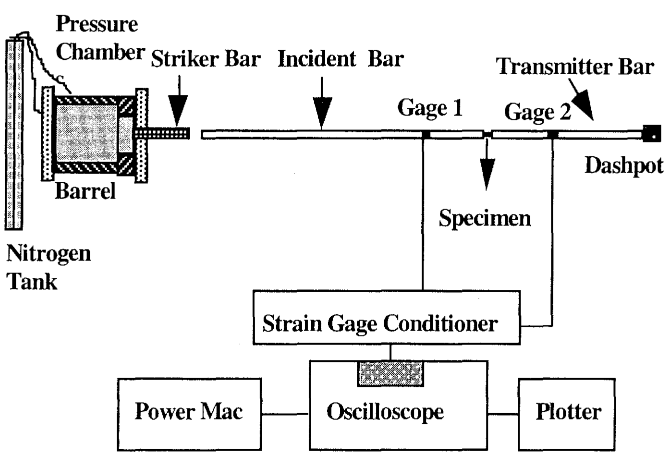

Figure 3: Schematic of Split Hopkinson Pressure Bar testing.

In both types of test, cylindrical foam specimens approximately 18 mm in diameter and 12 mm length were compressed. The diameter of the samples was slightly less than that of the bars (19 mm) and, due to the small Poisson's ratio of the foam, specimen diameters during deformation never exceeded the bar diameter within the studied strain levels up to 60% strain. The top and bottom surfaces of the plates were machined flat and parallel before specimens were core-drilled from them and weighed in order to calculate density and relative density, $\rho^*=\rho_f/\rho_m$, where "f" and "m" refer to the foam and precursor metal, respectively. The nominal densities of the four plates tested are: (1) 0.34 g/cm^3, (2) 0.47 g/cm^3, (3) 0.57 g/cm^3 and (4) 0.82 g/cm^3.

4. Results and Discussions

4.1 Results of quasi-static testing

Typical quasi-static compression stress-strain curves of the foam are shown for a sample of each density in Figure 2. The stress-strain curve can be divided into three regions, (1) linear elastic region, (2) collapse, and (3) densification. In Region 1 the only deformation that occurs is elastic and is due to cell wall bending. This is followed by Region 2, in which plastic collapse of the first cell wall occurs and the stress drops. In Region 3, the foam progressively collapses and densifies. It was observed that deformation in Region 3 was highly localized and proceeded by the advance of a densification front from deformed to undeformed regions of the sample. Since the deformation occurs discontinuously in adjoining cells in Region 2, oscillations in stress were frequently detected due to the repetitive nature of the process of cell collapse and densification. The oscillations were, however, generally superimposed upon a slowly increasing stress.

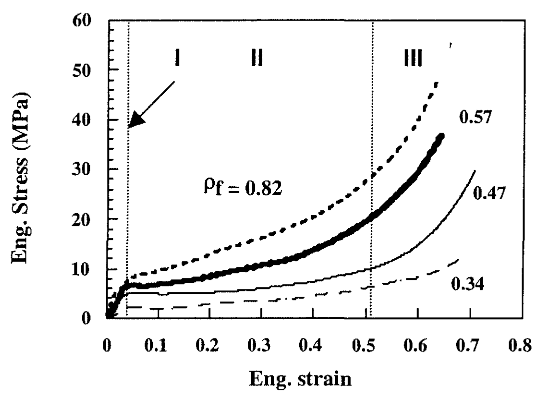

Figure 2: Quasi-static stress *vs.* strain curves for foam samples of each density (ρ_f).

4.2 Results of Split Hopkinson Pressure Bar testing

Figure 3 shows the flow stress at 10% strain plotted *vs.* density for all the samples tested at all strain rates. Although scatter exists, the flow stress correlates quite well with the density and can be plotted to a power law relationship of the form [3]:

Flow stress = 23.5 x $\rho^{2.2}$ MPa, Correlation coefficient (R) = 0.965 Eqn. 1

4.3 Microscopic observations

The sequence of deformation events was recorded digitally during quasi-static compression testing. A typical record is presented in Figure 4, as a montage of frames numbered from 1 to 12 representing a total strain of 0.18. Frame 1 shows an undeformed region of the foam that contained several cells with the compression loading axis horizontal. As soon as compression starts the thinnest sections of cell walls, approximately parallel to the compression axis, start to collapse, frame 2. In the later stage of deformation, see frames 6 and 9, cell walls normal to the compression axis tear due to the induced tensile strains. It may also be noted that deformation is highly non-homogeneous and localized in the mid-section of the region considered, see frame 12. These types of observations are characteristic of the deformation behavior of the foam in Regions 1 and 2, as was discussed earlier. As the deformation proceeds, all the cell walls crush and further compression stiffens the foam in Region 3.

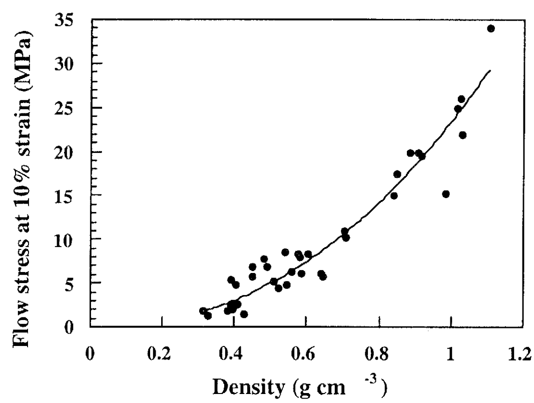

Figure 3: Flow stress at 10% strain *vs.* density for all samples.

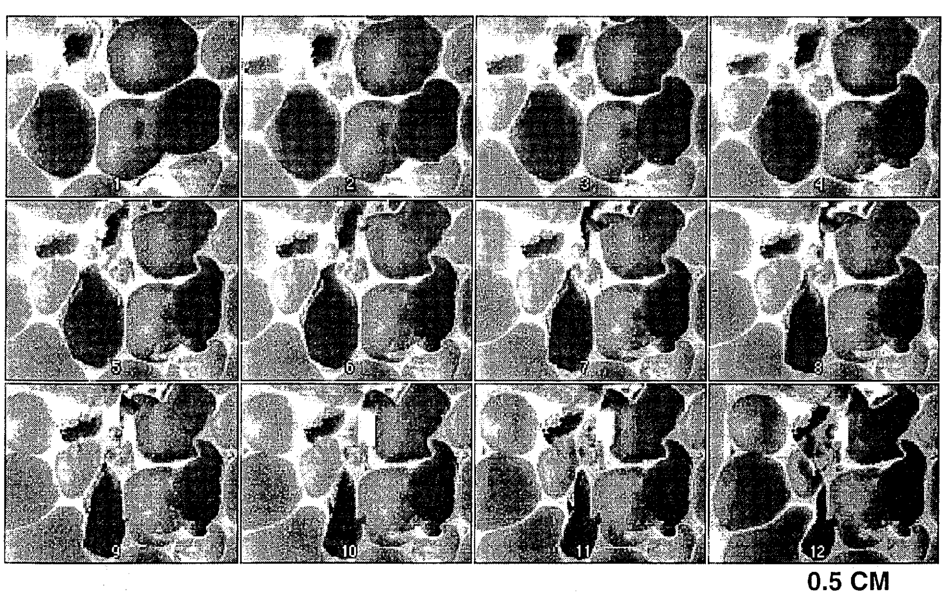

Figure 4: Sequence of frames during quasi-static crushing of foam sample. (Compression axis horizontal)

5. Metal Foams under Ballistic Impact

Experiments were also conducted on a ballistic target incorporating an aluminum foam insert. In these experiments, the strike plate of the ballistic target was impacted with 20-mm Fragment Simulating Projectile (FSP) travelling at a speed of 1,067 m/sec. The metal foam panel was inserted behind the strike plate to absorb the deformation energy. Figure 5 shows a schematic diagram of the target used in these experiments. The first two layers consisted of a impact tile made of AS109-ceramic matrix composite [4] and a steel plate, simulating the armor that was intended to arrest the penetrator. The Al2O3 ceramic plate is intended to simulate a "fragile component" that may be harmed by backface responses of the armor. The aluminum plates behind the ceramic plates were utilized to support the ceramic and enable post test recovery. Metal foam layers were located between the steel plate and the Al2O3 ceramic plate.

Figure 6 shows the representative microstructure indicating the deformation sequences of the cell structure after testing. It was suggested that the deformation energy first densified the upper portion of the aluminum foam. Subsequent deformation introduced tearing and shearing of the cell walls, as illustrated earlier in Figure 4, an effect of core shearing deformation for energy dissipation. In this case, the deformation energy was dissipated over a much larger area than that of the projectile. Similar deformation mechanisms can also be observed at low strain rates.

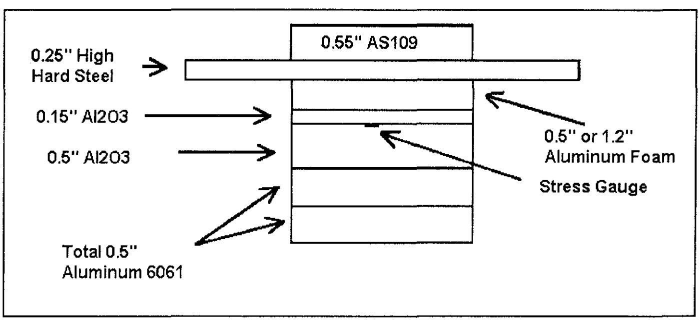

Figure 5: Ballistic target design

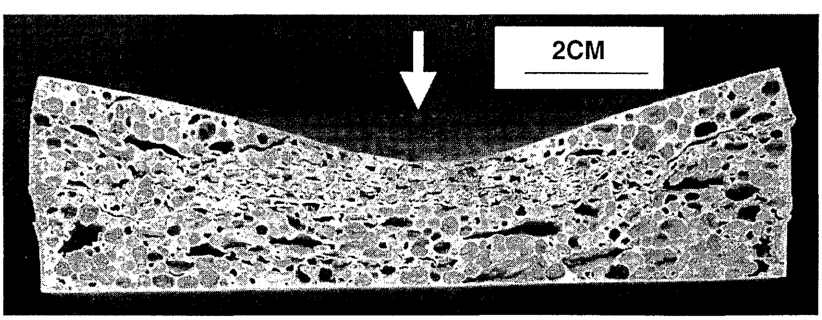

Figure 6: Cross-sectioned microstructure showing the deformation sequences.

6. Summary

The deformation energy absorption capability of aluminum 6061 foam was evaluated over a range of strain rates. The results from the quasi-static compression tests and the SHPB tests show that the compressive flow stress of the aluminum foam was a function of the relative density. Also, the flow stress is essentially independent of strain rate. Compression deformation of the foam was in the form of cell wall shearing and tearing, which occurred locally, then progressed throughout the sample. Finally, the foam was densified due to cell wall touching. Results from the ballistic testing of armor targets with aluminum foam inserts indicate that the transmitted deformation energy dissipated over a large volume within the metal foam. The aluminum foam may be utilized to reduce backface deformation and to suppress spalling. Thus, it provides added protection to equipment or personnel behind the target.

Future work will focus on maximizing the energy absorption capability by adjusting the foam parameters such as cell size, wall thickness, and uniformity. Different alloying elements and density levels in metal foams will be fabricated for further evaluation.

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(4) AS109 is a ceramic matrix composite produced by Lanxide Armor Products, Inc.