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Improving the energy absorption of closed cell aluminum foams

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Closed cell aluminum foams have received much recent attention as energy absorbing materials on account of their ability to undergo extensive deformation at a relatively low stress called the plateau stress. Several studies describe the improvements in energy absorption to be obtained, relative to their empty counterparts, when foam filled tubes are crushed either quasi-statically or dynamically [1–4]. Al foams are also of possible interest for ballistic applications because they present a very large acoustic impedance mismatch with common armor materials, offering the possibility of being able to modify the way in which elastic waves travel through multi-component armor [5].

Two cases of energy absorption are of particular practical interest. The first concerns blast protection, in which loading occurs over a broad area, and the second concerns resistance to penetration by small projectiles, in which severe point loading is experienced. The potential advantages that foam can offer in the first case are most clear if the foam remains in contact with a face sheet during deformation because the face sheet serves to spread the deformation throughout the foam and prevent local perforation. However, in the second case, the tendency is for the foam to perforate locally and little energy is absorbed when impacted by a small object.

A key factor in this latter behavior is that metal foam has an approximately zero Poisson's ratio. Hence, no lateral deformation occurs and the only contribution to energy absorpotion is from material directly ahead of the impacting object. The objective of the present study, therefore, was to investigate whether it is feasible to increase the energy absorption by causing the deformation to spread sideways, e.g., by inserting tubes into the foam (rather than *vice versa*). Experiments have been performed with novel foam/tube architectures and it has been shown that it is possible to increase the energy absorbed when foam is subject to loading by a small blunt object. While this preliminary series of experiments is not exhaustive, the tests definitely confirm that foam-based architectures can be tailored to increase the energy absorption beyond that available from foams alone.

Aluminum foam blocks approximately $45 \times 45 \times 50$ mm were cut from larger foam blocks and visually examined to ensure a relatively consistent pore size and freedom from any major, visible defects. Gentle core drilling was used to prepare holes 7.15 mm in diameter in either a square or hexagonal array, Fig. 1. Al-3003 aluminum tubes, 0.4 mm wall thickness, were then inserted into the holes. Samples were weighed at each stage of preparation so that energy absorption can still be compared on a "per kg" or density basis. Aluminum tubes were chosen so as not to increase the density of the assembly much beyond that of the foam; ideally the weight of tube inserted should equal the weight of foam removed if the density is to be maintained constant.

Mechanical testing was carried out by subjecting the assemblies to indentation with a 12.7 mm diameter stainless steel indenter, at a penetration speed of $0.2\ \mathrm{mm \cdot s^{-1}}$. Data acquisition software was used to record load and penetration depth measurements during testing.

Force/indentation depth curves for typical samples are shown in Fig. 2 where it is clear that, for the same displacement, the hexagonal tube arrangement requires the greatest force. Although an attempt has been made to "standardize" the tests somewhat, it is clear that there are many factors related to the geometry of the samples, size, number of tubes, spacing of tubes, tube wall thickness, tube diameter, etc., that make direct comparison problematical.

The data were also converted to display specific energy absorption as a function of displacement using the equation

$$\bar{W}_{(s)} = \frac{W_{(s)}}{m} = \frac{\int_0^s F_{(s)}\,\mathrm{d}s}{m}$$

where s is the displacement, m the mass of the sample,

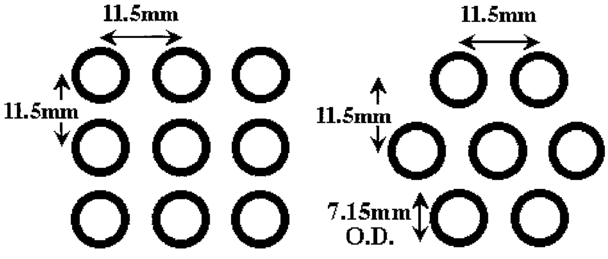

Figure 1 Sample configurations and dimensions: (a) square array and (b) hexagonal array.

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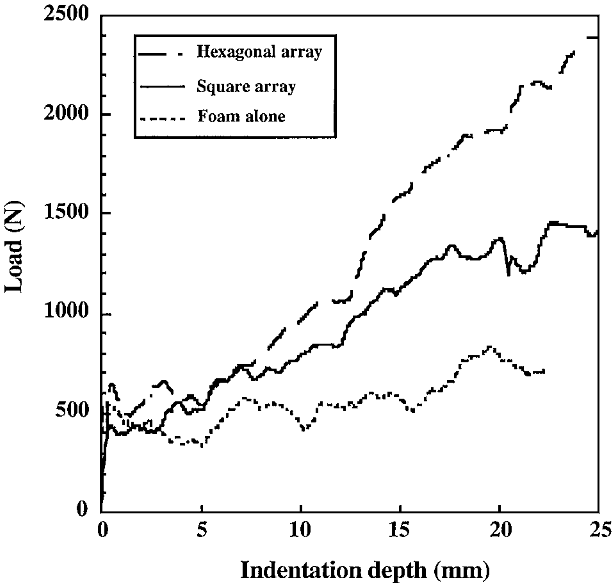


Figure 2 Typical applied load vs. indentation depth records.

and F the force. These data are plotted in Fig. 3 and again show clearly that the hexagonal arrangement absorbs the most energy. Specific energy absorption was calculated after a deformation of 23 mm and it was found that, when averaged over the whole series of tests, 10 in all, the hexagonal samples absorbed 43% more energy that the square ones and 82% more than the plain foam samples.

After testing, representative samples were cut and polished to examine the interior of the indented region and allow observation of the deformation modes, Fig. 4a and b. The square array sample shows no lateral deformation and tubes in the second row are still perfectly circular even though the indenter passed within 2 mm of them. In the hexagonal array on the other hand, tubes in the second row are severely deformed and deformation of the third row is already well under way. Comparison of the deformed volume in the respective samples also clearly shows that the hexagonal array causes greater deformation and, hence, specific energy absorption than the square array.

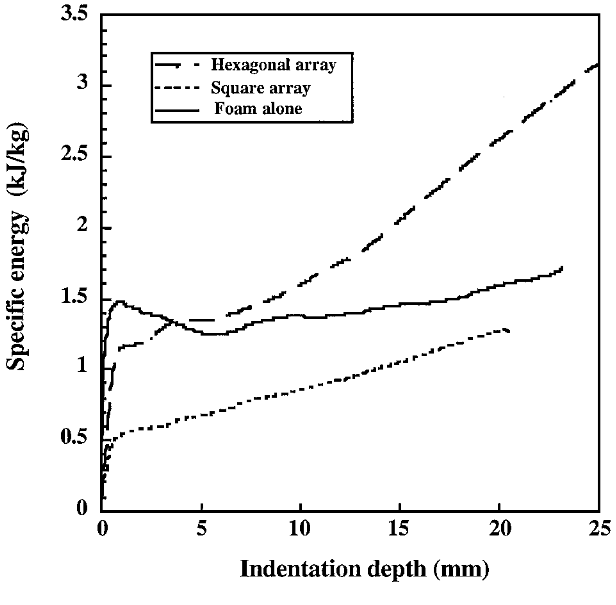
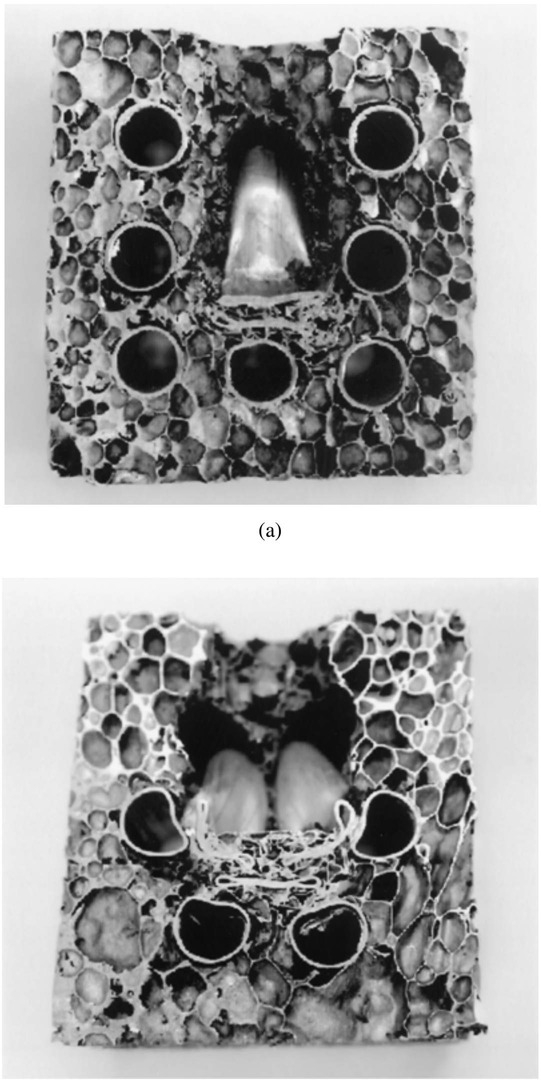


Figure 3 Specific energy absorption as a function of indentation depth.


(a)

(b)

Figure 4 Appearance of typical (a) square array and (b) hexagonal array samples after indentation.

Slight discrepancies between the tests were observed for the first few mm of deformation. For example, the hexagonal array sample shown in Fig. 2 did not begin to deform until a load of approximately 700 N was applied whereas all the others began to deform at loads in the region of 500 N. This is believed to be due to a surface "skin" present on some foam samples and to local variations in the undeformed foam structure wherein the cells may vary in diameter between $\sim$2 and 5 mm, with even larger cells occurring occasionally.

In order to remove this factor when comparing the data, the rate of specific energy absorption as a function of deformation was calculated, i.e., the gradient of each plot shown in Fig. 4. It is found that, on average, the rates of energy absorption for the regular foam, square array and hexagonal array samples were in the ratio of 1 : 3.2 : 5.1.

Again it is emphasized that there are many factors that will influence the actual measurements in experiments such as these. For example, in experiments on the square array, the indenter soon pushes directly upon

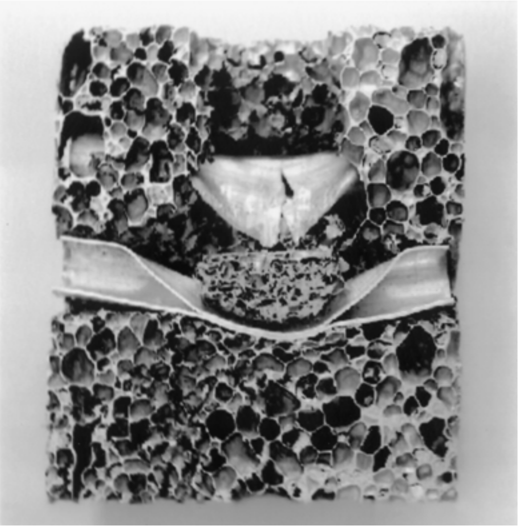


Figure 5 Section parallel to tubes after indentation of hexagonal array.

a single tube while in the hexagonal array it is soon pushing against very slightly more than 2 half-tubes. Consequently, it is seen from Fig. 4a and b that only one crushed tube is dragged down with the indenter in the square array while two are dragged along in the hexagonal array. Fig. 5, a section parallel to the tubes, shows more dramatically this effect of the tubes in "spreading" the deformation over a wider section of the foam. Despite the clear approximations in quantifying and correlating the effect from one architecture to another, these experiments have nevertheless demonstrated that the energy absorption efficiency of aluminum foams can be dramatically increased by suitably incorporating other load bearing elements that serve to distribute the deformation over a larger volume of material.

The simple arrangements used here are by no means optimized since in the square array only 2 out of 9 tubes have participated in the process whereas in the hexagonal array 7 out of 7 have participated. Once this is appreciated, other architectures immediately suggest themselves. For example, if tubes are to be incorporated in the x/y plane as here, it would be reasonable to incorporate layers alternately in the y direction and x direction so as to maximize the interaction between tubes. Alternatively, if low density requirments can be relaxed, strips of metal could be incorporated. Further experiments and modeling are planned to explore these possibilities and develop more efficient energy absorbing structures.

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