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Optimization of cellular solids for energy absorption

Aaron Wiest,[a,*] Craig A. MacDougall[a] and Robert D. Conner[a,b]

[a] *Product Engineering Department Naval Surface Warfare Center, Corona Division, Norco, CA 92860, USA*
[b] *Department of Manufacturing Systems Engineering and Management, California State University Northridge, Northridge, CA 91330, USA*

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Analysis of equations governing specific energy absorption for cellular solids indicates that silicate glass-based materials should outperform other cellular solids, including metallic foams. Quasi-static compression tests of silicate glass cellular materials fabricated by thermally bonding hollow spheres above the glass transition temperature (T_g) experimentally supports the analysis. Materials with some of the highest energy-absorbing capacities in the literature (14.8 MJ m^{-3} or 26.5 kJ kg^{-1}) are reported. Fabrication techniques are generalizable to any amorphous hollow spheres with thermal stability above T_g.
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Cellular solids and foams are used in a wide variety of commercial and military applications including energy absorption, thermal and acoustic insulation, lightweight structural components, and catalytic processes [1–5]. Current research activities in the field of cellular solids include increasing strength [6], stiffness [7], energy absorption [8], heat exchange [9], catalytic capacity [10], biocompatibility [11], nanostructured porous materials for functional applications [12], processing methods [13], cellular solids made of metallic hollow spheres [14] and cellular structures suitable for high-temperature applications [15]. Energy absorption is of interest for blast mitigation technologies as well as for improving safety and reducing vehicle weight.

The key figure of merit in specific energy absorption is maximum energy absorption at minimum density. Specific energy absorption (U) is a product of failure stress (σ) × densification strain (ε_D) or the area under the stress–strain curve divided by the cellular solid density (ρ). This is shown in the following equation:

$$U = \frac{\sigma \varepsilon_D}{\rho}. \tag{1}$$

A simple model for cellular solid failure stress is given by [3]:

$$\frac{\sigma}{\sigma_s} = A * \left(\varphi * \frac{\rho}{\rho_s}\right)^{3/2} + B * (1-\varphi)\frac{\rho}{\rho_s} + \frac{P_i - P_o}{\sigma_s}, \tag{2}$$

where φ is the volume fraction of material contained in the edges; ρ and ρ_s are the density of the cellular solid and bulk solid, respectively; σ and σ_s are the failure stress of the cellular solid and bulk solid, respectively; P_i and P_o are the pressures inside the cell and outside the cell, respectively (usually negligible); and A and B are constants depending on the material and failure mechanism.

Combining Eqs. (1) and (2), we obtain Eq. (3a) and a simplified version Eq. (3b):

$$U = \left\{\frac{\sigma_s}{\rho_s}\left[A\varphi^{\frac{3}{2}}\left(\frac{\rho}{\rho_s}\right)^{\frac{1}{2}} + B(1-\varphi)\right] + P_i - P_o\right\}\varepsilon_D, \tag{3a}$$

$$U \propto \frac{\sigma_s}{\rho_s}\varepsilon_D. \tag{3b}$$

The main contribution to U comes from the specific strength of the bulk material shown in Eq. (3b). Materials with maximum specific strength and high densification strain should be ideal for energy absorption applications. Table 1 contains the specific strengths of many materials.

While graphene has the highest specific strength values, it is a two-dimensional material and not useful for load-bearing three-dimensional cellular structures.

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[*] Corresponding author. Tel.: +1 951 273 4819; e-mail addresses: aaron.wiest@navy.mil; aaronwiest@alumni.caltech.edu

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Table 1. Specific strength of materials.

Material	Failure stress (MPa)	Density (kg m^{-3})	Specific strength (MJ kg^{-1})	Refs.
Graphene	130,000	1000	130	[16]
S-Glass	4995	2480	1.998	[17]
E-Glass	3450	2570	1.342	[17]
AISI A11 tool steel	5205	7450	0.699	[18]
2800 maraging steel	2693	8000	0.337	[19]
Zr based BMG	1723	6100	0.282	[20]
Titanium 11	1040	4500	0.231	[21]
2014-T6 aluminum alloy	483	2800	0.173	[22]

Table 1 shows that silicate glasses have much higher specific strengths than steels, bulk metallic glasses (BMGs), titanium and aluminum alloys. Theoretically, cellular solids fabricated from silicate glasses should have 3–10 times more specific energy-absorbing capacity than those made from metallic alloys, based on specific strength values.

To experimentally investigate this result, a method was developed for forming silicate glass cellular solids that involves heating 10–100 μm diameter amorphous hollow spheres (glass bubbles) above T_g, which induces a viscous flow transition causing the bubbles to expand or contract (depending on the pressure differential and surface tension) and ultimately bond together. The process, termed amorphous bubble bonding, is schematically depicted in Figure 1. Cell morphology depends on glass bubble properties as well as processing parameters. Figure 1 shows a scanning electron micrograph of cell morphology after processing. Note that the glass bubbles have bonded, deformed, and do not appear spherical. The process of amorphous bubble bonding is compatible with any material with sufficient thermal stability above T_g including BMGs, plastics, ceramic and oxide glasses.

Commercially available hollow glass sphere materials were processed at various temperatures and times to maximize cellular solid strength. IM16K glass bubbles manufactured by 3 M yielded the highest strength materials within the processing parameters explored. The product data sheet for IM16K glass bubbles indicates average sphere diameter = 20 μm, true density = 460 kg m^{-3}, isostatic crush strength = 110 MPa. The bulk material strength (failure stress) can be approximated by using the product data sheet information and assuming that the isostatic crush strength is comparable with the rupture pressure = $P_{\max}$ calculated by thin-wall pressure vessel theory when σ is set equal to σ_s. The thin-wall pressure vessel equation is given in Eq. (4) for hollow spheres. The wall thickness t is calculated using the true density and average sphere diameter and assuming a borosilicate glass bulk density of 2230 kg m^{-3}.

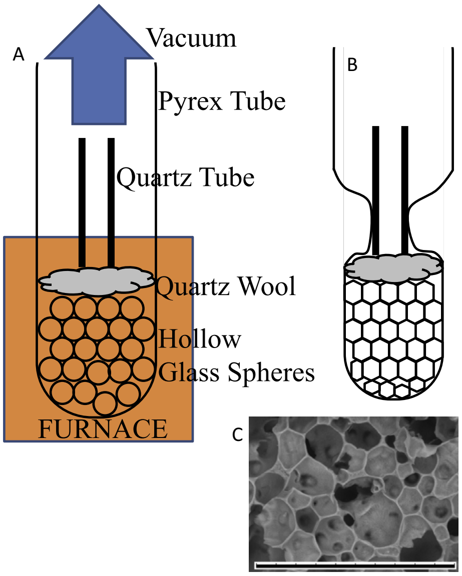

Figure 1. Amorphous bubble bonding. (A) Schematic drawing of processing setup prior to amorphous bubble bonding. (B) Schematic drawing of processing setup after amorphous bubble bonding. (C) SEM of post-processed cellular solid where the scale bar is 100 μm.

$$\sigma_s = \frac{P_{\max} r}{2t}. \tag{4}$$

σ_s = 744 MPa for IM16K glass bubbles. This calculated bulk failure stress value for IM16K glass is far lower than the failure stress for the other silicate glasses listed in Table 1.

Empirical results showed that amorphous bubble bonding the glass bubbles at 1116 K for 30 min under vacuum in Pyrex tubes yielded the highest-strength materials. One end of a Pyrex tube was sealed and hollow glass spheres were poured into the tube. A small plug of quartz wool was pushed through the tube until it rested on the glass bubbles. The glass bubbles, quartz wool, and a smaller-diameter clear fused quartz tube inside the Pyrex tube were inserted into a vertical furnace and vacuum was maintained with a roughing pump connection to the open end of the Pyrex tube during heating as shown in Figure 1. The Pyrex tube diameter decreased as a result of heating under vacuum. The decrease in Pyrex tube diameter compressed the glass bubble material. The cellular solid was removed from the Pyrex vessel using a slow-speed saw. Multiple sample density measurements were taken by determining the sample dimensions using calipers and the mass using an analytical balance. The density measurements varied from 550 to 570 kg m^{-3} along the length of the rod. Assuming a 60% random packing efficiency, the density of unbonded glass bubbles should be approximately 280 kg m^{-3}. The pre- and post-processing densities indicate that the material approximately doubled in density during processing.

The material was tested in compression at quasi-static strain rates of 10^{-2} and 10^{-3} s^{-1}. Stress–strain curves of the cellular solid tested at different strain rates and aspect ratios are presented in Figure 2. The peak stress, measured in quasi-static compression, was found to be 39 MPa and average stresses ranged from 14 to 18.5 MPa as seen in Figure 2.

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