Syntactic bulk metallic glass foam

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An amorphous metal foam with a bulk density of 3.4 g/cm³ is created by low-pressure melt infiltration of the bulk metallic glass-forming alloy Zr₅₇Nb₅Cu₁₅.₄Ni₁₂.₆Al₁₀ into a bed of hollow carbon microspheres, followed by rapid quenching. The foam consists of a glassy metallic matrix containing ~60 vol. % of homogeneously distributed carbon microspheres, 25–50 μm in diameter, with small amounts of ZrC at the interface. An amorphous foam with 5 mm diameter showed no measurable loss in thermal stability as compared to the amorphous alloy in bulk form.

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vacuum dried at the processing temperature (1250 K) for at least one hour to remove volatile components. A bed of dried spheres (~5 mm diameter and 8 mm height) was then placed into the sealed end of a stainless-steel tube (wall thickness <1 mm), and a thin perforated graphite disk was placed above the bed to prevent premature contact between bed and melt. The tube was given a light coating of Y_2O_3 to minimize reaction with the melt and prevent dissolution of the carbon microspheres into the steel, and the whole crucible assembly was then preheated to 1250 K under high vacuum (3 × 10^{-5} Torr). After 30 minutes of equilibration, a pre-alloyed charge of Zr_{57}Nb_{12.6}Cu_{15.5}Ni_{10.0}Al_{10} (base metals ≥99.5% purity) was lowered into the hot zone and allowed to melt for 3 minutes and collect on top of the spacer disk. This melt was then infiltrated into the microsphere bed using 153 kPa of 99.9996% pure Ar gas. After a 45-second infiltration period, the infiltrated sample was quenched by immersion of the tube in a large bath of chilled and strongly agitated 8.5 wt. % NaCl brine solution. Infiltration was found to be uniform only in the lowest 3 mm at the bottom of the bed, and the material in that region was used for all tests described below. This part of the sample is believed to have cooled mostly radially, because the crucible bottom was more than 2.5 times thicker than its walls.

Figure 1(a) shows an optical micrograph of a Vit106 foam produced by this method. The figure demonstrates that the foam structure is uniform across the entire cross-section, with no evidence of sphere agglomeration, porosity due to poor wetting, or other macroscopic defects. Figure 1(b) shows a higher-magnification image of the same sample and highlights some of the features visible in the foam microstructure, which include irregularly shaped spheres, infiltrated spheres, and sphere fragments, found among a majority of hollow, uninfiltrated spheres. Infiltrated necks as narrow as 1 μm were found between particles, indicating excellent wetting, though occasional uninfiltreted necks were also present. Analysis of several hundred particles reveals that the proportion of broken and infiltrated spheres is ~1%, and consequently these flaws only marginally impact overall density and properties; the proportion of misshapen spheres is much higher, ~18%, with the remainder (81%) being roughly spherical and intact. Image analysis also shows that the volume fraction of Vit106 in the foam is 41%, with an estimated error of 2%. The net foam density, measured by helium pycnometry, is 3.4 ± 0.2 g/cm³, corresponding to a relative density (ρ_{foam}/ρ_{Vit106}) of 50 ± 3%. This relative density is higher than the Vit106 volume fraction due to the additional mass of carbon. While the relative density is required for engineering design, the BMG fraction is expected to be more relevant to the mechanical properties of the foam, since the highly irregular thickness of the microsphere walls makes them unlikely to contribute appreciable strengthening.

Figure 2 shows x-ray diffraction data (using Cu-Kα radiation) verifying the amorphous structure of the foam and demonstrating the presence of ZrC, which was not visible using either optical or scanning electron microscopy. Submicron interfacial ZrC has been observed in studies of similar Zr-based alloys with carbon fibers and carbide particulates,14,15 where it was concluded that the formation of ZrC does not significantly affect the glass-forming ability of the host alloys. In a separate study,16 it was shown that interfacial ZrC allows for the reactive wetting of the BMG alloy Zr_{41.5}Ti_{13.8}Cu_{12.6}Ni_{10.0}Be_{22.5} (Vit1) onto carbon substrates above 1200 K. The present low-pressure infiltration of a viscous Vit106 melt around small carbon microspheres likely

![Image of the structure of syntactic Vit106 foam]

FIG. 1. Optical micrographs showing the structure of syntactic Vit106 foam: (a) Low magnification image demonstrating foam uniformity; (b) magnified image of the surface showing microscopic foam structure. Misshapen carbon microspheres are visible, as is a sphere wall fragment (indicated by arrow). Good wetting is inferred from the lack of interparticle porosity.

![Graph showing x-ray diffraction data]

FIG. 2. X-ray diffraction patterns collected from: (a) Fully dense amorphous Vit106; (b) the surface of the Vit106 foam shown in Fig. 1(a). Crystalline reflections are indicated by markers.
heat capacity of Zr, C, and ZrC, it is calculated that the endotherm on the same ingot used to make this foam, are shown in Fig. 3. 

From these facts, it is concluded that the fundamental crystallization pathway of the Vit106 matrix is unchanged in the foam after adjusting for its lower Vit106 content and the attendant loss of Zr from the matrix, during the scan.

In summary, a method has been developed to produce a closed-cell, amorphous Vit106 foam by low-pressure infiltration of carbon microspheres; the resulting foam exhibits a bulk density of ~3.4 g/cm^3 with no measurable loss in stability. This method should apply to any BMG alloy which reactivly wets microspheres at high temperature without contamination or nucleation inducing crystallization. Use of BMG alloys in foam architectures, where loads are carried mostly in bending by small strut sections, is expected to lead to marked improvements in macroscopic ductility relative to monolithic glass. It is also anticipated that these foams will show additional properties common to other metallic foams, including high density-compensated mechanical properties, mechanical energy absorption, and acoustic damping.

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![DSC thermograms indicating glass transition temperatures $T_g$ and onset temperatures of crystallization $T_x$ for: (a) Fully dense amorphous Vit106 from the sample analyzed in Fig. 2(a); (b) Vit106 foam from Figs. 1 and 2(b).](image)