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A metallic glass syntactic foam with enhanced energy absorption performance

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ABSTRACT

By using the high-pressure melt infiltration technique, a syntactic foam is fabricated with bulk metallic glass and alumina cenospheres. Compared to pure metallic glass foams, the new foam possesses a greatly enhanced energy absorbing capacity of 113.6 MJ m^{-3} due to the combination of high strength, stability and ductility. It is shown that the high strength of the foam primarily results from alumina cenospheres, which enhance its stability and induce a stable stress platform. Both the collapse of struts and multiple shear bands in metallic glass matrix accommodate large deformation.

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Metallic foams are recognized as attractive structural and functional materials for their unique combination of mechanical, physical and chemical properties such as high density-compensated strength, mechanical energy absorption and acoustic damping [1–4]. The increasing interest and importance in structural applications have motivated investigation of bulk metallic glasses (BMGs) as alternative materials of these foams on account of their ultrahigh strength, exceptional elasticity, excellent corrosion resistance, and process ability [5–9]. Therefore, considerable efforts on BMG foams with high strength and ductility have shown that their energy absorption capability is much better than those of pure Al and its alloy foams [10–17]. However, there are still some limitations in the application of metallic glass foams mainly because the existing preparation methods are too complicated to control. For example, to avoid heterogeneous nucleation leading to crystallization that reduces the strength of metallic glass matrix, BaF$_2$ particles with high melting point and thermal stability were used as placeholders [6,17]. Similarly, foaming by blowing agents is limited in some precious metals such as Pd-based metallic glasses [12–14]. In addition, compared with syntactic Al and high strength alloy foams, the existing metallic glass foams have no significant advantage in energy absorption [18–22]. Fortunately, it is shown that the addition of non-metallic such as brittle ceramic particles and fibers is an effective way to produce materials with attractive engineering attributes [23–26]. The high content of brittle second phases can increase both the strength and ductility of composites [25,26]. In this paper, using hollow ceramic microspheres as a reinforcer that are also effective in avoiding crystallization, we

fabricate a BMG syntactic foam through pressure infiltration, which was previously applied to make metal matrix composites with monolithic (non-hollow) ceramic reinforcement [27]. The results show that the combination of high strength and ductility of BMG syntactic foams leads to an enhanced energy absorption capacity, which is much higher than those of available BMG foams [10–20].

We chose the Zr$_{41.25}$Ti$_{13.75}$Cu$_{12.5}$Ni$_{10}$Be$_{22.5}$ system (Vit 1) as the parent material because of its high processability and fragility [28,29]. Alumina cenospheres with the average size of $500-600$ μm and a relative wall thickness of $t/R = 0.13$ were selected as placeholder particles. To prevent crystallization during infiltration casting, a material preparation device combining quick melting, pressure seepage and rapid cooling was invented. Master alloy button of Vit 1 was acquired by arc-melting the high-purity (R99.5%) constituent elements several times under a Ti-gettered Ar atmosphere. Then, the Vit 1 ingot was placed on the top of a graphite die that was filled with alumina cenospheres. Both the ingot and graphite die were picked up in a quartz tube sealed with a solenoid valve, which can be easily connected with a diffusion vacuum pump or an argon gas bomb. Initially, the solenoid valve was connected with the diffusion vacuum pump until vacuum in the quartz tube reached up to 6 MPa. Then, the master ingot was heated by an induction coil surrounding the quartz tube. After the master alloy was melted, the solenoid valve was connected with the argon gas bomb, and metal liquid was pressed into the graphite die to fill the space among alumina cenospheres. Almost at the same time, the tube was sub-merged by the mixture of saturated NaCl solution and ice cubes through a U-turn tube and cooled down quickly. For comparison, the pure Vit 1 foam with similar apertures was prepared by a similar method just replacing alumina cenospheres with soluble NaCl
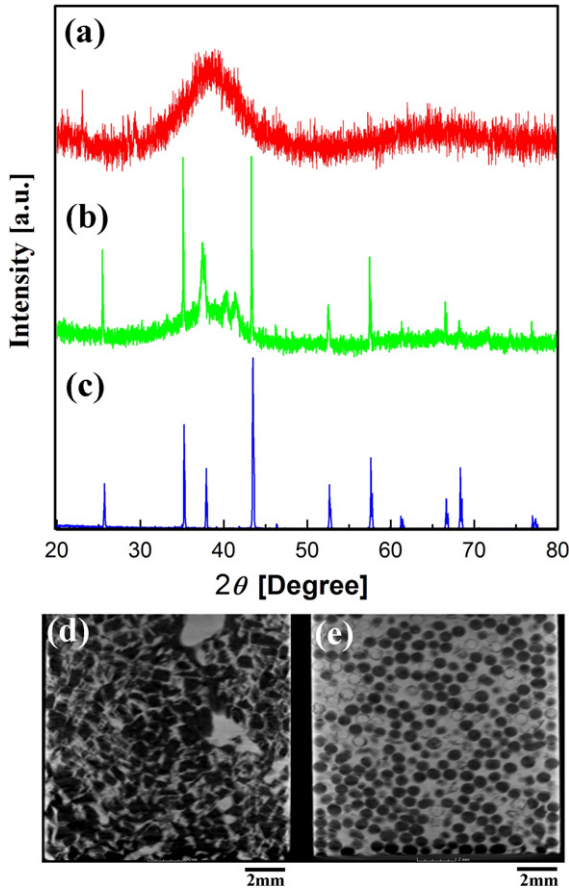
Fig. 1. (a)−(c) XRD patterns of Vit 1 foam, BMG syntactic foam and alumina powder; (d)−(e) computerized tomographies of Vit 1 and BMG syntactic foams.

placeholders, and dissolved salt particles by immersion in distilled water [16].

The amorphous phase nature of foam samples was analyzed by using X-ray diffraction (XRD) with Cu-Kα radiation (M18AHF). As seen from the XRD patterns in Fig. 1(a)−(c), the structures of Vit 1 and BMG syntactic foams are amorphous. The volume fraction V_f of cenospheres in the syntactic foam can be calculated by using the rule-of-mixture, that is

$$V_f = \frac{\rho_s - M/V}{\rho_s - \rho_c}, \tag{1}$$

where ρ_s is the density of BMG matrix, M/V is the density of syntactic foams with M the mass and V the volume of a foam, and ρ_c is the density of cenospheres. Based on measurements, the density of Vit 1 is 6.0 g cm^{-3}, the apparent density of BMG syntactic foams is 3.2 g cm^{-3}, and the density of alumina hollow spheres with an average size of $500 - 600$ μm is 1.4 g cm^{-3}. Thus, the volume fraction of cenospheres in syntactic foams can be obtained as 59.7%. The porosity of pure Vit 1 foam was about 67%. Then, the samples were scanned with the X-ray computerized tomography, and the images are shown in Fig. 1(d)−(e). The detailed geometry dimensions were also measured based on the image of BMG syntactic foams. The average diameter d of spherical pores in the BMG syntactic foam and the average center distance l between spherical pores are 567 and 735 μm, respectively.

Quasi-static uniaxial compression tests with a strain rate of 10^{-3} s^{-1} were performed on the MTS-810 material test system at ambient temperature. Cylinder specimens with a diameter of 10 mm made of pure Vit 1 and BMG syntactic foams were prepared by a diamond grinding wheel and a diamond wafering saw. Strain was calculated from the crosshead displacement, and corrected to take into account deflection
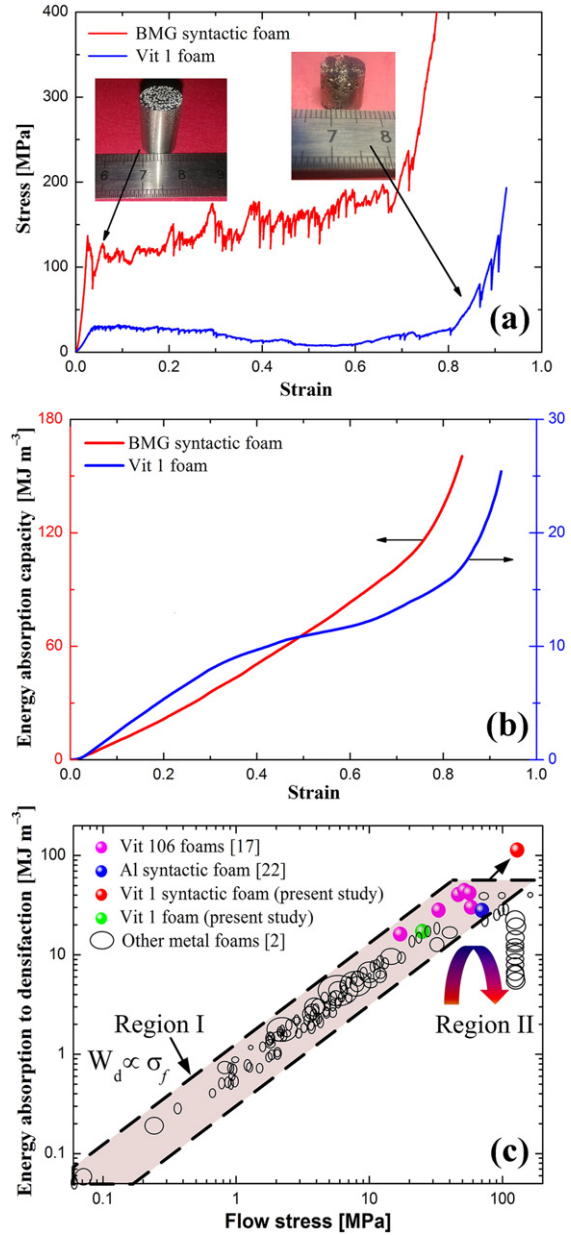

Fig. 2. Quasi-static compression tests at the strain rate of 1×10^{-2} s^{-1}: (a) stress–strain curves of two foams and (b) their corresponding EAC as a function of strain. (c) The log–log plot of EAC per unit volume to densification as a function of flow stress at 25% strain for different foams. In region I between two dashed lines, EAC to densification is proportional to flow stress and in region II, EAC to densification drops quickly.

of the load frame. As shown in Fig. 2(a), it is obvious that the BMG syntactic foam exhibits an initial linear stress–strain response until a stress peak appears at strain of about 2.5%. Here, we define the first peak stress on a compressive stress–strain curve as strength σ_y of the foam. Thus, the strength of the BMG syntactic foam is 137 MPa. After the linear deformation stage, there is a long stress plateau with numerous flow serrations that can be attributed to a sudden high elastic energy release. Beyond the deformation plateau, stress drastically increases as strain reaches about 75%, which indicates the occurrence of densification with the strain of ε_d. To represent the stability during a deformation process, we define the "strain-hardening" index as

$$n = \frac{\sigma_{pl} - \sigma_y}{\sigma_y}, \tag{2}$$

where σ_{pl} is the average plateau stress over the plastic flow region, defined as $\sigma_{pl} = \int_{\varepsilon_y}^{\varepsilon_d} \sigma d\varepsilon / (\varepsilon_d - \varepsilon_y)$ [30], and ε_y is the strain corresponding