Materials Science & Engineering A 631 (2015) 248–257

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

High strain rate behavior of composite metal foams

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ARTICLE INFO

Article history:
Received 23 October 2014
Received in revised form
26 January 2015
Accepted 11 February 2015
Available online 21 February 2015

Keywords:
Composite metal foam
Dynamic loading
Quasi-static loading
Hopkinson bar
Casting
Powder metallurgy

ABSTRACT

The mechanical properties of Composite Metal Foams (CMFs) under low speed loading conditions have been considered in a number of studies. This paper aims to extend the current knowledge by investigating the compressive behavior of CMF under higher loading rates. Hopkinson bar experiment was conducted on samples processed through powder metallurgy and casting techniques. The effect of loading rate, sample geometry and sphere size on the mechanical properties and energy absorption capacity was studied. The obtained results reveal that increasing the loading rate improves the strength of CMF especially at strain levels below 30%. This strengthening due to high strain rate loading is mostly attributed to the strain rate sensitivity of the parent metals and the pressurization of the entrapped air inside the spheres.

1. Introduction

Composite metal foams (CMFs) are new class of closed cell metal foams known for their promising energy absorption capacity. They are consisted of random loose packed hollow metallic spheres embedded in a metallic matrix. Due to having fairly uniform cellular structure, CMFs do not experience premature failure at the onset of collapse bands formation. Moreover, the existence of a ductile matrix provides a firm bonding between the spheres and stabilizes their thin walls. As a result, each cell shares an equal portion of the load and deformation occurs uniformly throughout the entire foam [1–3]. All of these make CMFs undergo significant amount of plastic deformation at extremely high stresses. Thus, the energy absorption capacity is considerably (7–10 times) higher than that of other metal foams made with similar material [3].

A number of studies have been devoted to characterize the mechanical and microstructural properties of CMF [1,2,4–6]. It has been shown that the bonding strength between the matrix and the hollow spheres, and the relative density of the foam are the two main factors controlling CMFs performance under loading [1,2]. The former depends on the gradient of chemical composition between the spheres and the matrix, and also surface roughness of the spheres. The latter is a function of the porosity percentage in the matrix and at the spheres' wall.

Potential applications of CMF are in various lightweight safety structures such as collusion management systems [7], blast protection and ballistic armors [8], and radiation shielding [9]. In order to fully utilize the energy absorption capabilities of CMF, understanding its behavior under high speed loading is crucially important. The current work was initiated to address this concern by comparing the quasi-static and dynamic behavior of composite metal foams at strain rates ranging from 5×10^{-3} to 3.5×10^{3} 1/s. For this purpose, Hopkinson bar experiments were utilized and the role of sample size and geometry as well as the sphere size were studied. In order to have deeper understanding of the failure mechanism and governing parameters, microstructural analysis was conducted using Scanning Electron Microscopy (SEM).

2. Materials, processing and experimental procedures

2.1. Materials and processing

Composite metal foams used in this study were fabricated by filling the vacancies between the packed steel hollow spheres either by a steel or an aluminum matrix. The CMF with steel matrix is called steel–steel composite metal foam (S–S CMF) and the one with aluminum matrix is called aluminum–steel composite metal foam (Al–S CMF). The S–S CMF was produced using powder metallurgy technique and the Al–S CMF was processed via casting.

Steel hollow spheres with three different outer diameters of 2, 4, and 5.2 mm were selected to fabricate the CMF samples. The spheres were produced by Hollomet GmbH (Dresden, Germany)

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http://dx.doi.org/10.1016/j.msea.2015.02.027
0921-5093/

using a powder metallurgy process [10]. All the spheres have a constant wall thickness to outer diameter ratio of 0.05 with a small variation in their wall porosity percentage and chemical composition. Table 1 shows the wall thickness, porosity percentage in the wall and chemical composition of the spheres. As it can be seen, the chemical composition of all spheres is close to that of 316 stainless steel with the exception of higher carbon and lower manganese content.

2.1.1. Processing of steel–steel composite metal foam

Bimodal mixture of 316 L stainless steel powder (produced by North American Hoganas High Alloys LLC) with two particle sizes (sieved to −100 mesh (149 μm) and −325 mesh (44 μm)) was used as the matrix material in S–S CMF. The mixture had 75% of 149 μm powder and 25% of 44 μm powder mixed inside a rotating jar for about 20 min. It has been shown that this mixing ratio of small and large particles provides the maximum packing density of powder particles [11].

Two permanent molds were fabricated from 304 stainless steel with cylindrical cavities of 25.4 mm and 38.1 mm diameter, and 93.98 mm height. The mold with smaller cavity was reserved for samples with 2 and 4 mm spheres and the one with larger cavity was used for samples with 5.2 mm spheres. These sizes were selected to make sure enough number of cells fit across the diameter of the samples in order to minimize the edge effect [12]. Prior to processing each sample, the inner surfaces of the molds were cleaned and then coated with a boron nitride mold release to facilitate the removal of the samples. The matrix powder and the hollow spheres were placed inside the mold and vibrated to achieve a dense packing arrangement. Then, a hydraulic press was used to make a green product of CMF by compressing the mixture of the spheres and the powder. Finally, the S–S CMF samples were sintered by heating the mold to 1250 °C and soaking for about 45 min at that temperature in a vacuum furnace. Further details of the processing of CMF using PM technique can be found elsewhere [2,6]. It must be noted that, the sintering temperature is slightly higher in this study and a bi-modal mixture of powder was used instead of single-modal one.

2.1.2. Processing of aluminum–steel composite metal foam

The matrix material for Al–S CMF is aluminum casting alloy A356. This alloy was selected due to its high strength to density ratio, ease of casting, distinctly lower melting temperature compared to the steel hollow spheres, and reduced shrinkage during solidification. A permanent mold of 304 stainless steel with a sprue, runner, melt filter, overflow riser, and four cylindrical cavities (similar to PM molds) was used for casting the aluminum around the steel spheres. The hollow spheres were placed inside the mold cavities, held at the top with a stainless steel mesh, vibrated to pack in to its maximum arrangement density and pre-heated up to 700 °C in a high temperature furnace, where the aluminum was melting simultaneously in a clay graphite crucible. This pre-heating prevents premature solidification of aluminum during casting. Right after pouring the aluminum into the mold, a pressurized air was injected through the sprue to force the aluminum melt to penetrate every small spacing between the hollow spheres. Overflow of aluminum was also allowed to minimize the possibility of air bubbles tapping inside the mold. With the casting process complete, the mold was air cooled using shop air down to 200 °C. More details of the casting procedure can be found elsewhere [2,5].

Table 1
Geometrical characteristics and chemical composition of hollow spheres.

Sphere size (mm)	Wall thickness (μm)	Porosity in the wall	Chemical composition (%)						
			Fe	C	Mn	Si	Cr	Ni	Mo
2.0	90	3.4%	Balance	0.68	0.13	0.82	16.11	11.53	2.34
4.0	196	6%	Balance	0.63	0.11	0.73	16.91	12.35	2.19
5.2	244	4%	Balance	0.87	0.07	0.34	17.09	12.60	2.12

2.2. Sample preparation

The CMF samples for quasi-static and high speed testing were cut into small pieces with diameter to length ratio of 0.7 using a precision saw equipped with a diamond wafering blade. In a number of the cut samples with 4 mm spheres, a center hole was drilled to fabricate two batches of S–S and Al–S hollow cylindrical samples. All solid and hollow cylindrical samples were then subjected to density calculation by accurate weighting and dimensional measurement.

Having three different sizes of spheres and two processing methods plus two batches of hollow samples, a total of eight groups of samples were subjected to quasi-static and dynamic compression testing. Nominal dimensions of the test samples along with their measured density are listed in Table 2.

Samples selected for microstructural observation were then ground and polished progressively using 180–1200 grit papers and 3 μm diamond slurry followed by a progression of 1, 0.3, and 0.05 μm alumina paste to obtain a mirror finish. All samples were cleaned in an ultrasonic cleaner between each grinding and polishing step to prevent cross-contamination.

2.3. Microstructural characterization

Optical microscopy was performed using a Buehler Unimet Unitron 9279 microscope with digital image capturing capabilities to evaluate the porosity percentage in the cross-section of the individual spheres as well as the matrix in CMF structure. A JEOL JSM-6010PLUS/LA Scanning Electron Microscope (SEM) equipped with Energy Dispersive X-ray Spectroscopy (EDS) capabilities is utilized to study the bonding between the spheres and the matrix and to chemically characterize the various phases in the microstructure.

2.4. Mechanical testing

Quasi static compression tests were performed in an MTS servo hydraulic universal testing machine under the displacement

Table 2
Nominal dimensions of the test samples along with their average density.

Samples	Solid samples						Hollow samples	
	S–S			Al–S			S–S	Al–S
Sphere size (mm)	2	4	5.2	2	4	5.2	4	4
Sample inner diameter (mm)	–	–	–	–	–	–	8.47	8.47
Sample outer diameter (mm)	25.4	25.4	38.1	25.4	38.1	38.1	25.4	25.4
Sample length (mm)	17.78	17.78	26.67	17.78	26.67	26.67	17.78	17.78
Sample density (gr/cm^3)	2.85	2.79	3.06	1.95	1.94	1.96	2.81	1.90