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Effect of various parameters on properties of composite steel foams under variety of loading rates

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ABSTRACT

Steel–steel composite metal foams (CMF) are manufactured using steel hollow spheres (with variety of different sphere sizes, surface roughness and carbon content) embedded in a stainless steel matrix through powder metallurgy technique and are investigated experimentally under compression loading with variety of loading rates. The microstructural and mechanical properties of the material were studied using optical and scanning electron microscopy, energy dispersive spectroscopy, quasi-static, and dynamic compressive loading up to 26 m/s. It is observed that the yield and plateau strength as well as the energy absorption capabilities of the composite foams are increased with increasing loading rate and by decreasing sphere sizes. Such mechanical properties improved by additional carbon content in the sphere wall at strains below 17% while the effect of density, resulted from porosity content, showed an improvement on the densification strain and plateau strengths at higher than 17% strain. The effect of spheres surface roughness and carbon content on mechanical properties of CMF seemed to be minimal compared to other parameters. As a result, the features controlling the life time and performance of composite metal foams under static and dynamic loading have been categorized into two main groups. The first group that controls the yield and plateau strength of the foam at lower strain levels includes bonding strength between the spheres and matrix which is a function of the sphere surface roughness and the gradient chemical composition between the spheres and matrix. The second group that controls the relative density, densification strain and plateau strength at higher strain levels belongs to the sphere diameter and the porosity content in both spheres and matrix. Moreover, increasing the loading rate improves the yield strength of all CMF samples.

1. Introduction

Metal foams are a special class of materials known for their high strength-to-weight ratio and high impact energy absorption capabilities. Under compression, their cellular structure allows them to deform at a relatively constant stress during large amounts of strain, providing them a high energy absorption capability. When compressed at high loading rates, metal foams exhibit an increase in strength and energy absorption capabilities [1–8]. This has allowed metal foams to be used in a variety of applications such as fillers in vehicle crumple zone structures offering additional crash protection [9–11]. The mechanical properties of metal foams are highly influenced by their constituent materials and cell size and shape.

Composite metal foam (CMF) that has been designed to provide regular cell shape and sizes has offered higher strength at quasi-static and cyclic loading compared to other metal foams. The regularity of the cell structure allows CMF to offer isotropic mechanical properties and a uniform deformation mechanism under loading, eliminating the formation of collapse bands and premature failure. The presence of the matrix between spheres provides a better bonding between spheres and reinforces the thin sphere wall, further improving the mechanical properties of the foam. These characteristics provide CMF high strength and energy absorption capabilities under compression unmatched by any other metallic foam [12–18].

The mechanical properties of steel–steel CMF have been widely studied under a variety of loading conditions including quasi-static [12,13,16] and cyclic loading [17,18]. However, since an increasing number of applications are being explored for composite metal foams, which may include dynamic loading, a fundamental understanding of their behavior is necessary under such loading conditions. In the present study, we catalog the results of quasi-static and dynamic loadings on composite metal foams, their deformation behavior, failure mechanisms and correlation between their mechanical and microstructural properties. The effects of sphere size, sphere surface roughness, and chemical composition on the microstructural and mechanical properties of composite foams are being analyzed and reported.

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2. Materials, processing, and experimental procedure

2.1. Materials and processing

Steel–steel composite metal foam (S–S CMF) was manufactured through the powder metallurgy (PM) technique. These foams are created by filling the vacancies between the packed steel hollow spheres with stainless steel powder and sintering them into a solid cellular structure. In this study, three different types of S–S CMF samples were manufactured using hollow spheres with outer diameters of 2.0, 2.2, 4.0, and 5.2 mm and 100, 104, 196 and 244 μm sphere wall thicknesses, respectively. A ratio of about 5% is maintained between the wall thickness and the outer diameter of all spheres. The chemical composition of the hollow spheres used in this study is shown in Table 1 and compared to those used in our previous experiments reported elsewhere [16]. It is notable that the chemical composition of the matrix material (316L stainless steel) is the same in all previous and current CMF samples. However, the chemical composition of spheres is close to that of 316L stainless steel with the exception of higher carbon and lower manganese contents. 316L stainless steel powder used as the matrix material was produced by North American Hoganas High Alloys LLC with particle size sieved to −325 mesh (95%) and −200/+325 mesh (5%). Composition of the stainless steel powder is also shown in Table 1. The steel hollow spheres used were made by Fraunhofer and Hollomet GmbH in Dresden Germany [19]. The spheres and powder were placed inside a stainless steel mold and vibrated at 20 Hz frequency for approximately 50 min in order to achieve a dense packing arrangement of the spheres in the matrix. The S–S CMF samples were sintered at 1200 °C in a vacuum hot press to bind the powder and spheres together. Further processing details of S–S CMF can be found elsewhere [16]. In our previous experiments, an excellent bonding at the interface of the spheres and the matrix was achieved with a high percentage of porosity, about 46%, in the matrix [16] resulted from pressureless sintering of the material. In this study the carbon and manganese contents of spheres are different from those in the matrix and in the spheres used in our previous studies. A comparison between the properties of this new arrangement with our previous studies will provide a complementary insight on the effect of the gradient chemical composition between spheres and matrix materials.

2.2. Sample preparation

Thin slices of samples were used to investigate their microstructure using digital, optical and scanning electron microscopy (SEM) imaging, while rectangular cuboids and cylindrical samples of CMF were used for mechanical testing. The cutting of samples into the desired sizes was conducted using a Buehler Isomet linear precision saw equipped with a wafering blade at a constant blade speed of 2500 rpm and a blade feed rate of 1.2 mm per minute. The test samples for microstructural observations were then surfaced by progressive grinding and polishing using a progression of abrasive papers and slurries on a Buehler Automet 2 Power Head grinding and polishing stations. Grinding was done at 150 rpm speed using a progression of 180–1200 grit papers. All samples were polished at 150 rpm speed using a 3 μm diamond slurry followed by a progression of 1, 0.3, and 0.05 μm alumina paste to obtain a mirror finish. Samples were cleaned in an ultrasonic cleaner between each grinding and polishing step to prevent cross-contamination. Some samples were etched using a 50% HCl–50% H_2O solution and dipped into a 5% HNO_3–95% H_2O solution followed by a final rinsing with water to reveal the grain structure and any potential phases or precipitations.

The mechanical test samples were machined using a linear precision saw to the desired size in the lateral and longitudinal directions. Several sets of samples were cut into different sizes and shapes to accommodate each mechanical testing procedure. Table 2 shows a list of different samples used for mechanical testing.

For the quasi-static compression tests performed in the servo-hydraulic machine, rectangular cuboids were cut from 2.2, 4.0, and 5.2 mm sphere S–S CMF samples. A minimum of 6 spheres was maintained across each side of the samples' cross section to avoid edge effects. All samples maintained a height/width ratio of 1.75.

For the dynamic testing performed in a Split Hopkinson Pressure Bar (SHPB), due to the limitation of the equipment capacity and the need to maintain a minimum of 6 spheres across the diameter of the sample, only the 2.2 mm sphere CMF samples were tested. In this case, cylindrical samples with a 19 mm diameter were cut to a 9.5 mm height giving a height/diameter ratio of 0.5.

Table 1
Chemical composition of hollow spheres and the stainless steel powder used for manufacturing S–S CMF.

CMF material component	Chemical composition (wt%)						
	Fe	C	Mn	Si	Cr	Ni	Mo
2.2 mm diameter spheres	Balance	0.68	0.13	0.82	16.11	11.53	2.34
4.0 mm diameter spheres	Balance	0.58–0.69	0.07–0.15	0.32–1.14	16.48–17.34	12.28–12.42	2.11–2.28
5.2 mm diameter spheres	Balance	0.87	0.07	0.34	17.09	12.60	2.12
2.0 mm spheres (previous studies)[a]	Balance	0.17	0.15	0.9	16.2	13.3	2.2
316L Steel matrix powder	Balance	0.03	2.00	1.00	16.00–18.00	10.00–14.00	2.00–3.00

[a] Ref. [16].

Table 2
Geometry of S–S CMF samples used in a variety of mechanical test experiments.

Experimental procedure	Average sphere diameter (mm)	Sample size (mm)
Quasi-static compression rectangular Cuboids (Previous studies)	2.0	24x24 × 46
Quasi-static and low-speed dynamic compression rectangular cuboids	2.2	24 × 24 × 42
	4.0	24 × 24 × 42
	5.2	36 × 36 × 63
Split Hopkinson Pressure Bar (Cylindrical samples)	2.2	19 × 9.5 (D × L)