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A study on processing of a composite metal foam via casting

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Abstract

The research sited in this paper involves the development of a new closed cell composite metal foam using gravity casting techniques. The foam is comprised of steel hollow spheres packed into a random dense arrangement, with the interstitial space between spheres infiltrated with a casting aluminum alloy. The measured density of the material is 2.4 g/cm^3, with a relative density of 41.5%. The composite foam developed in this study displayed superior compressive strength and energy absorption capacity. The compressive strength averaged 67 MPa over a region of 10–50% strain, densification began at approximately 50% strain, and the energy absorption at 50% strain is 30 MJ/m^3. Scanning electron microscopy (SEM)–energy dispersive X-ray spectroscopy (EDX) compositional analysis affirmed the presence of expected phases in the hollow spheres and aluminum matrix. This novel material has promising applications in the aerospace, automotive, and biomedical industries.

Keywords: Closed cell foam; Hollow spheres; Casting; Energy absorption; Composite metal foam

1. Introduction

Metal foams are engineered materials with a unique combination of physical and mechanical properties, yielding an attractive material for use in the aerospace, automotive, and biomedical industries, among several previously identified applications [1]. Compared to solid materials and polymer foams, metal foams offer high specific stiffness, high strength to weight ratios, increased impact energy absorption, and tolerance to high temperatures and adverse environmental conditions. By altering the size, shape, and volume fraction of cells, mechanical properties can be engineered to meet the demands of a wide range of applications [2–4].

The cellular structure in closed cell metal foams is typically disordered, due in part to three main imperfections. These phenomena are wavy distortions of the cell walls, cell wall thickness variation, and non-uniform shape and size of the cells [5]. These non-uniformities lead to anisotropic physical and mechanical properties, making it difficult to predict the foam's performance characteristics.

These non-uniformities can be overcome through producing metal foam incorporating preformed hollow spheres. The metal hollow spheres used in this study have very uniform cell size and wall thickness, and can be arranged into a dense arrangement of repeatable cell structure. Aluminum alloy is cast into the interstitial spaces between spheres to create a closed cell nature composite foam and to enhance the strength. This composite metal foam has advantages in uniformity, isotropy, and mechanical properties that allow for consistency in engineering design applications. Mechanical, physical, and microstructural properties of the produced composite foam have been studied using various techniques including monotonic compression testing, scanning electron microscopy (SEM), and energy dispersive X-ray spectroscopy (EDX).

2. Experimental procedure

2.1. Materials

The materials chosen to produce the metal foam samples were low carbon steel hollow spheres and aluminum 356

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Table 1
Weight percentage of alloying elements in the cast aluminum 356 alloy

Element	Weight percentage
Si	7.01
Fe	0.50
Mg	0.39
Mn	0.28
Cu	0.11
Ti	0.09
Zn	0.06
Cr	0.02
Al	Balance

casting alloy. Due to the nature of the casting process used, two materials were selected with distinctly different melting temperatures. This was done to maintain the structural stability of spheres during casting and to prevent the penetration of liquid metal into the cavities of spheres. The hollow spheres were designed in collaboration with the Fraunhofer Institute in Dresden, Germany, and subsequently produced via a powder metallurgy process [6]. The sphere composition is <0.002% oxygen, <0.007% carbon, and the balance is iron. The average outside diameter is 3.7 mm, with 80% of the spheres between 3.5 and 3.9 mm, a wall thickness of 200 μm, and wall porosity <5%.

Aluminum 356 alloy was chosen as the interstitial matrix material due to its low density, high strength and stiffness, and ease of casting. The main alloying elements in 356 alloy are silicon and magnesium, aiding in casting and adding to the strength of the matrix [7]. The compositional analysis of aluminum 356 alloy is shown in Table 1.

2.2. Casting mold design

A permanent casting mold was designed and fabricated for producing composite foam samples, as shown in Fig. 1. It is a gravity fed design made of carbon steel, incorporating a sprue, runner, melt filter, and overflow riser. The choice of steel allows for repeated exposure to molten aluminum and preheating temperatures of 700 °C. Liquid metal is poured into the sprue, it travels through the runner and then up through a slide gate (not shown) and melt filter, fills the spaces between the hollow spheres, and then fills an overflow riser. This bottom-up filling approach allows the liquid aluminum to push out the air as the metal fills the interstitial space between spheres. The slide gate provides for easy de-molding after solidification and the melt filter serves to remove any solid impurities or oxides in the melt. The overflow riser feeds any shrinkage during aluminum solidification. The mold was designed for easy assembly, technical simplicity (i.e. no vacuum or pressurization during casting), easy part removal, and easy modification.

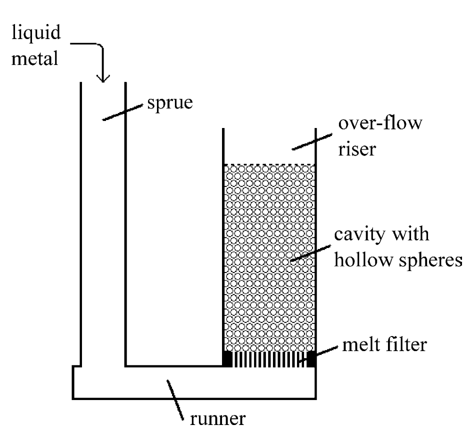

Fig. 1. Gravity casting mold design for producing composite metal foam samples.

The cavity of the mold is in the shape of a rectangular block, with a 54 mm minimum length dimension. This allows for a foam sample with a minimum of 14 spheres per edge using 3.7 mm diameter spheres. It is necessary to maintain at least 8–10 cells per side to eliminate any edge effects and yield a statistically meaningful sample representative of a bulk quantity of material [8].

2.3. Processing method

In addition to the casting mold, some of the additional equipment used include a high temperature furnace, graphite crucible, and various handling utensils. The steps in processing a foam sample are: (1) the mold is cleaned and coated with a boron nitride (BN) mold release agent. This serves to protect the mold surfaces from oxidation and to allow for easy demolding upon solidification. (2) The mold is assembled with the hollow spheres in place. (3) The assembly is manually vibrated to achieve a dense arrangement of spheres. (4) The mold assembly is preheated in the furnace at 700 °C. This hinders premature freezing of the molten aluminum upon contact with the mold and spheres during casting. The aluminum is simultaneously melted in the furnace up to 700 °C. (5) The aluminum is cast into the mold. (6) The mold is allowed to air cool and the sample is removed.

2.4. Qualification

2.4.1. Metallographic sample preparation

After processing, foam samples were subsequently prepared for mechanical testing as well as optical and electron microscopic imaging. Each sample was segmented using a Buehler Isomet 4000 linear precision saw. Utilizing a diamond tipped wafering blade rotating at 4000 rpm, samples were cut using a feed rate of 5 mm/min. Samples prepared for scanning electron microscope imaging were surfaced using Buehler Automet 2 Power Head grinding and polishing stations. Wet grinding was done using a progression of 180–1200 grit grinding papers, 60 rpm wheel rotational speed, and 2.3 kg loading. Polishing was done first using a progression of diamond slurries (9, 6, and 3 μm particle size), and then finished with alumina paste (0.05 μm particle size). All polishing was done using a 60 rpm wheel rotational speed and 1.8 kg loading.