Journal of Alloys and Compounds 693 (2017) 55–60

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

The effect of particle shape on mechanical properties of perlite/metal syntactic foam

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ARTICLE INFO

Article history:
Received 1 September 2016
Received in revised form
15 September 2016
Accepted 16 September 2016
Available online 17 September 2016

Keywords:
Metal matrix composites
Syntactic foam
Cell shape
Microcomputed tomography
Mechanical properties

ABSTRACT

In a previous work, a natural porous volcanic glass, expanded perlite (EP), was introduced for fabrication of cost-efficient metallic syntactic foams. Perlite metal syntactic foams (P-MSF) were produced by counter gravity infiltration of a packed bed of porous expanded perlite (EP) particles with molten aluminium. In the current study, the effect of EP particles shape on the mechanical and structural properties of foams were investigated. The irregular shape and coarse surface of raw EP particles were turned to near spherical shape with smooth surface using a tumbling process. Foams containing rounded EP particles showed higher mechanical strength at a constant density. The superior mechanical properties of foams with rounded EP particles are likely due their regular positioning and less structural defects.

1. Introduction

The mechanical response of metallic foams under compression depends largely on structural and microstructural characteristics of the cell walls. It is well established that the mechanical strength of metallic foams increases with the foam density [1]. Since higher density of metallic foams is usually not desirable due to weight constraints, other approaches have been investigated to improve the mechanical properties. Refining the microstructure of cell walls by heat treatment improves the mechanical properties in case of heat treatable materials [2]. The effect of cell size on the mechanical properties of metallic foams has been a controversial issue. In a previous work, we showed that number of cells across the sample diameter does not have a direct effect on the mechanical properties of the foams when a minimum of 7 cells is considered. However, superior microstructural characteristics and geometrical homogeneity of the cell-wall obtained by using smaller EP particles enhance the mechanical properties [3].

Structural irregularity proved to have an important effect on mechanical properties of foams. According to Fazekas et al., irregularity is caused by cells with large size differences or cells with irregular shapes [4]. There are some 2D numerical investigations on the effect of wall geometry, wall thickness distribution, and geometrical imperfections on mechanical properties of cellular solids with low density [4–10]. Fazekas et al. showed that homogeneous cell structures result in higher compressive strength compared to that of perturbed structures [4]. However, Li et al. reported that the foam stiffness increases as the foam becomes more irregular [8]. In a comprehensive 3D numerical analysis, Simone et al. showed that the thickness distribution of cell walls has a significant effect on the stiffness of foams. According to the authors, there is an optimum ratio between the solid fraction of joints and struts in which the maximum stiffness is achieved [10]. Zargarian et al. reported similar findings [7]. Most of these studies are focused on simplified porous patterns which limits their validity for actual configurations. Moreover, the effect of cell morphology was often disregarded. Cho et al. applied finite element method to investigate the effect of pore shape on mechanical properties of porous metals [11]. Comparing ellipsoidal and spherical pore shapes, they found that models with ellipsoidal pores have inferior mechanical properties compared to models containing spherical pores.

So far, there is a limited number of experimental studies on the effect of pore shape on mechanical properties of metallic foams. It is difficult to control the pore shape and structural homogeneity in manufacturing processes using gas releasing agent or direct

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http://dx.doi.org/10.1016/j.jallcom.2016.09.168
0925-8388/

blowing. In a recent study, Lehmhus et al. modified the pores shape of aluminium closed cell foams by annealing the TiH_2 blowing agent for 4 h at 500 °C. They observed significant increases in mechanical properties of foams produced by heat treated blowing agent due to a high level of structural homogeneity [12]. However, the structural modification can be easily achieved in the case of replicated foams or syntactic foams. In such foams, the porosity is established by a space holder which either is removed from the structure (replicated foams) or remains in the structure (syntactic foams). Bekoz et al. investigated the effect of carbamide space holder shape on mechanical properties of replicated aluminium foams. They found that foams with spherical pores have superior mechanical strength [13]. According to the authors, the foams with irregular pores had compressive yield strengths between 20 MPa and 92 MPa depending on density of foams (0.83–1.66 g/cm^3). This range increased to 25 MPa - 112 MPa in the case of foams with spherical pores and same density range. Jiang et al. produced open cell foam with infiltration of elongated and spherical carbamide space holders. They also reported that the foams with spherical pores have higher compressive strength [14]. However, to the author's knowledge there is no experimental study in the literature focusing on the effect of space holder shape in case of metallic syntactic foams at the time of work.

In recent studies, we introduced expanded perlite (EP) [15] and pumice [16] as novel filler materials to produce aluminium syntactic foams. Results showed that the EP particles do not directly contribute to the mechanical response of foams because of their low mechanical strength. However, using smaller EP particles results in a refined aluminium microstructure with smaller grain size and more uniform foam geometry which improve the mechanical properties [3]. In the current study, the effect of pore shape on compressive strength and structural properties of EP/aluminium syntactic foam is investigated.

2. Materials and methods

2.1. Samples preparation

Expanded perlite (EP) was supplied by Australian Perlite Company. Syntactic foams were produced by counter gravity infiltration of a packed bed of EP particles with molten A356 aluminium alloy. The chemical composition of constituents and a detailed description of the infiltration process can be found in Ref. [15]. Samples were subjected to a T6 heat treatment comprising solution treatment at 540 °C for 16 h followed by quenching in water at room temperature and aging at 160 °C for 10 h. In order to investigate the effect of particle shape on the mechanical properties of EP/A356 syntactic foams, EP particles were spheroidized using a simple rotary tumbling machine. The machine container was filled to two third of its volume and rotated with the speed of 60 rpm for 5 h. Raw and rounded EP particles with the size of 2–2.8 mm were used in this study. To this end raw particles with a slightly larger initial size were filled in to the tumbling machine container in order to obtain spheroidized EP particles of the desired size.

2.2. Structural investigations

The roundness of particles was investigated by optical image analysis. To this end, high resolution digital photographs were taken from a large number of raw and rounded particles dispersed on a black surface. Subsequent thresholding was applied on the images using Image J software (http://imagej.net) to create binary black (background) and white (particles) images. The segmented images were then subjected to 2D analysis using a purpose-written Matlab code. The code measures the aspect ratio of the projected particles by dividing the shortest with the longest axis. A higher aspect ratio, with a maximum possible value of 1, indicates a more circular projection. Ellipsoid particles are more likely to rest on their longer side and thus this method is likely to yield lower values for particle sphericity.

The structure of syntactic foams was investigated by micro computed tomography (μCT). μCT scans were prepared using an Xradia MicroXCT-400 machine with a Hamamatsu L8121-03 X-ray source and a constant voxel size of 35.32 μm. The selected acceleration voltage was 140 kV and the current 70 μA. Due to its low density, perlite is transparent and appears as dark areas in μCT images. The raw μCT images of each sample were subjected to thresholding process and segmented based on the actual volume fraction of metal. The thresholding constant was selected through an iterative process so that the volume fraction of white voxels (metal) matched the volume fraction of aluminium in the scanned sample. The procedure to determine the volume fraction of aluminium based on the mass of particles and metal in the foams is explained in Ref. [15].

2.3. Mechanical testing

Compression tests were conducted following the ISO-13314 standard on an uni-axial computer-controlled 50 kN Shimadzu testing machine. A constant crosshead speed of 3 mm/min corresponding to an initial strain rate of 10^{-3} s^{-1} was used in all tests. Stress-strain curves were obtained by dividing the recorded load and displacement by the initial surface and height of samples, respectively. The unloading slope, yield stress, plateau stress, and the energy absorption of foams were derived from the stress strain curves based on the ISO 13314 standard [17].

3. Results

3.1. Structural properties

Unexpanded perlite rock is extracted in mines and crushed to small fragments with polyhedral shapes. After heating and subsequent expansion, the irregular shape of expanded perlite particles is a projection of the shape of the unexpanded particles. The as-received expanded perlite particles have irregular elongated, platy, or near spherical shapes (see Fig. 1a). Expanded perlite has a highly porous structure with about 95% internal porosity. Microstructural investigations showed that pore walls have a low average thickness (500 nm) [15] and are thus fragile and have a low mechanical strength. As a result, abrasion takes place in a short time after exposure of EP particles to the tumbling process. This removes the angular sections, corners, and edges and results in a rounded shape (see Fig. 1b). Moreover, the rough surface of raw EP particles becomes smoother as small protrusions are removed. During the tumbling process, the elongated particles break into smaller particles and most of the platy particles are crumbled completely and subsequently removed as dust. Domokos et al. [18] showed that regardless of the initial shape, tumbled particles would change to spheres in two stages. First, particle edges rapidly round without any change in axis dimensions until the shape approximates an ellipsoid. Subsequently, abrasion is driving the particles to become spherical and the axis dimensions are slowly reduced [18][18][18].

A Matlab code was used to measure the aspect ratio of individual particles by measuring the shortest and longest axes of each particle projection. The processed images are shown in Fig. 1 and the shortest and longest particle axes are marked by red lines. Comparing the processed images of raw and rounded EP particles, one can see how the tumbling process results in near spherical shape with smooth surface. The surface protrusions and uneven