Materials and Design 66 (2015) 294–303

Contents lists available at ScienceDirect

Materials and Design

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

On the particle size effect in expanded perlite aluminium syntactic foam

M. Taherishargh *, M.A. Sulong, I.V. Belova, G.E. Murch, T. Fiedler

Centre for Mass and Thermal Transport in Engineering Materials, Discipline of Mechanical Engineering, University of Newcastle, University Drive, Callaghan, NSW 2308, Australia

ARTICLE INFO

Article history:
Received 11 September 2014
Accepted 26 October 2014
Available online 4 November 2014

Keywords:
Syntactic foam
Expanded perlite
Cell size
Mechanical properties
Thickness

ABSTRACT

Packed beds of expanded perlite (EP) particles with three different size ranges (1–1.4, 2–2.8, and 4–5.6 mm) have been infiltrated with molten Al to produce EP/A356 Al syntactic foam. A T6 heat treatment was applied to the foams. The effects of EP particle size on microstructural, geometrical, and mechanical properties of the foams were investigated. The EP particle size determines the number of cells across the sample diameter (7–25). It also influences the microstructural characteristics of the cell-wall alloy and the homogeneity of the cell-wall geometry. Enhanced microstructural characteristics and a greater geometrical homogeneity of the cell-wall in the case of smaller EP particles result in superior mechanical properties. The compressive deformation becomes more uniform by decreasing the EP particle size resulting in smoother and steeper stress–strain curves. As a result, these foams exhibit higher plateau stresses and improved energy absorption. The number of cells across the sample diameter does not have a significant effect on the mechanical properties of the samples considered.

1. Introduction

Metallic foams are characterized structurally by their cell type (open or closed), porosity, cell shape, and cell size [1–3]. Such structural properties can be tailored by utilizing hollow or porous particles to introduce the porosity in case of metallic syntactic foams [4–7]. It has been shown that the mechanical response of the metallic foams under compression depends on the structural characteristics. There has been good agreement on the effect of density and cell shape on the mechanical properties. It is now well accepted that the plateau stress and energy absorption of the metallic foams depends on density [1,8–12] and cells geometry [3]. In the case of metallic syntactic foams, the density and cell shape cannot always be varied freely since they depend on the filler particles' morphology and density [13]. However, the cell size can be controlled easily by the filler particle size. Studies have shown that reducing the particles' size enhances the mechanical properties of syntactic foams containing high strength hollow spheres [4,14–17]. The explanation is in the fact that the wall thickness to diameter ratio is higher in the case of smaller particles [4,14,15,18]. However, there are some contradictions on the effect of cell size on the mechanical properties of foams containing no filler materials. Some researchers reported that the mechanical properties of the foams improve as the cell size decreases [11,12,19], while others have shown that there is an optimum cell size at which the foam has superior mechanical properties [9,20,21]. Interestingly, some reports have shown that decreasing the cell size reduces the plateau stress and the energy absorption of the foams [1,22,23].

In a previous study, we introduced expanded perlite (EP), a natural porous volcanic glass, as a new filler material which offers lower density and cost for metallic syntactic foams [13]. However, unlike other porous filler materials [24–26] EP does not have a direct strengthening effect in EP/A356 Al syntactic foam. These foams show mechanical behaviour similar to metallic foams that contain no filler material because of the low mechanical strength of EP. Heat treatment proved to be an efficient process to improve the mechanical properties of the EP/A356 syntactic foam [27]. While changing the particles' size could be a good approach to tailor mechanical properties, this has not been reported in the case of syntactic foams containing low strength porous filler particles. In the present study, we report on an investigation of the effect of EP particle size on mechanical properties of heat-treated EP/A356 syntactic foam.

2. Experiment

2.1. Foam preparation

Syntactic foams composed of A356 aluminium alloy and EP particles were synthesised by a counter gravity infiltration process. The A356 aluminium alloy with a composition of 7.2 wt% Si, 0.4 wt% Mg, 0.1 wt% Ti, 0.12 wt% Fe, and the balance aluminium,

* Corresponding author. Tel.: +61 432620029.
E-mail address: Mehdi.Taherishargh@uon.edu.au (M. Taherishargh).

http://dx.doi.org/10.1016/j.matdes.2014.10.073
0261-3069/

provided by the supplier (Hayes Metals), was used as the matrix. According to their product specification, the EP particles have the composition of 75 wt% SiO_2, 14 wt% Al_2O_3, 3 wt% Na_2O, 4 wt% K_2O, 1.3 wt% CaO, 1 wt% Fe_2O_3, 0.3 wt% MgO, 0.2 wt% TiO_2 with traces of heavy metals. The EP particles were sieved to 3 size ranges (1–1.4 mm, 2–2.8 mm, 4–5.6 mm) and thus have a 40% size increase within and between the groups. The sieving process was done by a vibrating machine with frequency of 50 Hz. The sieves with the standard ASTM mesh sizes were used (ASTM No. 18, 14, 10, 7, 5, and 3.5 corresponding to 1, 1.4, 2, 2.8, 4, and 5.6 mm openings). A detailed description of the infiltration process along with the set-up configuration can be found in [13]. The samples underwent a T6 heat treatment comprising a solution treatment at 540 °C for 16 h followed by water quenching. Subsequent aging was performed at 160 °C for 10 h.

The exact height (h) and diameter (d) of the cylindrical samples were measured using a digital calliper and the foam volume was calculated. The density of samples was calculated by dividing the sample mass by this volume.

2.2. Microstructural observations

Sections were cut from some of the foam samples with a silicon carbide disc cutter. Standard grinding was performed manually using 180-, 240-, 320-, 600-, and 1200-grit silicon carbide papers on disc rotating with speed of 240 rpm. Subsequent polishing with 0.5 μm and 0.05 μm diamond powder suspended in distilled water resulted in mirror-like surfaces. The microstructure of the cell walls was investigated using an Olympus BX60 M optical microscope.

2.3. μCT observations

μCT scans were prepared from samples containing small, medium and large EP particles. All images were captured using an Xradia MicroXCT-400 machine with a Hamamatsu L8121-03 X-ray source with a constant voxel size of 35.32 μm. The selected acceleration voltage was 140 kV with a current of 70 μA.

2.4. Compression test

Compression tests were conducted according to the ISO-13314 standard [28]. Five cylindrical samples for each particle size were prepared to generate statistically significant data. The compression tests were conducted on a uni-axial computer-controlled 50 kN Shimadzu testing machine with the crosshead speed 3 mm/min corresponding to a strain rate of 10^{-3} s^{-1}. Both ends of the samples were ground and lubricated by a silicon lubricant to reduce the friction between the samples surface and loading platens. The load and cross-head displacements were recorded by the data acquisition software Trapezium2. The engineering stress–strain data was then calculated based on the initial sample cross-section and height.

3. Results

3.1. Samples porosity and μCT observations

Fig. 1 shows the syntactic foams with small sized particles (SP), medium sized particles (MP), and large sized particles (LP) and a constant diameter of 30 mm. The dense packing and uniform distribution of the EP particles throughout the sample is a result of the 5-step filling and vibration of the mould [13]. Most of the surface particles were removed from the pores during the machining and surface grinding due to the weak bonding between the EP particles and Al matrix.

It has been shown that the surface and internal pores of EP particles are not infiltrated by molten Al [13]. Accordingly, the volume fraction of EP particles (F_P) can be calculated as:

$$F_p = \left(\frac{V_{sf} - ((m_{sf} - m_p)/\rho_{Al})}{V_{sf}}\right) \quad (1)$$

where V_{sf} is the foam volume, m_p is the combined perlite mass, m_{sf} is the syntactic foam mass, and ρ_{Al} is the density of aluminium (2.68 g/cm^3 according to the mixing rule). Also, the density of EP particles (ρ_P) can be calculated as:

$$\rho_p = \frac{m_p}{V_{sf} - ((m_{sf} - m_p)/\rho_{Al})} \quad (2)$$

The total porosity of syntactic foam (F_{TP}) is then obtained as:

$$F_{TP} = F_p \times \left(1 - \frac{\rho_p}{\rho_s}\right) \quad (3)$$

where ρ_s is the density of the solid part of the perlite particles (2.79 g/cm^3) [13]. Table 1 shows the density data of the Ø30 mm samples with different EP particle sizes. The standard deviations of density are 0.04, 0.018, and 0.008 mm for SP, MP, and LP foams respectively. Accordingly, the SP foams exhibit the highest scattering of density. This scatter decreases significantly as the particle size increases. The smaller particles create a higher fraction of narrow regions between neighbouring particles which require a higher pressure for effective infiltration with molten metal [29]. However, based on the lower density of small EP particles (see EP particle density in Table 1), one can assume that they have a lower strength which makes them more susceptible to collapse at high pressures. Accordingly, small variations in infiltration pressure may either result in incomplete infiltration or the collapse of EP particles thus causing the relatively high scatter of density in the SP samples.

Micro-computed tomography (μCT) data was obtained for one additional sample of each particle size. In the first step of the μCT analysis the raw μCT data of each sample was segmented. To this end, the perlite volume fractions of the scanned samples were determined using Eq. (1). In an iterative process a grey-scale threshold was then adjusted until the volume fraction of the μCT matches this reference value [30]. As a result, voxels can be attributed to either the perlite particles (black voxels) or the metallic phase (white voxels). It should be mentioned here that perlite appears transparent in the μCT data due to its low density and wall thickness.

In the following, the geometrical characteristics of the foam structure are evaluated based on the μCT data. The uniformity of the aluminium phase, i.e. the material distribution between the struts and joints is analysed. A set of segmented images with 600 × 600 × 600 voxels and a voxel side length of 35.32 μm was loaded into the open-source software ImageJ [31]. The calculations were performed using the BoneJ plugin [32]. This plugin calculates the local thickness by determining the diameter of the largest sphere which can be grown inside the segmented (aluminium) phase [32,33]. A summary of the analyses is shown in Table 2. As expected, the average value of the local thickness decreases as the EP particles size decreases. Furthermore, the coefficient of variation (CoV) of the local thicknesses was determined. A high coefficient of variation indicates a strong deviation of the local thickness. This can be caused by (a) struts with differing diameters and (b) by a conical shape where struts narrow towards their centre. Accordingly, the CoV predominantly quantifies the uniformity of the aluminium phase. The values of the CoV in Table 2 indicate that the strut thickness is more uniform in SP samples (0.36) compared with MP (0.40) and LP (0.51) samples.