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On the mechanical properties of heat-treated expanded perlite–aluminium syntactic foam

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ABSTRACT

In this paper, a syntactic foam is fabricated by counter-gravity infiltrating packed bed of expanded perlite particles with A356 aluminium alloy. The samples are subjected to a T6 heat treatment. The impact of heat treatment on microstructure characteristics, mechanical properties, deformation behaviour, and cell wall fracture mechanism are investigated. The compression stress–strain curves of the heat treated foams showed the three stages of elasticity, stress plateau and densification. Heat treatment resulted in a significant increase in plateau stress and absorbed energy. It is found that the effect of density on mechanical properties after heat treated conditions is more significant in comparison to untreated conditions. Under compression, the heat treated foams shows more uniform deformation. The improvement in compression characteristics by heat treatment is found to be a result of refined microstructure and higher ductility of the cell walls. Heat treatment reduces the deleterious impact of the columnar dendritic structure of the cell wall and the casting defects on mechanical properties. It limits the crack propagation by increasing the aspect ratio and interparticle distance of the Si particles in the Al matrix.

1. Introduction

Metallic syntactic foams are composed of hollow or porous particles embedded in a metal matrix [1]. The filler material, either in the form of hollow particles each consisting of a solid shell with a large internal cavity, or porous particles, is mainly responsible for the porosity. However, it may also have a strengthening effect [2]. Up till now, numerous synthetic hollow filler particles including steel, [3–5], ceramics [6], carbon [7], glass [8,9], and fly ash (cenospheres) [10,11] have been used in the fabrication of metallic syntactic foams. A few studies have focused on syntactic foams containing porous particles [12–14]. In a previous paper, the authors introduced expanded perlite (EP) as a new porous filler material to tackle the cost and high density of syntactic foams [15]. The low EP particle density (0.18 g/cm^3), due to more than 95% volume of porosity, resulted in a technologically attractive low-density aluminium base syntactic foam [15].

The mechanical properties of syntactic foams depend on both filler material and matrix properties [1,16]. It has been reported that incorporation of high strength hollow ceramic particles increases the strength of syntactic foams [6,10,12,16–18] when compared with metal foams with no filler material. These syntactic foams are susceptible to brittle fracture [1,13,19] and show premature cracks at early stages of deformation [1]. This limits the energy absorption of the foam [20]. Porous particles do not give a considerable strengthening effect [12–15], but they result in a more ductile and steady deformation of the syntactic foam [13,15,19]. Porous particles like EP can improve the mechanical properties of syntactic foams as space holders by controlling the size, geometry, and distribution of the cells [15]. The mechanical properties of the syntactic foams containing low strength porous particles may be enhanced by adjustment of the metallurgical state of the matrix by heat treatment. Heat treatment has been shown to be an effective way to tailor the mechanical properties of metallic foams [21,22]. Up till now, few results of the impact of heat treatment on the mechanical properties of syntactic foams have been reported. Interestingly, the reports revealed no significant effect of heat treatment on mechanical properties of syntactic foams containing high strength hollow spheres [18,20]. A likely explanation is that the mechanical properties of these foams are highly dependent on the filler material rather than the matrix. There has been no work reported on the effect of heat treatment of syntactic foams with low strength porous particles although it would seem to be an effective way to improve the mechanical properties of such materials. Accordingly, the objective of the present paper is to report on the investigation of the effect of heat treatment on the mechanical properties of an EP/A356 aluminium alloy syntactic foam.

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2. Experimental procedure

2.1. Preparation of metal foam

EP/A356 syntactic foams were fabricated by a counter gravity infiltration process that is described in detail in [15]. A356 alloy had the composition of 7.2 wt% Si, 0.4 wt% Mg, 0.1 wt% Fe, and 0.12 wt% Ti. EP particles in the size range of 3–4 mm, with an average particle density of 0.18 g/cm^3 [15], and 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 (provided by supplier, Australian Perlite Pty) were introduced into a graphite mould. The filling process was performed in five equal steps interrupted by vibration in order to achieve a dense and uniform particle packing. A stainless steel mesh was attached to the mould on top of the particles to fix them in place. The filled mould along with other set-up parts were placed in a glove-box with a controlled argon atmosphere. The low vacuum (10^{-3} bar) followed by purging with argon gas (1 bar) in glove-box antechamber effectively removed the oxygen inside the EP particles pores in order to reduce the oxidation of the Al melt during infiltration. A block of the Al A356 was placed at the bottom of a graphite crucible and the filled mould was inserted upside-down. The crucible was then put in a stainless steel container with an air-tight lid to maintain the inert atmosphere. The whole set-up was then placed inside a furnace and its temperature increased to 730 °C. After a 20 min holding time the container was removed from the furnace and the mould was pushed into the molten metal forcing EP particle infiltration. The mould was cooled in air and the sample was removed.

2.2. Heat treatment process

Over the past decade, the T6 heat treatment conditions of the A356 alloy have been the focus of several studies [23–25]. In a comprehensive work, Tiryakioglu investigated the impact of different solution and aging times, ranging from 1 to 64 h and 1–30 h respectively, on mechanical properties of the A356 alloy [24]. Based on the conditions under which the optimum mechanical properties were achieved, the following heat treatment parameters were used in the present study. The specimens were solution treated at 540 °C for 16 h and quenched in stirred icy water. The specimens were then artificially aged at 160 °C for 10 h and cooled slowly in air.

2.3. Microstructural, and fractography characterization

The microstructure of the syntactic foams was investigated using an Olympus BX60M optical microscope. Sections were cut from the solid and foam materials for standard grinding and polishing. Samples were ground using 180-, 240-, 320-, 600-, and 1200- grit silicon carbide papers. A mirror-like surface finish was achieved by subsequent polishing with 0.5 μm and 0.05 μm diamond powder suspended in distilled water. The fracture surfaces of the cell walls were analysed using a FEI XL30 scanning electron microscope after the compression test. To remove the crashed perlite dust from the surface, samples were first put in an ultrasonic cleaner for 30 min.

2.4. Compression test and macro imaging

The diameter d, height h and weight of the cylindrical syntactic foam samples were measured and recorded. The density of the foams was calculated by dividing the samples weight by their macroscopic volume $V = \pi \cdot h \cdot d^2/4$. Compression tests were carried out on a uni-axial computer-controlled 50 kN Shimadzu testing machine. In order to minimize friction effects the compressive loading plates were lubricated with silicone release spray. The data acquisition software (Trapezium2) recorded the load–displacement data during the test. Engineering stress–strain curves were obtained based on the initial sample cross sectional area and initial height.

3. Results and discussion

EP particles are not perfectly spherical and have irregular, though near spherical, shapes (see Fig. 1a). The highly uniform porous structure of the particles results in reasonable crushing resistance [15]. Fig. 1b shows a slice of the produced EP/A356 syntactic foam which has been cut from a foam sample. As discussed in [15] and above, a uniform distribution of the EP particles is achieved by a five-step filling and vibrating procedure of the particles in the mould.

3.1. Microstructural observations

Fig. 2a shows the microstructure of untreated (UT) A356 alloy which has been solidified under the same conditions as the foam matrix metal. It comprises a network of aluminium-rich primary and secondary dendritic arms. The eutectic structure constituting the aluminium-rich and silicon phases forms between the dendritic arms [26]. The silicon phase grows with rod-like or plate-like morphologies, which in the two-dimensional metallographic section appear as particles or rods [27].

Fig. 2b and c show the typical microstructure of the UT EP/A356 syntactic foam. The cell wall exhibits identical features to those of the A356 solid alloy except the grain morphology. In as-cast A356 alloy, the dendritic growth results in equiaxed grains with a random shape and size distribution. In syntactic foams, however, the columnar dendritic grain morphology is the prominent structure of the cell walls. The dendrites nucleate at the surface of the particles. But in most cases, the dendritic growth in one direction dominates the others which results in a columnar dendritic structure (Fig. 2b and c). Similar observations in the solidification structure of Mg-based syntactic foams have been reported in [11]. Investigations showed that changes in temperature gradient and or convection in the melt during solidification are the reasons for changes in microstructure of binary alloys containing inert particles [28]. Nucleation of dendrite arms from the EP particles' surfaces indicates good wetting between the A356 melt and EP under the processing conditions.

Dendritic arm spacing (DAS) and secondary dendritic arm spacing (SDAS) have an important impact on mechanical properties of the UT A356 alloy. In general, the mechanical properties improve with finer DAS and SDAS [27]. The DAS and SDAS were obtained as the distance between the centres of well-defined adjacent arms. The average DAS and SDAS are 270 μm and 65 μm for the as-cast alloy, and 230 μm and 50 μm for the EP/A356 syntactic foam respectively. Comparing these values, it can be noted that the EP particles slightly refine the microstructure of the alloy.

In the metallographic images of the cell wall, some solidification porosity was detected. These casting defects are indicated by black arrows in Fig. 2c and d respectively. The small porosities occurred because of shrinkage resulting from the volume contraction accompanying dendritic solidification [29]. The inadequate liquid metal mobility (poor feeding) is the reason for large porosity formation in the cell wall. This kind of porosity may be a result of lack of infiltration and forms in the interspace of touching EP particles with narrow melt channels. Fig. 2d shows that the macro porosity is closer to the narrower melt channel shown with larger white arrow. These phenomena have been reported in the case of