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Low-density expanded perlite–aluminium syntactic foam

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ABSTRACT

This paper addresses an innovative syntactic foam (SF) formed by counter-gravity infiltration of a packed bed of low-cost expanded perlite (EP) particles with molten A356 aluminium. The uniform distribution of EP particles in foams causes an even density throughout the height. Due to the low density (~0.18 g/cm^3) of EP, the average density of these foams is only 1.05 g/cm^3 which is considerably lower than most studied SFs. Owing to the high porosity of the filler material (~94%), the total porosity of the new foam reaches 61%. Microstructural observations reveal no sign of damage or unintended EP particle infiltration. EP shows a good wettability whilst essentially no reaction occurs at the EP–metal interface. Under compression, EP/A356 syntactic foam shows stress–strain curves consisting of elastic, plateau and densification regions. On account of its consistent plateau stress (average value 30.8 MPa), large densification strain (almost 60%), and high energy absorption efficiency (88%) EP/A356 syntactic foam is an effective energy absorber.

1. Introduction

In recent years, metal matrix syntactic foams (MMSFs) have been studied extensively because of their superior mechanical and energy absorbing properties and relatively lower cost in comparison with conventional metal foams [1–4]. By definition, MMSFs consist of a metallic matrix containing hollow or porous particles [1,2,5]. Such foams can be produced by powder metallurgy [6] or stir casting [5]. Pressure infiltration is probably the most promising process due to its lower cost and a higher achievable volume fraction of filler particles [7].

The minimum achievable density of MMSFs is higher than that of metallic foams [6,8,9]. This has been a major limitation. The density of MMSFs is determined by the volume percentage and density of filler material. The volume percentage of randomly packed, similar size filler particles barely exceeds about 64%, the dense random packing density of mono-size spheres [2,7,10,11]. Thus one can say the density of MMSFs depends largely upon the density of the filler particles [10]. Over the last two decades, various types of hollow particles (hollow spheres (HS)) including metal [12–14], ceramic [8], carbon [15], glass [5,16], and fly ash (cenospheres) [17,18] have been used in the preparation of MMSFs. However, such particles have a relatively high density, reportedly more than 0.6 g/cm^3 (see Table 1) [6,19,20] which limits the minimum density of MMSFs. In addition, unintended infiltration of the spheres caused by failure of the filler particle shell can increase the density of MMSFs [21,22]. Because of the above reasons, the minimum reported aluminium syntactic foam densities are typically greater than about 1.4 g/cm^3 (see Table 1) [7,19,22,23].

Generally, HSs are produced synthetically via methods such as sol–gel processes, sacrificial core, or nozzle blowing [24] which add to the cost of the MMSF. As a by-product of coal-fired power plants [5,18], cenospheres are the most cost effective filler materials. However, their size limitation (typically less than 300 μm) dictates the need for a complicated infiltration process [1].

Up till now, the application of ceramic and glass HSs in MMSFs has been broadly investigated, but there are limited reports on utilizing porous particles [4]. In this context, HSs refer to filler particles with a solid or porous skin containing one large internal cavity whereas a porous particle describes geometries that contain a multitude of small pores. In this paper, we propose the use of porous expanded perlite (EP) particles to produce low-cost low-density aluminium syntactic foam.

EP is produced by heating raw perlite rock to 870 °C. Raw perlite is a hydrated silicate base volcanic glass typically containing 2–6 vol% of water in its structure [25,26]. Perlite is expanded to 15–20 times of its original volume due to the large volume change of trapped water during its liquid–vapor phase transition in the softened structure. [27]. The content of SiO_2 is more than 70%, which is 10% more than that of a typical glass or ceramic HS [28], while the Na_2O/K_2O ratio is less than one [27]. Owing to its low density, high porosity, chemical inertness, fire resistance and

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Table 1
Data of some studied MMSFs.

Matrix	Filler material	Filler size	Filler particle density (g/cm^3)	MMSF density (g/cm^3)	Total volume porosity %	Ref.
Pure Al	Cenosphere	90–150 μm	1.00–0.74	1.52–1.43	40.7–43.7	[1]
A356	Cenosphere	45–250 μm	0.7	1.25–2.1		[17]
Al4047	Ceramic HS: $33Al_2O_3$–$48SiO_2$–19 Mullite	150 μm	0.6	1.35		[16]
Pure Al	Ceramic HS: 45 SiO_2–35 Al_2O_3–20 Mullite	100–1450 μm	0.57–0.81	1.43–1.49	41–47.6	[11]
Pure Al	Ceramic HS: $60SiO_2$–$40Al_2O_3$	250–500 μm	0.75	1.38	51	[4]
Al 6082	Ceramic HS: $60SiO_2$–$40Al_2O_3$	75–125	0.6	1.45		[2]
A356	Ceramic HS: SiC	1 mm	1.160	1.819	38	[8]
Al2024	Ceramic HS: Alumina	3–4.25 mm		1.25		[9]
Pure Al	Glass HS: $60SiO_2$–$15Al_2O_3$–15CaO–$10Na_2O$	0.5–4 mm	0.95–0.65	1.58–1.88	44–31	[4]

sound absorption, EP has been broadly used in asphalt, resin-based castings, combating oil spillage [25], filtration systems [29], and construction elements [26,27]. In the present study, EP/A356 Al alloy syntactic foam was fabricated by a counter gravity infiltration technique. The structure and density of the foam and EP particles were investigated. The interface between the EP particles and base metal was examined and mechanical properties of the foam were evaluated.

2. Materials and experimental procedures

2.1. Materials

EP particles were obtained from Australian Perlite Pty and particles with a size range of 3–4 mm were used. According to their product data sheet, 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. A356 aluminium alloy with the composition of 7.2 wt% Si, 0.4 wt% Mg, 0.1 wt% Fe, and 0.12 wt% Ti was used as the matrix metal. Because of its high Si content, it has good castability, a short solidification time, good resistance to hot cracking and a low solidification shrinkage [17,21]. The presence of Si and Mg results in improved mechanical properties in both plain and heat-treated conditions [30]. Moreover, the Mg content of the alloy improves the wettability of the particles [31].

2.2. Experimental procedures

The counter-gravity pressure infiltration equipment used for the manufacturing of the syntactic foam is illustrated in Fig. 1. Prior to casting, EP particles were dried in a furnace for 30 min at 250 °C. In order to minimize the oxidation of the aluminium, filling and assembling of the components shown in Fig. 1 took place inside a glove-box containing a controlled argon atmosphere. In the glove-box antechamber, EP particles and set-up parts were exposed to a low vacuum (10^{-4} MPa) followed by purging with argon gas (0.1 MPa). This procedure was repeated three times. Inside the glove-box, a stainless steel mesh was placed at the graphite mould ventilation hole to prevent particles from blocking it. To achieve uniform tightly packed EP particles, the graphite mould was filled in five equally sized batches and vibrated for 1 min after each step. The EP particles mass (m_p) was measured by subtracting the weight of the mould before and after filling (correcting for the mass of the stainless mesh). A second stainless steel mesh packed the mould to both guard against the displacement of EP particles and filter any possible aluminium oxide on the surface of the molten metal. A block of room temperature A356 alloy was placed in a graphite crucible and the filled mould was rotated and placed on top of it. The volume of the solid aluminium was twice the combined volume of the EP particles to

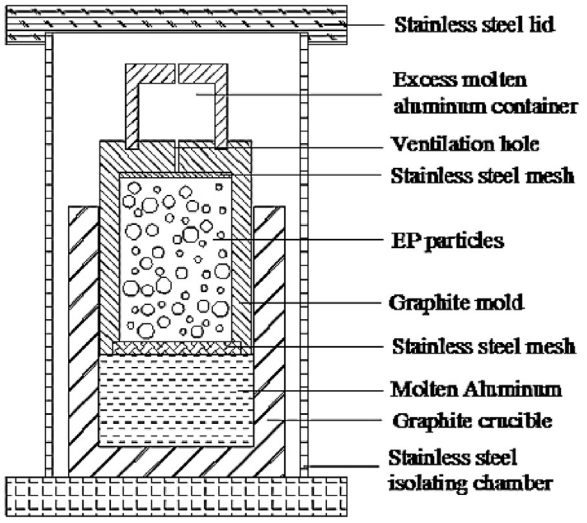

Fig. 1. Counter-gravity pressure infiltration set-up for producing EP/A396 Al syntactic foam.

ensure full infiltration during casting. The assembled crucible was put into a stainless steel isolating chamber (SSIC) that maintained the protective argon atmosphere. After removal from the glove-box, the assembly was placed in an electric furnace and heated from room temperature to 720 °C and held at this temperature for 30 min. Then, the assembly was removed from the furnace and the stainless steel lid of the SSIC was removed. The mould was pushed downwards within the graphite cubicle thus forcing the molten aluminium into the graphite mould causing infiltration. Two 1 mm diameter ventilation holes allowed the escape of air and excess aluminium. The assembly was cooled down under atmospheric conditions. Finally, the sample was manually pushed out of the mould. The upper and lower surfaces of the cylindrical sample were machined to remove the stainless steel meshes.

Samples for metallography were cut from the as-infiltrated EP/A356 syntactic foam using a low-speed silicon carbide saw. They were polished using SiC paper, followed by 6 μm and 1 μm water-based diamond suspensions. The microstructure of EP particles and syntactic foam was examined using scanning electron microscopy (FEI XL30 SEM) and optical microscopy. The elemental X-ray mapping of the EP-A356 alloy interface was investigated by a JEOL 6100 SEM equipped with an Oxford ISIS EDS system.

To evaluate the uniformity and distribution of the EP particles, micro-computed tomography (μCT) imaging with a spatial resolution of 48.2 μm was performed. In addition, to investigate the density gradient, samples were accurately cut in equal pieces with 7 mm height and the volume and mass (density) of each piece was measured. The height (h) and diameter (d) of the samples were measured with a precision electronic calliper to calculate the volume of the cylindrical sample (i.e. $V_{sf} = 1/4\pi d^2 h$). The density