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Dynamic compressive loading of expanded perlite/aluminum syntactic foam

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ABSTRACT

This paper addresses the analysis of expanded perlite/aluminum (EP/A356) syntactic foams under dynamic compressive loading conditions. Experimental and numerical analysis are conducted in order to determine compressive stress–strain response, effective material properties and deformation mechanisms. Foam samples are manufactured by combining A356 aluminum alloy with expanded perlite particles that introduce 60–65% porosity. Under compressive loading these pores gradually collapse resulting in an approximately constant macroscopic stress level of the syntactic foam. Testing at different compression velocities shows that the expanded perlite particles increase the compression resistance at higher strain rates. The effective material properties of the syntactic foam increase both with density and loading velocity. Infrared (IR) thermal imaging and finite element analysis allowed the independent identification of the dominant deformation mechanism: single struts that are parallel to the loading direction buckle and trigger the formation of multiple collapse bands that are approximately perpendicular to the loading direction.

1. Introduction

Recently, metallic foams have been considered as potential replacements of conventional materials in energy absorption applications in automotive industry [1]. This is due to their high strength-to-weight ratio, negligible spring back in case of impact deformation, and excellent durability in atmospheric conditions [2]. The high specific energy absorption capacity of metallic foams is due to plastic deformation over a prolonged compressive strain at a relatively constant stress, the so called plateau stress. Lots of research has focused on the important quasi-static compressive behaviour of metallic foams. However, in applications as energy absorbers (i.e. in motorcycle helmets [3] or car seat components [4]) they are subjected to distinctly higher strain rates that may affect their mechanical response. The degree to which the strain rate influences the mechanical properties of aluminum foams depends on the particular alloy, the foam structure i.e. open or closed cell [5,6], the loading direction [1], the strain rate [5,7] and the pore filler (if any). In most cases, the plateau stress and energy absorption of closed cell foams increase by increasing the strain rate [6,8–12] whilst some works reported little or no strain rate sensitivity for slightly different foams [2,13]. It is widely accepted that open cell foams are almost insensitive to the strain rate [6,11,14,15]. However, Barners et al. reported that beyond a critical strain rate, the plateau stress of open cell foams increases due to shock development [5].

Metallic syntactic foams comprise a metallic matrix containing hollow or porous particles and have a lower cost in comparison to conventional metallic foams. Different dynamic compressive behaviors of syntactic foams have been reported in the literature. Zou et al. [16] and Dou et al. [17] reported that the compressive strength of Cenosphere/Al syntactic foam increases by increasing the strain rate while according to Geol et al., there is a critical strain rate beyond which the compressive strength drops [7]. Geol et al. also reported that at lower strain rates, the plateau stress is almost independent of the strain rate [18]. Aluminum base syntactic foams containing Alumina hollow spheres [19] and SiC hollow spheres [20] showed insignificant strain rate sensitivity. It should be noted that the strain rate sensitivity of the cellular structure might be affected by the presence of a gaseous pore filler (e.g. air, H_2) [21,22]. The strain rate sensitivity effect is usually more apparent for structures with higher initial pore pressures or higher relative densities [23,24].

Metallic syntactic foams have some limitations in their minimum achievable density and cost due to the relatively high density and price of the conventional filler materials [20,25–27]. A

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previous work [27] introduced expanded perlite (EP) as a novel low-cost filler material. With a density of 0.17 g/cm^3 this natural porous volcanic glass overcomes the high density limitation of current filler materials. Because of its low mechanical strength, it does not directly improve the mechanical properties of the foam in quasi-static loading [27]. However, heat treatment has shown to significantly improve the mechanical properties of EP/A356 syntactic foam [28]. In addition, the effect of the EP particle size (ranging from 1 to 5.6 mm) on microstructural and mechanical properties of EP/A356 syntactic foam was investigated [29]. It was found that the microstructural and geometrical properties of foams are enhanced as the EP particle size decreases. This results in superior mechanical properties ωηεν compared to foams containing larger EP particles.

In the current study and for the first time the effect of the loading velocity on EP/Al356 syntactic foam is investigated. The precise knowledge of the strain rate sensitivity is essential for the potential use of this novel material as a strain energy absorber. The study further introduces the first numerical study of the syntactic foam. In order to capture the complex geometry, numerical models were derived from micro-computed tomography data. Results have been verified by comparison with compressive stress strain data as well as infrared (IR) thermal imaging. The combined approach allows for the determination of effective material properties and the identification of dominant deformation mechanisms at loading velocities up to 284 mm/s.

2. Experimental details

2.1. Sample preparation

Aluminum alloy (A356) with a composition of 7.2 wt% Si, 0.4 wt% Mg, 0.1 wt% Ti, 0.12 wt% Fe, and the balance aluminum was used for the casting of the metallic matrix. According to their product specification the EP particles contain 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. Syntactic foams were synthesized by counter gravity infiltration of packed beds of EP particles with the molten aluminum alloy. A detailed description of the infiltration process is provided in [27]. In order to investigate the effect of EP particles on mechanical properties, the particles were removed from some of the samples by applying a high pressure water jet (see Fig. 1). These samples are subsequently referred to as washed samples.

In the experimental program a total of 20 cylindrical samples with the constant diameter $D=30.7$ mm and heights $h=21.5$–22.1 mm were tested. Their average density (ρ) was calculated by dividing the sample mass with the cylinder volume. The corresponding values are $\rho=0.97$–1.09 g/cm^3 for syntactic foam samples and $\rho=0.90$–1.00 g/cm^3 for washed samples. All samples underwent a T6 thermal treatment comprising solution at 540 °C for 16 h followed by water quenching. Subsequent aging was conducted at 160 °C for 10 h. Fig. 1c shows the microstructure of an A356 aluminum strut after thermal treatment. It comprises a network of aluminum-rich primary and secondary dendritic arms. The eutectic structure constituting the aluminum-rich and silicon phases forms between the dendritic arms [28]. Geometric information of the tested samples is shown in Table 1.

2.2. Quasi-static and dynamic compressive tests

The setup used for the dynamic tests is shown in Fig. 2. Behaviour of cylindrical specimens was evaluated by deformation driven quasi-static and dynamic compressive testing using the servo-hydraulic testing machine INSTRON 8801 according to the standard ISO 13314: 2011 [30,31]. The specimens have been subjected to either quasi-static loading velocity of 0.1 mm/s or two dynamic loading velocities of 142 mm/s and 284 mm/s. The dynamic loading resulted in initial strain rates of 6.8/s and 13.6/s, respectively. The testing machine support plates were lubricated with the silicone oil to minimize the friction between the specimens and the support plates. During the tests the force and cross-

Table 1
Physical properties of syntactic foam samples and loading velocities.

No. [–]	Height [mm]	Mass [g]	Density [g/cm^3]	Loading velocity [mm/s]
1[a]	21.44	14.86	0.94	142
2[a]	21.06	14.89	0.96	142
3	21.51	17.02	1.07	142
4	21.32	16.94	1.07	142
5	21.33	17.03	1.08	142
6	21.01	16.91	1.09	142
7[a]	21.48	14.26	0.90	284
8[a]	20.74	14.48	0.94	284
9	21.15	15.25	0.97	284
10	21.33	15.84	1.00	284
11	21.28	16.01	1.02	284
12	21.92	17.15	1.06	284
13	21.13	16.59	1.06	284
14	21.46	17.17	1.08	284
15[a]	21.63	14.81	0.92	0.1
16[a]	20.89	15.49	1.00	0.1
17	20.95	15.72	1.01	0.1
18	21.54	16.21	1.02	0.1
19	21.25	16.35	1.04	0.1
20	21.45	16.89	1.06	0.1

[a] Washed sample.

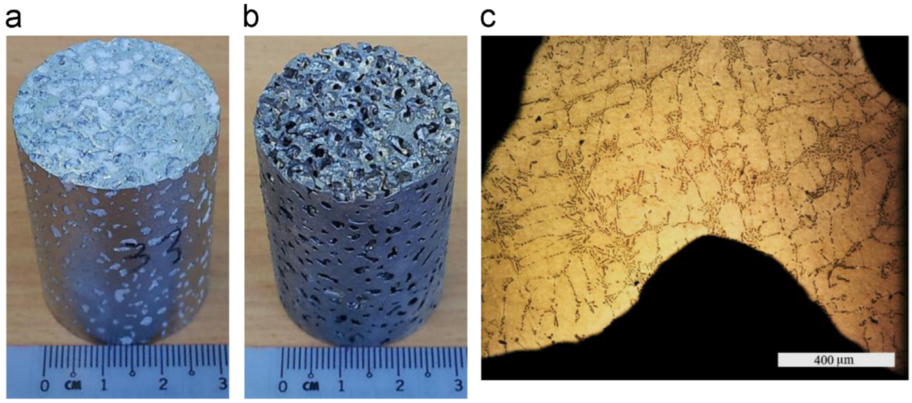

Fig. 1. (a) EP/A356 syntactic foam, (b) washed sample, (c) Al356 micro-structure after T6 thermal treatment.