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Strength enhancement of aluminium foams and honeycombs by entrapped air under dynamic loadings

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ABSTRACT

The strength enhancement of cellular metals including aluminium foams and honeycombs under dynamic compression is experimentally studied in the present paper, with a focus on the intermediate strain rate from 1 to 200 s^{-1}. Previously data in this range are very limited due to the difficulty in the experimental techniques. The plateau stress in relation to the strain rate of these materials is discussed based on experimental results and compared with data from literature. It has been found that the studied cellular metals are sensitive to the strain rate in plateau stress but not in densification strain. The causes of the strength enhancement are then discussed with a focus on the contribution of the entrapped air during compression. The results show that the pressure change of the entrapped air during dynamic compression is a direct source of strain hardening for aluminium honeycombs whereas it has less influence on the strain hardening of aluminium foams.

1. Introduction

Cellular materials, including metallic honeycombs and foams, have high strength to weight ratio and good energy absorption capacity, which make them attractive for many structural applications in automotive and aerospace industries. Abundant studies on the quasi-static and high strain rate compression of these materials have been conducted in the past decades to reveal the relations between the relative density, strain rate and plateau stress [1–9]. However, due to the complexity of these materials under dynamic loading, the studies on the strengthening mechanisms of cellular materials are still limited both experimentally and theoretically, especially in the intermediate strain rate range from 1 to 10^2 s^{-1}. Zhao et al. [5] summarized four main sources of the strength enhancement from the study on the impact behaviour of metallic cellular materials. The present authors conducted a series of experimental study on the dynamic crushing of aluminium foams and honeycombs [10–14] at intermediate strain rates. It has been found that strength enhancement of cellular materials was mainly from two macroscopic sources. Firstly, the plateau stress increased with the increase of strain rate. Secondly, under dynamic compression, a significant strain hardening was observed, which was attributed to the increase of the pressure of the entrapped air in honeycombs during the dynamic out-of-plane compression [10,11].

In this paper, the dynamic compressive properties of aluminium foams are further studied over the strain rates from 10^{-3} to 200 s^{-1} by using MTS and Instron machines. The relationship between plateau stress, relative density and strain rate for Alporas aluminium foams is experimentally fitted and analysed together with data from literature. Similar semi-empirical relationship for aluminium honeycombs is also discussed after comparing the experimental data obtained by the present authors in literature [10,11] with those from literature. Possible reasons for the strength enhancement are finally discussed, with an emphasis on the entrapped air contribution in dynamic compression.

2. Experimental procedure

2.1. Materials and sample preparation

Alporas closed-cell aluminium foams and HexWeb® CR III aluminium honeycombs are studied in this paper. Alporas aluminium foams have a nominal relative density of 10%, with the actual values ranging from 8% to 12%. The average cell size of Alporas foams is approximately 3 mm. The properties of the Alporas foam used in the current study were listed in Table 1 as provided by the suppliers. Cylindrical Alporas foam specimens with

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Table 1
Properties of Alporas aluminium foam (data was provided by the supplier)

Composition (%)	Density (kg/m^3)	Young's modulus (GPa)	Shear modulus (GPa)	Shear strength (MPa)
Al + 1.5%Ca + 1.5% Ti	230 ± 20	1.1 ± 0.1	0.33 ± 0.02	1.2 ± 0.05
Tensile strength (MPa)	Bending strength (MPa)	Poisson's ratio	Compressive peak stress (MPa)	Average cell size (mm)
1.6 ± 0.2	2.8 ± 0.3	0.33	1.9 ± 0.3	2.88

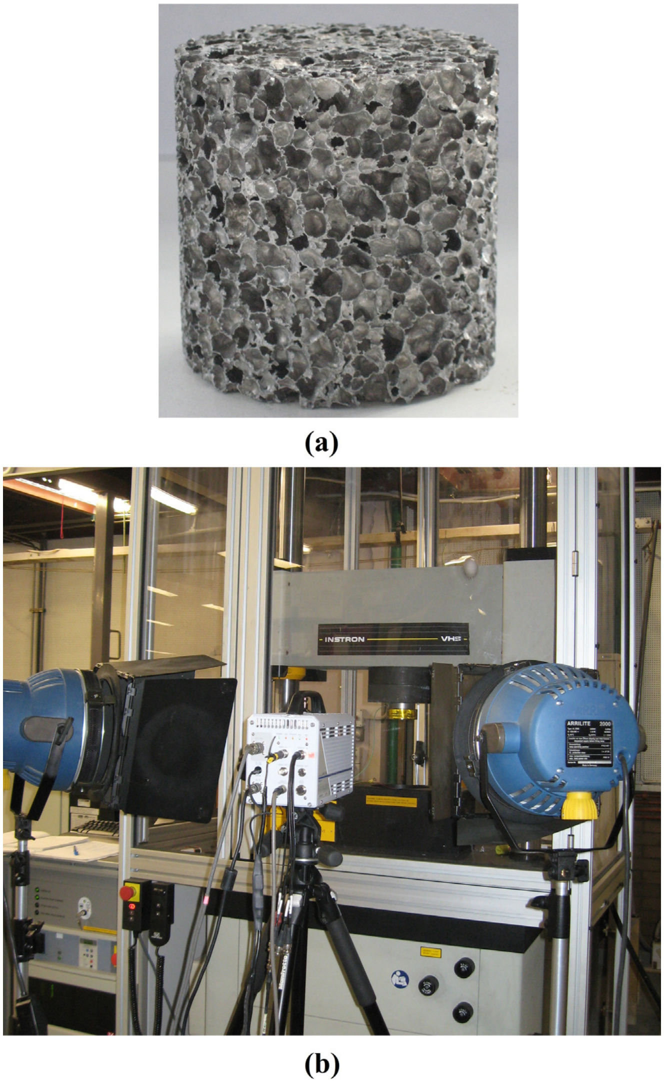

Fig. 1. (a) A typical aluminium foam specimen and (b) Instron 8800 VHS high rate testing system.

50 mm diameter and 50 mm thickness were prepared by wire cutting. Each specimen contains more than 7 cells in all directions to avoid the boundary effect [1]. A typical test specimen was shown in Fig. 1a. Three types of HexWeb® CR III honeycomb (5052-H39) with different cell size and cell wall thickness were carefully cut according to the construction of periodical "Y" shape units [10]. The detailed experimental study on the intermediate strain rate compression of honeycombs can be found in two previous papers by the present authors [10,11]. Honeycomb specimens contained 9 × 9 cells, which was large enough to represent the bulk properties of materials previously studied [10].

2.2. Quasi-static and dynamic testing

Quasi-static and low strain rate tests were conducted on an MTS machine. The MTS machine has a load capacity of 250 kN and can reach a maximum velocity of 0.2 m/s in compressive tests. The load cell of the MTS machine was calibrated from 2.5 kN, which provided sufficient accuracy for the current study. During the compression, specimens were placed on the fixed lower platen. The upper platen moved downwards to crush the specimens. Constant velocities of 5×10^{-5}, 5×10^{-4}, 5×10^{-3} and 5×10^{-2} m/s, respectively, were applied to specimens corresponding to nominal strain rates of 10^{-3}, 10^{-2}, 10^{-1} and 1 s^{-1}, respectively, for specimens 50 mm thick. The nominal strain rate was defined as the ratio of the loading velocity to the original thickness of the specimen. When the specimen was compressed, the thickness of the specimen decreased. Although the loading velocity was constant, the instant strain rate changed with the instant specimen thickness. Thus a nominal strain rate was defined and used in the paper. The nominal strain rate was defined as the ratio of the loading velocity to the original thickness of the specimen.

Dynamic compressive tests were conducted on an Instron 8800 high rate testing system, as shown in Fig. 1(b). The system is equipped with VHS software, which helps to maintain a constant velocity during the compression of specimens. The Instron machine can achieve a maximum velocity of 10 m/s in compression and has a load capacity of 100 kN. The Kistler load cell of the Instron machine was calibrated in a range of 20 kN, which ensured the accuracy of the measurement. Honeycomb specimens were sitting on the lower platen. During the compression, the lower platen moved upwards together with the specimen to impact the upper fixed platen. To prevent the specimens from dis-connecting with the low platen during the compression, very thin and weak glue was used to stick the specimen to the lower platen. This Instron machine was used to conduct tests at nominal strain rates 10, 100 and 200 s^{-1}, for which the corresponding crushing velocities are 0.5, 5 and 10 m/s, respectively, for specimens 50 mm thick.

The experimental data obtained by MTS and Instron machines were identical at compressive velocity 0.05 m/s, as experimentally demonstrated previously [10]. Therefore, the stress-strain curves characterized by the two machines could be analysed together. Details of the tested foams are summarized in Table 2 and data for dynamic compression of honeycombs can be found in two papers of the present authors [10,11], which are only cited and analysed in the present paper.

2.3. Data processing

There are great uncertainties to determine the densification strain and the plateau stress by using normal methods. Therefore, energy efficiency method proposed by Avalle et al. [15] was employed in the current work. The energy efficiency coefficient (function of strain), η, is defined by

$$\eta(\varepsilon) = \frac{1}{\sigma(\varepsilon)} \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \tag{1}$$

The strain range of the integral in Eq. (1) was set to be from 0 to ε. The densification strain was then defined as the point where the efficiency coefficient reached the maximum on the efficiency–strain curve, i.e., $\varepsilon_d = \varepsilon[\eta(\varepsilon)]_{\max}$.