Materials Science & Engineering A 659 (2016) 278–286

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

The trapped gas effect on the dynamic compressive strength of light aluminum foams

O. Sadot *,[a], O. Ram [a], I. Anteby [b], S. Gruntman [a], G. Ben-Dor [a]

[a] Mechanical Engineering Department, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel
[b] Nuclear Research Center Negev, Beer-Sheva 84190, Israel

ARTICLE INFO

Article history:
Received 25 January 2016
Received in revised form
9 February 2016
Accepted 10 February 2016
Available online 23 February 2016

Keywords:
Shock mitigation
Aluminum foams
Strain-rate dependence

ABSTRACT

Light aluminum closed-cell foams (4% relative density to solid aluminum) were experimentally studied in order to determine the added dynamic compressive strength facilitated by the trapped gas. A compression machine, an impact pendulum, and a shock tube were used to compress foam samples in strain rates varying from $10^{-3}\,s^{-1}$ to $700\,s^{-1}$. Very similar results were recorded from the compression machine and the impact pendulum experiments. The shock tube results exhibited a significantly higher compressive strength. An experiment was designed to isolate the compressive strength contribution from the gas trapped inside the foams. It was shown that, in light aluminum foams, gas compression contributes the additional dynamic stress. It was also shown that, in the samples used in this study, gas compression caused as much as 50% of the dynamic compressive strength. An isentropic model was used to analytically explain the gas contribution to the dynamic compression stress recorded in the experiments.

1. Introduction

Porous, closed-cell, metallic foams can act as a lightweight additive for structural elements that enhance their energy absorption capabilities under dynamic loadings [1]. These materials, which are usually made from aluminum alloys, have been demonstrated to absorb large amounts of energy owing to their large number of buckling elements and their ability to sustain large plastic deformations [2]. The energy absorption capability of metallic foams has been previously tested in various configurations. The best results, in terms of energy absorption, were obtained by including metallic foam as part of a multi-layer structure (see e.g., [3–5]). Owing to their light weight, these materials also provide a good option for the outer layer of lightweight protected vehicles and other blast resistant mobile structures. The energy absorption capabilities in blast protection scenarios were demonstrated in field experiments [6,7]. Bastawros et al. [8] highlighted the complexity of the geometric structure and the plastic energy absorption mechanisms. They meticulously recorded the course of events occurring during the compression of aluminum foams. They found that the collapse of these materials occurs along discrete bands that contain sets of neighbor cells that experience plastic deformation. These bands compress until local hardening occurs, prompting other bands to start collapsing.

Effectively incorporating metallic foams in the design of structural elements requires appropriate material models. During the past decades, some studies have focused on finding these models. Hanssen et al. [9] proposed the use of several constitutive numerical material models from the LS-DYNA library (LSTC, Troy MI). However, discrepancies between the models were found even for relatively simple load configurations. The most important conclusion was the need for further development of more robust fracture models for the Al-foam.

Mukai et al. [10] noted that the effect of the strain rate was one of the important issues that needed to be resolved. They demonstrated strain rate dependency in dynamic stress tests using the Split-Hopkinson bar (SHB), which provided a strain rate of $2500\,s^{-1}$, and found that the absorption energy of the foams increased dramatically with increasing strain rate. Following their study, a number of studies have been later performed to find the response of aluminum foams to various loadings in various strain rates. Dannemann and Lankford Jr. [11] tested closed-cell *Al*-foams under static and dynamic loads in the strain rate range of 400–$2500\,s^{-1}$. This range was also achieved by using an SHB apparatuses. They found that the strain rate effect is significant in high density *Al*-foams and attributed the strain rate hardening effect to the gas flow between the porous medium cavities but did not provide any justification for this statement. Paul and Ramamurty [12] further validated these results by finding a strain rate dependency in much lower strain rates and extrapolated their results

---

* Corresponding author.
E-mail address: sorens@bgu.ac.il (O. Sadot).

http://dx.doi.org/10.1016/j.msea.2016.02.031
0921-5093/

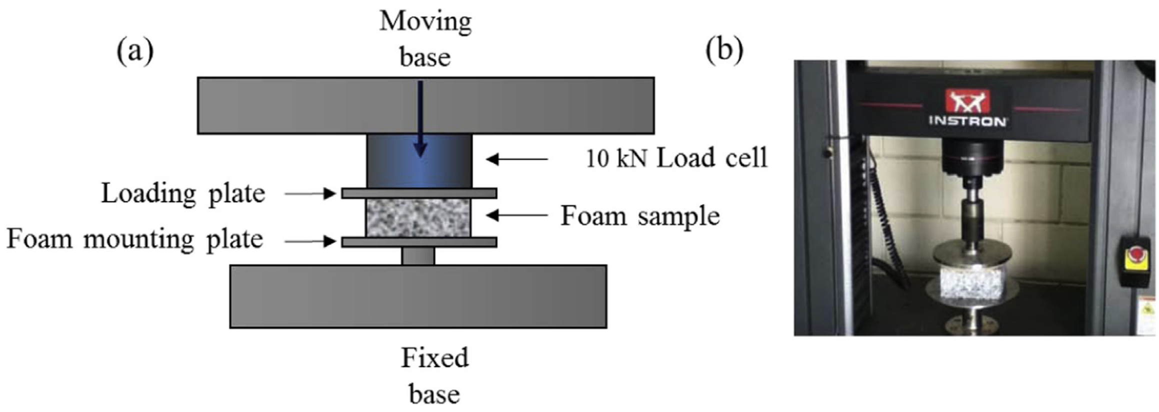

Fig. 1. (a) Schematic illustration of the compression test experimental setup. (b) Image depicting a foam sample placed in the Instron machine.

to conclude that their results had good agreement with Dannemann and Lankford Jr. [11].

Remarkably, not all experiments that were performed on porous media found a consistent strain rate dependency. In contrast to the foregoing discussed findings, Deshpande and Fleck [13] compared their results from similar SHB tests performed on both open- and closed-cell aluminum foam to the ones obtained by Dannemann and Lankford Jr. [11] but found no strain rate dependency. They tried to calculate the trapped air contribution inside the closed-cell foams based on the relationships proposed by Gibson and Ashby [14] and concluded that the air contribution was very small. However, they did use samples that were very small and had a small number of cells in them (6–8 in all directions); whereas, Dannemann and Lankford Jr. [11] found high strain rate dependency in samples with more than twice the number of cells. Sadot et al. [7] also recorded a strain rate dependency by comparing samples that were dynamically loaded by an impact pendulum to samples that were loaded by a shock wave in a shock tube. They found that in the shock tube experiments, which provided higher strain rates, apparent hardening was recorded. Mukai et al. [15] performed additional experiments and found more evidence of the strain rate dependency. Further affirming these reports, Wang et al. [16] used a controllable dynamic compression machine in rates of up to 450 s^{-1} to conduct dynamic testing of aluminum alloy foams and found a significant strain rate dependency as well. These tests show a distinct hardening throughout a very wide spectrum of strain rates ranging from 10^{-3} s^{-1} to 450 s^{-1}.

Tan et al. [17] provided another example of the complexity of these materials that not only demonstrated the existence of the strain rate dependency but also showed that the mechanical properties of aluminum foams depend on the direction of the loading with respect to the plates formed by the manufacturer. They found that in aluminum foam plates, the cell size distribution depends on the direction and the cell size affects the failure modes, thus changing the mechanical response to loading in each direction. Duarte et al. [18] reported similar results. Hangai et al. [19] showed that such effects can be beneficial since they enable control over the mechanical properties of the foams; they used different materials that effectively formed graded aluminum foam layers.

The present study is focused specifically on the contribution of the air trapped inside the closed cells to the dependence of the dynamic response of aluminum foams on the strain rate. This study employs three loading methods to investigate the dynamic behavior of Al-foams: an Instron compression machine was used for low stain rates, an impact pendulum was used for moderate strain rates, and a shock tube apparatus was used for high strain rates. In the following, the three experimental systems are briefly described followed by the obtained results. Then, a methodology is proposed to distinguish between the trapped air contribution to the dynamic response of aluminum foams, and a simple modeling technique is proposed to incorporate the gas effects in uniaxial compression scenarios.

2. Experimental setup

In this study, stress–strain curves of closed cell Cymat SmartMetal™ aluminum foams were measured using three experimental facilities. The facilities are located at the laboratories of the Protective Technologies R&D Center of the Faculty of Engineering Sciences of the Ben-Gurion University of the Negev.

2.1. Compression machine

A compression machine was used to obtain low strain rates on the order of 10^{-3} s^{-1}. The experimental setup is schematically illustrated in Fig. 1(a); for these experiments, an Instron compression machine, model 5982, was utilized. The samples were placed on a thick steel plate and were pressed using a second thick steel plate. The stress–strain data were measured using the imbedded load cell and displacement gauges pre-calibrated by the manufacture. An image of the tests setup is shown in Fig. 1(b).

2.2. Impact pendulum

For moderate strain rate of 47 s^{-1}, an impact pendulum was used. An illustration of the system is presented in Fig. 2(a). In this setup, an impact pendulum hung from four points to ensure a planar impact at the foam Target. The impact pendulum was loaded with lead blocks to weigh 500 kg and was raised to an initial height of 0.5 m, which provided an impact velocity of approximately 3.1 m/s. The aluminum foam samples were placed on a rigid heavy steel plate in front of the pendulum impactor. The displacement of the impactor was monitored throughout the experiment using a Phantom V12.1 high-speed camera. The values the of displacement were extracted from the imaging analysis using TEMA motion software from Image Systems, which is capable of tracking moving objects in a video with high accuracy. An image of the impact pendulum experimental setup is presented in Fig. 2(b). Additional details on the impact pendulum system can be found in Sadot et al. [7].

2.3. Shock tube facility

For higher strain rates ranging from 290 s^{-1} to 700 s^{-1}, a standard shock tube facility was used. In this facility, which is