INVESTIGATION OF DEFORMATION BEHAVIOUR OF ALUMINIUM FOAM UNDER HIGH-STRAIN RATE LOADING AND COMPARISON WITH CONVENTIONAL ENERGY ABSORBING MATERIAL

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Summary: *The aim of this study is proper description of stress-strain behaviour of the metal foam structure Alporas under high-strain rate loading. Stress-strain response of Alporas specimens is measured during an impact test using a drop tower experiment. Strain of the specimens is evaluated by two independent approaches: i) double numerical integration of acceleration data and ii) digital image correlation technique. Thus, experimental setup is equipped with triaxial accelerometer and high speed camera. Resulting stress-strain curves are compared with behaviour of polystyrene material samples (polystyrene material is commonly used as a shock absorber) obtained from the same testing procedure and with stress-strain function determined from Alporas quasi-static compression testing.*

Keywords: *digital image correlation, impact test, polystyrene, metal foam*

1 Introduction

Aluminium metal foams are highly porous structures with unique material properties such as ability to absorb significant amount of deformation energy in combination with their very low specific weights. This capability of the metal foams is promising for using them as the impact bearing component in traffic collision protection (bumpers, helmets [1] etc.). Description of deformation behaviour of such a material under high-strain rate loading is necessary for design of shock absorbers [2] as well as for its numerical modelling. Stress-strain curve measured with various strain-rates are commonly taken as input to define material model [3] in explicit FE codes (e.q. Fu-Chang material model formulation).

2 Materials and methods

2.1 Sample preparation

Two types of energy absorbing materials were used for testing: closed-cell aluminium foam Alporas (Shinko Wire Ltd., Japan) with the mass density 260±15 kgm^{-3} and extruded polystyrene EPS 200 S with mass density approximately 30 kgm^{-3}. Cuboid samples of Alporas and polystyrene with the same dimensions (60×60 mm in plane and 50 mm in thickness) were cut from a slab and front side of each sample was sprayed with a granite sputter to obtain non-reflective and contrast surface suitable for performing digital image correlation (DIC). Prepared samples for impact testing are shown in Fig. 1-left.

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2.2 Impact tests using a drop tower

Impact tests were carried out using a custom-designed drop tower (see Fig. 1-right). The device enables to vary impact energies by selecting initial height (maximal height up to 1750 mm) and mass of the impactor. The impactor is placed into a cage guided with three sliding bearings on three rails. Impactor consists of selected weight and triaxial accelerometer (EGCS3, Measurement Specialties, USA) located in its upper part with ± 1000 g measuring range. Accelerometer data are recorded using analog input module (NI 9234, National instruments, USA) with 51.2 kSs^{-1} maximum sampling rate. High speed camera (NX3, Integrated

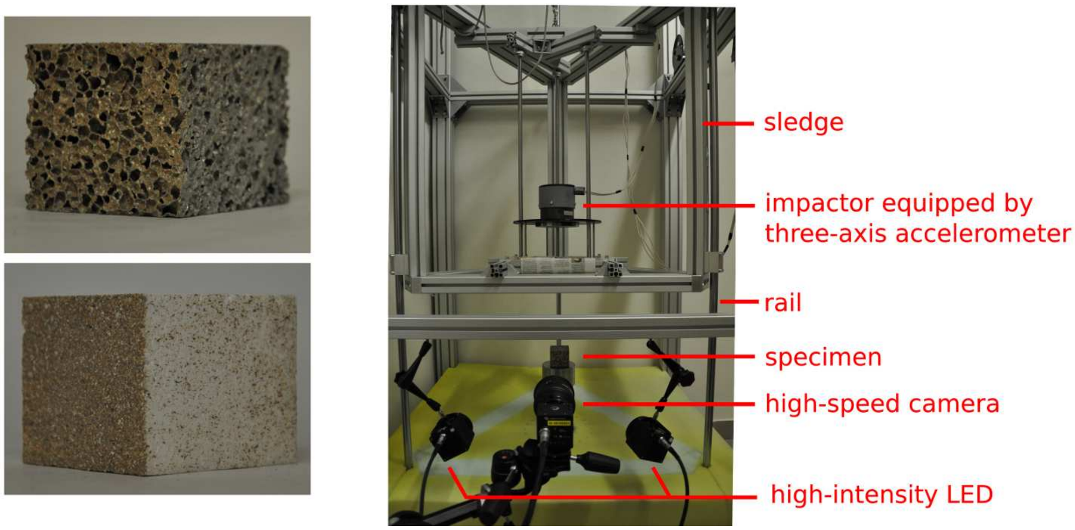

Figure 1: Alporas (top left) and polystyrene (bottom left) samples prepared for the impact test; drop tower with high-speed camera and LED lights (right).

Design Tools, Inc., USA) was used to capture a deformation of the sample during impact test for consequent strain evaluation using DIC technique. Maximal rate 2.500 fps with 1280×1024 pixel resolution can be increased by reducing of region of the interest (ROI). Quality of images (and further strain evaluation) is strongly dependent on proper illumination. A couple of the high intensity LED lights (Constellation 60, Veritas, USA) was employed to obtain suitable illumination of the scene. Image data and measured acceleration are synchronised by using an induction sensor (IPS-18, IBEST electrical, China).

Specimens were fixed on the bottom compression plate to avoid any possible slip and the impactor was positioned to a defined distance from the top of the sample to achieve the required impact velocity. Set of tests with three different impact velocities were performed for both types of the sample. Parameters of these tests are summarised in Tab. 1.

Table 1: Parameters of impact tests using drop tower

sample type	num. of tests	impactor mass [g]	impact velocity [ms^{-1}]	strain rate [s^{-1}]
Alporas	3	6030	4.32	86.4
	3		5.27	105.4
	3		5.86	117.2
polystyrene	3	6504	2.80	56.0
	3		3.13	62.6
	3	6030	3.43	68.6

3 Results and discussion

Primary experimental data were acceleration-time dependencies of the impactor. Fig. 2a shows comparison of measured acceleration of Alporas and polystyrene sample. Impact tests of Alporas and polystyrene could no be performed at the same impact velocity because of low impact energy absorption of a polystyrene. Velocity higher than maximal v_0 =3.43 ms^{-1} used for polystyrene sample could cause complete deformation (destruction) of the sample and contact between impactor and the bottom plate (a risk of overloading of the accelerometer and its damage). As it can be seen from graph the Alporas metal foam is able to absorb high portion of impact energy in comparison with polystyrene, however, the acceleration peak and rate are significantly higher. As was mentioned above the material's stress-strain curves have been evaluated using two approaches. The first approach was based on double numerical integration of acceleration data according to:

$$\varepsilon_{\text{eng}} = \frac{\int \left(\int a(t)\mathrm{d}t \right) \mathrm{d}t}{h} \tag{1}$$

where $a(t)$ is measured time dependent acceleration and h is the original sample height. Engineering stress was computed as

$$\sigma_{\text{eng}} = \frac{ma}{A} \tag{2}$$

where m is the impactor mass and A is the sample cross-sectional area. The true stress-strain curves were calculated from the engineering stress-strain curves and fitted by polynomial function to eliminate measured noise. Different deformation behaviour were observed for metal foam and polystyrene materials. Deformation of Alporas is described with three deformation stages (linear elastic, constant plastic flow and rapid hardening caused by final densification). Due to relatively small impact velocity which was limited by the drop tower height, the hardening stage could not be observed in experiments. The short linear stage was followed by a long flow plateau as is illustrated in Figure 2a and 2b. In contrast, the polystyrene is characterised by initial linear-elastic response followed with slowly hardening stress curve (Figure 2 a and 2d). As it was expected, with the higher strain rate the stress values of the flow plateau of the metal foam are slightly increased as is illustrated in Figure 2a whereas polystyrene flow plateau is insensitive to strain rate changes (see Figure 2d).

In addition to dynamic loading of metal foam, two samples were quasi-statically loaded to obtain uniaxial compression stress-strain curves. Custom compression setup was used for strain evaluation using both methods i.e., DIC and a platen movement (see result in Fig. 2b). As it is shown in detailed view in Fig. 2c, the stress-strain curves of the quasi-static test evaluated by DIC and platen movement were significantly different particularly in a linear part where the elastic modulae E_{DIC} ≈1.2 GPa and E_{platen} ≈0.15 GPa were determined. Elastic modulus evaluated by double integration of acceleration data was calculated also very low (E_{dynamic} ≈0.16 GPa) in comparison with quasi-static DIC test (nature of the strain evaluation from double integration is similar to strain evaluation from platen movement as in case of the quasi-static test). Underestimation of elastic modulus can be caused by boundary conditions (artifacts on ends of the sample, improper contact between the sample and the platen etc.). Thus, the elastic properties of metal foam structure should be determined only by DIC method.

The second evaluation of stress-strain curves was based on sample deformation tracking in acquired images using DIC toolkit [4] based on Lucas-Kanade algorithm [5] implemented in Matlab toolkit. The basic principle of DIC is tracking of the selected points (or pixels) between two images (reference and deformed subset) recorded during the deformation process (see Fig. 3) and evaluation of the similarity degree based on a normalised cross-correlation (NCC). Strain evaluation in case of our tests consists of four main steps: i) selecting two rows of markers in an image of the intact state of the sample (see Fig. 3); ii) tracking markers position through image sequences; iii) distance calculation between top and bottom pairs (in vertical line)

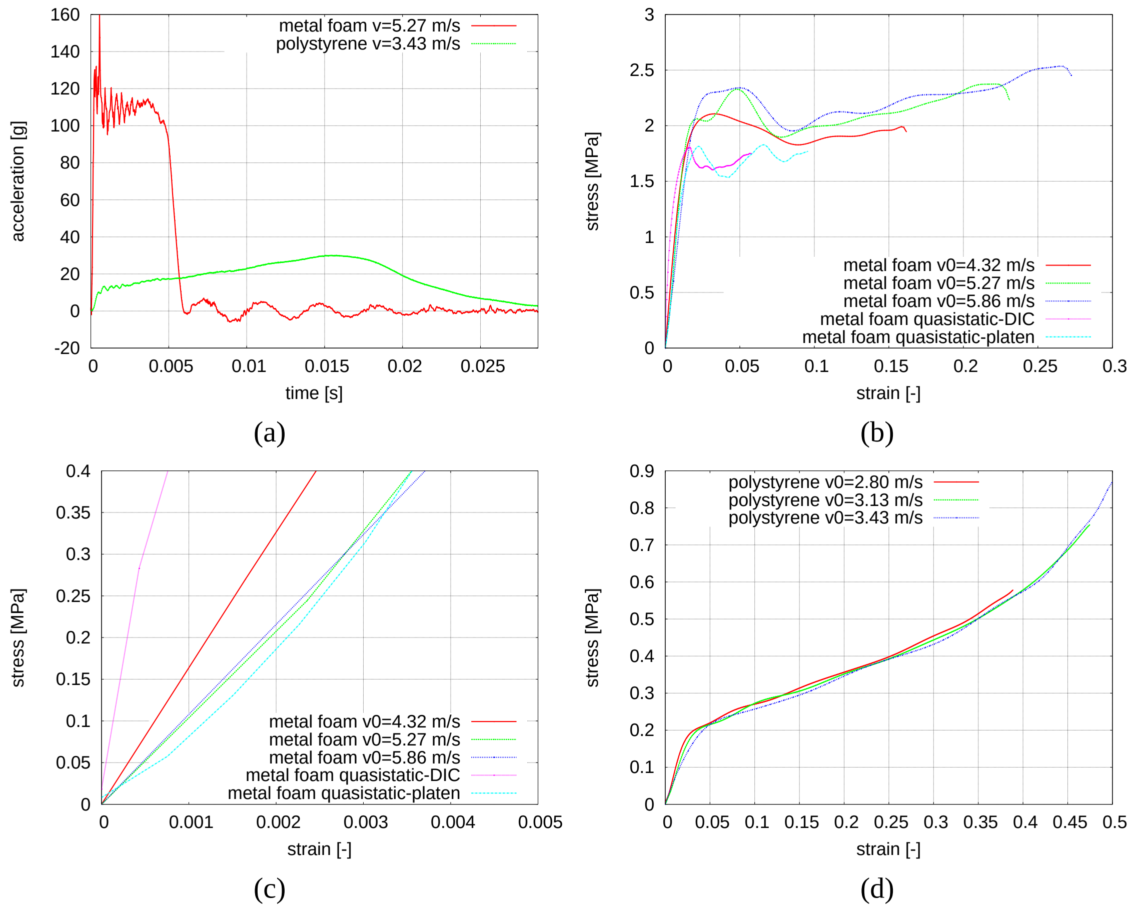

Figure 2: Measured acceleration and calculated stress-strain curves (average curve of 3 measurements for each impact velocity) based on an impactor movement for (b and c) Alporas, (d) polystyrene. Detailed view (c) shows initial elastic part of the metal foam sample.

of markers in each deformed image and iv) strain evaluation based on comparison of calculated distance (average from all pairs) through all deformation states and the initial one.

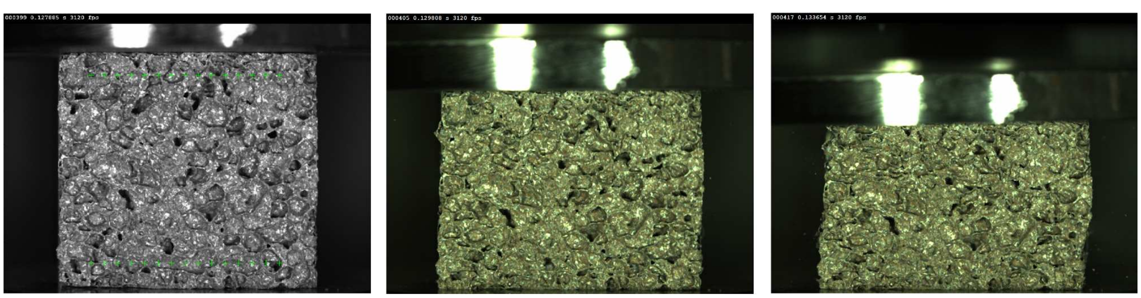

Figure 3: Deformation propagation in the metal foam sample during impact test. Initial state with rows of correlation markers is shown in the first subfigure.

Strain evaluation was performed using images captured by IDT NX3 high-speed camera with maximal 3280 fps rate limited by the size of the ROI. Graph in Fig. 4a shows that maximal sampling rate can not be able to capture sufficient number of frames in a linear part of stress-strain curve. Thus, full elastic and yielding phase were described by only one point which leads to inability to reliably determine elastic properties as well as yield point from the stress-strain curve. On the other hand, plastic flow is relatively slow process and could be plotted with sufficient accuracy.

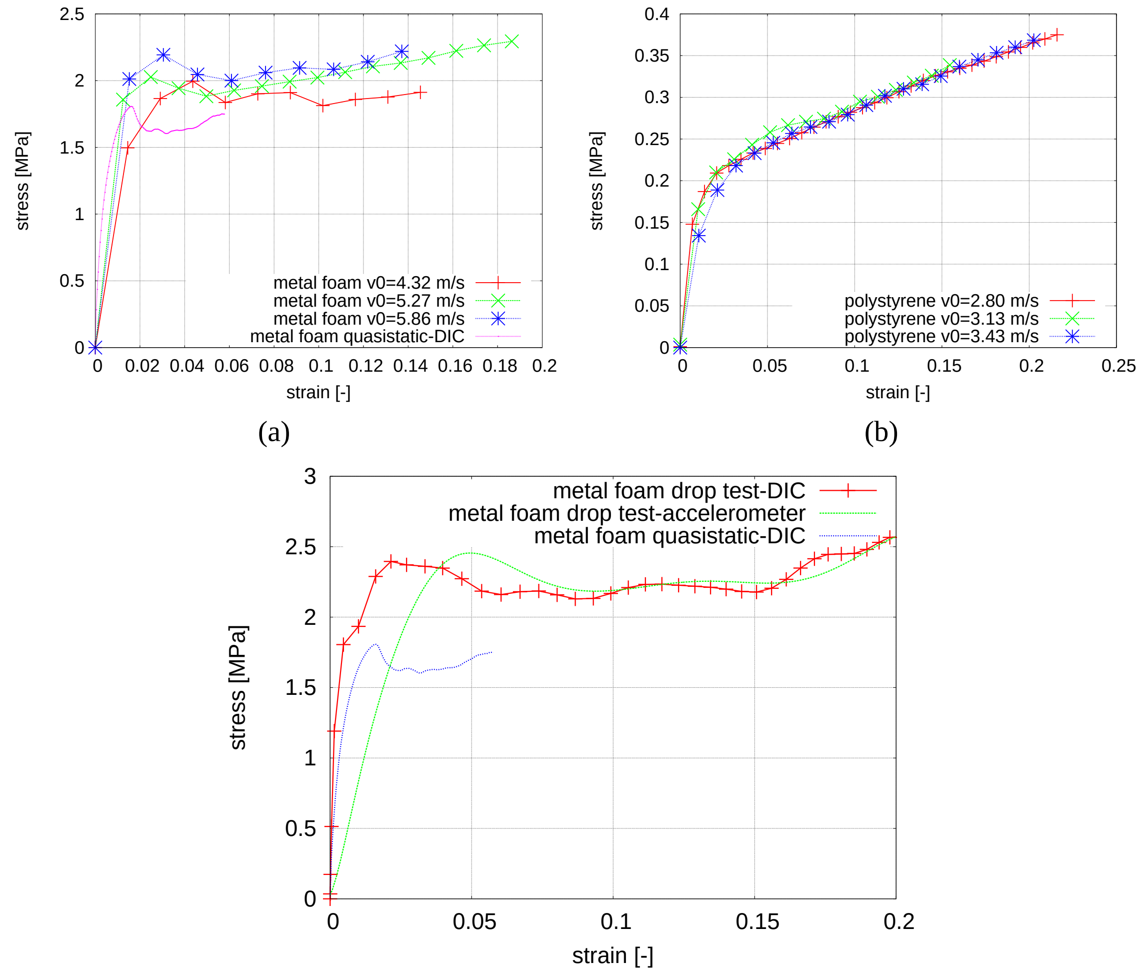

Figure 4: Calculated stress-strain curves (average curve of 3 measurements for each impact velocity) based on DIC method (a and c) Alporas, (b) polystyrene at various impact speeds. Stress-strain curve (c) was calculated based on images captured with 10.000 fps sampling rate.

In contrast, it was possible to perform one drop test with a high-end high-speed camera (FASTCAM SA5, Photron, Japan) which allows to sample images with 10.000 fps rate (approximately 3$\times$ larger than in case of IDT NX3) with sufficient ROI. Larger sampling rate obviously leads to more precise description of the linear phase of the stress-strain curve (see Fig. 4 c) and evaluated elastic modulus (E_{DIC} =0.951 GPa) was relatively close to the value obtained from quasi-static tests.

4 Conclusions

In this work the characteristics of metal foam and polystyrene samples under high-strain rate loading were investigated. True stress-strain curves were calculated using two approaches: (i) double integration of measured acceleration and (ii) using DIC technique. Elastic properties obtained from double integration approach were significantly lower (reasons have been discussed above). However, the plastic flow was reliably measured by this technique. For reliable assessment of elasto-plastic properties the DIC should be preferred for strain evaluation because this method is insensitive to improper boundary conditions. Although image data were captured by high-speed camera the maximal sampling rate (3280 fps) was unable to capture sufficient number of images in elastic region of the stress-strain diagram. Thus, for pure determination of elastic properties it is necessary to use a camera with frame rate higher than 10.000 fps (for a strain rate similar as in our tests). Stress-strain curves evaluated from images with lower fps can be used for description of flow plateau only. Despite the fact that elastic properties were not accurately measured, the stress-strain functions can be used for further analysis (e.q. numerical modelling) because elastic part can be replaced by the stress-strain curve taken from quasi-static testing. There is no reason to assume that the elastic properties are strain-rate dependent.

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