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ENERGY ABSORPTION OF CELLULAR FOAMS IN HIGH STRAIN RATE COMPRESSION TEST

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Abstract: *Aluminum foams are structural materials with excellent energy absorption capacity jointed with very low specific weight and high stiffness. Products of aluminum foams are used in a wide range of structural and functional applications (e.g. as a part of composite protection elements) due to its attractive properties. Full characterization of deformation behaviour under high-strain rate loading is required for designing these applications. The aim of this study is to compare stress-strain behaviour and energy absorption of the aluminium foam structure with conventional energy absorbing materials based on polystyrene and extruded polystyrene commonly used as protective elements. The compressive deformation behaviour of the materials was assessed under impact loading conditions using a drop tower experimental device.*

Keywords: Impact test, Energy absorption, Alporas, Polystyrene, Extruded polystyrene.

1. Introduction

In recent years there has been a significant increase of interest in products made of aluminum foams. Due to their exceptional mechanical and physical properties, they are used in a wide range of industries, ranging from automotive (e.g. bumpers) to building industry (e.g. sound proofing panels). This highly porous material is characterized by closed cellular structure with large pores (~1-13 mm in diameter) and very thin cell walls (~0.1 mm). Mechanical properties of aluminum alloys foam in quasi-static conditions (such as compressive strength, tensile strength and elastic modulus) have been extensively studied and reviewed by many authors (Paul et al., 2000; Gibson et al., 1997; Koudelka et al., 2012). The foam has a long and well-defined phase of plastic straining stress-strain diagram under compression (Gibson et al., 1997), which is recognized by the "plateau stress" and densification strain in the stress-strain diagram (Gibson et al., 1997). This plateau region is responsible for a high ability of the material to absorb deformation energy, which can be used also for the construction of composite protective devices such as motorcycle and bicycle helmets (Pinnoji et al., 2010). For such a use, it is necessary to know an exact deformation behavior of the foam and accurately evaluate energy dissipation under the high strain rate loading. Mechanical properties of aluminum alloy foams in quasi-static conditions (such as compressive strength, tensile strength and elastic modulus) have been extensively studied and reviewed (Paul et al., 2000; Gibson et al., 1997; Koudelka et al., 2012).

The most widely used technique to investigate material behavior at different high strain rates is a split Hopkinson pressure bar (SHPB) (Ma et al., 2009; Yi et al., 2001; Shen et al., 2010). Some authors (Shen et al., 2010; Paul et al., 2000) dealt with the strain rate effect on the energy dissipation capacity of an aluminum foam. These studies showed that the energy dissipation capacity of the foam significantly

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increases with the increasing strain rate. However, studies on the deformation behavior of aluminum foams with direct impact loading (with the strain rate not constant) are rare (Merrett et al., 2013).

The objective of the presented research was to perform an experimental investigation of the deformation behaviour and energy absorption capacity of commercially produced aluminum alloy Alporas (Shinko Wire Ltd., Japan) under impact loading conditions using a drop tower experimental device and to compare the characteristics with the behaviour of widely used protective materials like plain and extruded polystyrene in the same testing conditions.

2. Experimental Methods

Three types of energy absorbing materials were used for testing and evaluation - closed-cell aluminum foam Alporas (Shinko Wire Ltd., Japan) with the mass density of 260±15 kg/m^3, polystyrene EPS 200 S with the mass density ~30 kg/m^3 and extruded polystyrene foam Styrodur ROOFMATE SL-A with the mass density ~33 kg/m^3. The density of Alporas was detected by weighing of samples with the known volume assuming the density of walls to be equal to pure aluminum (2700 kg/m^3). An example of the test samples is shown in Fig. 1. Morphological features and detailed microstructural description of the Alporas samples have been previously studied by the authors and can be found in (Němeček et al., 2013). Rectangular specimens having 60×60 mm^2 cross-sectional dimensions and thickness 40 mm for polystyrene and extruded polystyrene and 35 mm for Alporas were cut from larger material blocks.

Fig. 1: Samples for impact tests – polystyrene, extruded polystyrene foam, Alporas foam (left to right).

Impact tests were conducted using a drop tower experimental device. This drop-weight rig can be used to generate impact velocities up to 5.4 m/s. A sledge with impactor is guided during free fall by rollers on three rails. The rig is equipped by triaxial accelerometer (EGCS3, Measurement Specialties, USA) and high speed camera (NX3, Integrated Design Tools, Inc., USA) to capture deformation of the sample. A photograph of the experimental setup is shown in Fig. 2. Specimens were placed on the bottom compression plate and the impactor was positioned at a defined distance from the top of the sample to achieve the required impact velocity. Sample was fixed on the bottom platen to avoid any possible slip of the specimen. The total mass of the impactor used in this study was 5020 g and the potential energies related to the top surface of the specimens were 16.5 J (for impact velocity 2.5 m/s) and 30.8 J (for impact velocity 3.5 m/s). Each specimen was impacted only once.

Fig. 2: Photograph of the experimental set up for impact tests.

3. Results and Discussions

The acceleration of the impactor was recorded in time during its drop. An average displacement of the top sample surface and compression force were calculated from the acceleration. Overall engineering strain in the sample was assessed taking into account the sample height. Finally, the engineering stress-strain curve was constructed as shown in Fig. 3. Three tests were conducted for each material. The compressive stress–strain curve of Alporas foam, either quasi-static or dynamic one, exhibits three deformation regions (Yi et al., 2001): an initial linear-elastic response; an extended plateau region with a nearly constant flow stress and a final densification region in which the cells collapse and are compacted together. The final region is not present in our stress-strain curves due to an insufficient impact velocity. Polystyrene and Styrodur are characterized by similar qualitative behaviour to Alporas (Fig. 3).

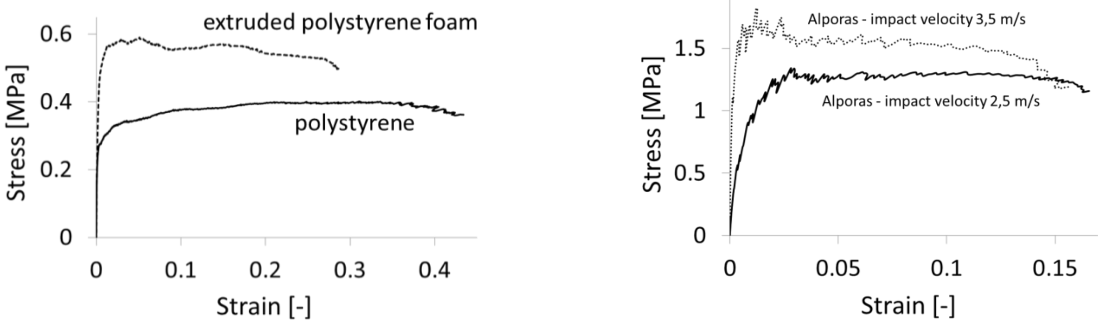


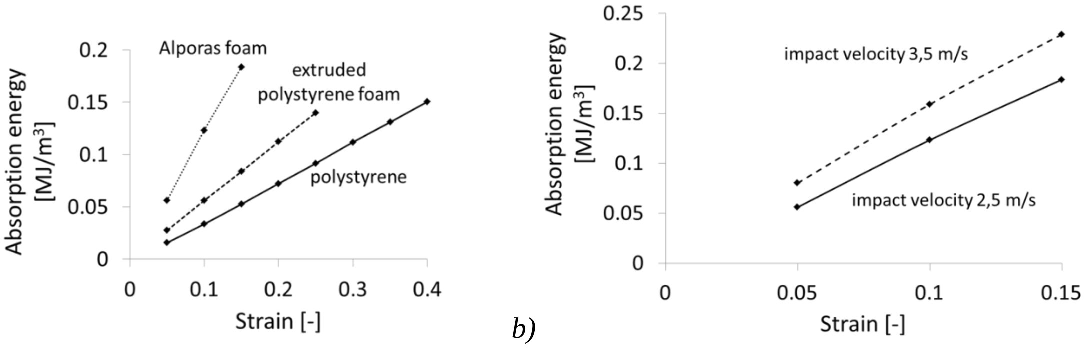
Fig. 3: Dynamic compressive stress-strain curve of tested samples.

Fig. 3 also shows large differences in yield stress for the studied samples. This difference is quite large for polystyrene and extruded polystyrene foam (impact velocity 2.5 m/s) in contrast to small difference in their mass densities. In the case of Alporas foam, which was measured at two impact velocities, the yield stress is (as expected) much higher. It also increases with the impact velocity. Fig. 3 further shows that linear elastic part of the stress-strain diagram only appears at very low strains for the studied cases (smaller than about 0.001).

The energy absorption capacity is defined as the energy necessary to deform a given specimen volume to a specified strain. The absorption energy per unit volume of a sample up to a strain ε_0 can be evaluated by integrating the area under the stress–strain curve as follows:

$$W = \int_0^{\varepsilon_0} \sigma(\varepsilon) d\varepsilon \qquad (1)$$

Fig. 4 and Tab. 1 show the absorption energy for different tested material at compression strains of 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35 and 0.40 and at different strain rates.



a) *b)*

Fig. 4: Absorption energy for: a) Impact velocity 2.5 m/s and b) Alporas foam at two different impact velocities.

The experimental results show that the yield stress of Alporas foam increases with the impact velocity, so the area under the stress–strain curve also increases. The difference between the absorbed energy of Alporas foam with impact velocity 2.5 m/s against impact velocity 3.5 m/s is about 24% for strain 0.15 for the respective averages (Tab. 1). Mean values of the energies fluctuated within approx. 10% between the samples of the same category and are summarized in Tab. 1. The difference in the obtained energies points out the importance of the impact velocity which has to be known when designing the protective foam layers in a specific application.

Tab. 1: Absorbed energy (mean values) of tested samples at different strains [MJ/m³].

Type of material	Impact velocity	Strain							
	[m/s]	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4
Polystyrene	2.5	0.016	0.034	0.053	0.072	0.092	0.112	0.131	0.151
Styrodur		0.027	0.056	0.084	0.112	0.140			
Alporas		0.056	0.123	0.184					
Alporas	3.5	0.080	0.159	0.229					

4. Conclusion

Dynamic impact tests were performed for three types of energy absorbing materials (Alporas, polystyrene and extruded polystyrene foams) using a drop tower experiment device. The energy absorption capacity was evaluated for all materials. Two impact velocities (2.5 and 3.5 m/s) were tested in the case of Alporas. The dynamic compressive stress-strain curves of the materials were determined from the record of acceleration. Both yield stress and the absorbed energy of Alporas increased with increasing impact velocity and it was significantly larger than in the case of polystyrene and extruded polystyrene (tested for impact velocity of 2.5 m/s). Interestingly, the yield stress of extruded polystyrene foam was also significantly larger than for polystyrene even if there is a small difference in their mass densities.

It was proven by the presented investigations that the Alporas foam can absorb significantly higher energies compared to conventional materials and its behaviour at high impact velocities can be very useful for designing new impact protective devices.

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