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# PROPERTIES OF POLYMER-FILLED ALUMINIUM FOAMS UNDER MODERATE STRAIN-RATE LOADING CONDITIONS

## LASTNOSTI ALUMINIJEVIH PEN, NAPOLNJENIH S POLIMERNIMI MATERIALI, PRI ZMERNIH OBREMENITVAH

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This paper deals with an experimental study of deformation response of open-cell aluminium foams under a moderate strain-rate compressive loading. Generally, porous metals show a promising potential in energy-absorption applications. However, the low strength of open-cell metal foams is a limiting parameter for such applications. Furthermore, the strain-rate sensitivity of mechanical properties is typically observed in closed-cell metal foams. On the other hand, open-cell foams provide a better control over the morphological parameters of a cellular structure. To enhance the properties of an open-cell microstructure an aluminium open-cell foam cured with polymeric filling was comparatively tested against the deformation-energy-absorption capabilities of the 'as-delivered' foam under a moderate strain-rate compressive loading. Prismatic samples with square cross-sections were prepared from the open-cell aluminium foam and a selected set of the samples was then filled with the thixotropic polyurethane putty. The specimens were tested with quasi-static compression, using a custom drop tower at several levels of the impact energy. The drop tests were instrumented with a tri-axial accelerometer and a high-speed camera to measure the mechanical response and the strain evolution during the impact. The comparison of the quasi-static behaviour with the results of the dynamic tests showed insignificant changes in the deformation curves in the case of the 'as-delivered' open-cell foam and an increasing energy-absorption capacity in the case of the samples equipped with the polymeric filling.

Keywords: interpenetrating-phase composite, compression, aluminium foam, polyurethane, moderate strain-rate loading

Članek opisuje eksperimentalno študijo o deformacijskem odzivu odprtoceličnih aluminijevih pen pri zmernih kompresijskih obremenitvah. Kovinske pene so obetajoč potencial pri absorpciji energije. Kljub temu manjša moč kovinske pene deluje omejujoče pri tovrstnih aplikacijah, obremenitvena občutljivost pa je pretežno opazovana pri zaprtoceličnih kovinskih penah. Po drugi strani pa odprtocelične pene omogočajo boljši nadzor nad morfološkimi parametri celične strukture. Da bi izboljšali lastnosti odprtoceličnih kovinskih pen, smo preizkusili polimerna polnila skupaj s peno. Primerjalna raziskava vzorcev odprtoceličnih aluminijevih pen je potekala v dveh skupinah: (i) 'kot dobavljeno' in (ii) polnjena s poliuretanskim polnilom. Iz odprtocelične aluminijeve pene smo pripravili romboedrske vzorce s kvadratnim prerezom. Druga skupina vzorcev je bila nato opremljena s tiksotropičnim poliuretanskim kitom. Vzorce smo preizkusili s kvazistatično kompresijo in z uporabo naključnega stolpa za padanje pri različnih stopnjah udarne energije. Preizkus padanja je bil omogočen s triosnim pospeševalnikom in kamero pri visoki hitrosti, ta pa je izmerila mehanski odziv razvoja obremenitve med udarcem. Primerjava kvazistatičnega vedenja z rezultati dinamičnega preizkusa je pokazala neznačilne spremembe deformacijskih krivulj v primeru odprtocelične pene, označene 'kot dobavljeno,' in povečano zmogljivost absorpcije energije v primeru vzorcev, ki so bili polnjeni s polimernim polnilom.

Ključne besede: kompozit z interpenetracijskimi fazami, stiskanje, aluminijeva pena, poliuretan, obremenjevanje z zmerno hitrostjo

## 1 INTRODUCTION

In the recent years, metal foams have been of renewed interest, particularly in the transport industry[1]. This interest led to an improvement in the production of metal foams that can be nowadays produced with many manufacturing techniques showing quite different results in the final product quality measured, e.g., the quality of the pore shape and size, the cell shape and wall thickness.

Structurally optimized cellular materials filled with a material sensitive to the strain rate[2,3] which form interpenetrating-phase composites (IPCs) have a broad range of applications ranging from lightweight crash-safe cars to structural protection against ballistic impact from projectiles or blast protection from explosives. The influence of design parameters[4,5] (volume fraction of the polymeric filling, pore size, wall thickness or pore shape and connectivity) on the resulting material properties and energy-absorption capability still limits the applicability of this prospective material in various industries.

Dynamic impact response of IPCs is a key parameter in the applications of a material where shock resistance in impact loading is required. One of the experimental methods used to measure the energy absorbed in a material during impact loading is a drop test. This test, in which a dead weight is dropped onto a sample from predefined heights to load the sample with a predefined energy, is suitable for moderate strain rates depending on the drop height and weight of the impactor. The results of these tests are essential for the development of the strain-rate-sensitive constitutive models for numerical modelling using, e.g., the finite-element (FE) method. A thorough validation of the material parameters of these constitutive models is required for a successful application of FE simulations in the later analysis, design and verification.

## 2 MATERIALS AND METHODS

### *2.1 Specimen preparation*

In the experimental study an open-cell aluminium foam manufactured using the EN-AW-6101 aluminium alloy was tested. According to the data provided by the manufacturer of the foam the porosity reaches approximately 93 % with the pore size corresponding to 6.3 $cm^{-1}$ (16 ppi, pores per inch). The cells are of a dodecahedral shape with the typical cell-edge thickness from 0.35 mm to 0.50 mm.

For a comparative study two groups of samples were prepared. Prismatic samples with dimensions of 50 mm × 30 mm × 30 mm were cut from the delivered slabs of the foam. One set of the samples was kept in the 'as-delivered' state while the second group was filled with one-component thixotropic polyurethane putty to form an IPC with the strain-rate-sensitive mechanical behaviour. A comparison between the plain aluminium foam and the filled structure is depicted in **Figure 1**.

In order to enable an optical strain evaluation one face of each sample was polished and sprayed using granite paint to create a random pattern for automatic displacement tracking.

### *2.2 Quasi-static tests*

Quasi-static compression tests were performed in a custom uniaxial loading frame with a loading capacity of 2 kN. The loading tests were displacement driven and the final displacement corresponded to a strain of 0.25–0.35. The loading rate set at 20 μm $s^{-1}$ corresponded to the strain rate of $4 \cdot 10^{-4}$ $s^{-1}$. Based on the results of the quasi-static compression, the amount of the absorbed energy was estimated in order to set an appropriate impact velocity for the low-energy impact tests. For the displacement tracking the loading scene was captured by a CCD camera (Manta G504B, Allied Vision Technologies, GmbH, Germany) attached to bi-telecentric lens (TCZR 072, Opto Engineering, Italy). A custom read-out software based on OpenCV library[6] was used for the image acquisition. The resolution of the acquired image data was 2452 px × 2056 px and the frame rate was 2 $s^{-1}$ (frames per second, fps).

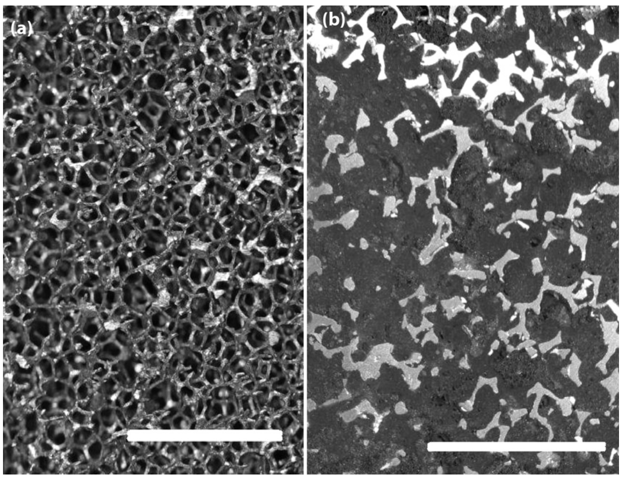


**Figure 1:** Open-cell aluminium foam: a) plain and b) filled with polyurethane. Scale bars correspond to 10 mm.
**Slika 1:** Odprtocelična aluminijeva pena: a) navadna in b) polnjena s poliuretanom. Dolžina črte ustreza 10 mm.

### *2.3 Low-energy impact tests*

Low-energy compressive-impact tests were performed using our laboratory drop tower (**Figure 2**). Stress values were computed from the accelerograms acquired with a tri-axial accelerometer (EGCS3, Measurement Specialties, USA) connected to the read-out electronics (9234, National Instruments Corporation, USA) with a sampling rate of $51.2 \cdot 10^3$ $s^{-1}$. The strain was measured optically using a high-speed CMOS camera (NX3, Integrated Design Tools, Inc., USA). The frame rate was 4770 $s^{-1}$ and the resolution of the acquired images was 536 px × 896 px. The exposure time for the 'as-delivered' group and for the IPC specimens was 49 μs and 19 μs, respectively. A longer exposure time was required due to a higher diaphragm number, which enabled us to extend the depth of the field for the open cellular structure.

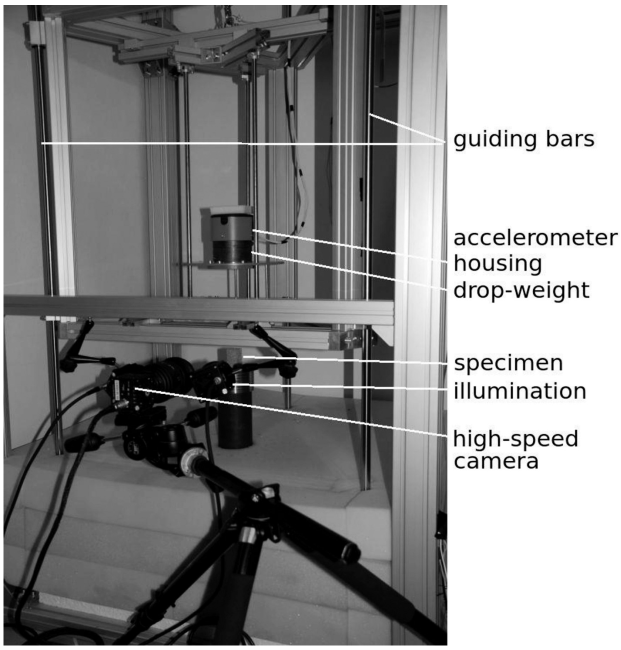


**Figure 2:** Drop tower and high-speed camera set-up
**Slika 2:** Nastavitev stolpa padanja in visokohitrostne kamere

For both the 'as delivered' and IPC specimens, the impact tests at three initial height levels were used: i) 600 mm and ii) 1000 mm. Additionally, the initial heights of iii) 1400 mm and iv) 1750 mm were used for the impact test of the filled specimen. The strain rates corresponding to the used hammer heights were (68.6, 88.6, 104.8 and 117.2) $s^{-1}$, respectively. The drop mass was 6504.57 g.

### *2.4 Strain measurement*

For both the quasi-static compression and low-energy impact tests, an optical strain measurement was used. In the first image of the captured sequence tracking features were selected and arranged in two horizontal lines in the lower and upper parts of a specimen. Using a custom digital-image correlation software[7] based on the Lucas-Kanade tracking algorithm[8] displacement paths were tracked. During the tracking procedure the neighbourhood of each tracking feature is searched for the highest correlation coefficient in the subsequent image. From the tracked displacements the logarithmic strain was computed.

## 3 RESULTS AND DISCUSSION

From both the quasi-static and moderate strain-rate compression tests, stress-strain diagrams were obtained. The stress-strain curves are depicted in **Figure 3** (the plain open-cell foam) and **Figure 4** (the IPC). The stress-strain curves of the 'as-delivered' foam exhibit the deformation behaviour of a typical cellular metal. The initial linear elastic part is followed by a constant stress-plateau region caused by a collapse of the cell edges during the compression. Since the cell edges in the entire microstructure collapse gradually, the stress plateau exhibits an insignificant scatter. As expected, the stress plateau is similar in both the quasi-static and dynamic loading.

The deformation curves for the IPC samples showed linear behaviour up to the stress level similar to the stress plateau of the plain foam, followed by an apparent deformation of the polymeric filling represented by a gradual increase in the stress in the compaction region. The amount of the deformation energy absorbed during the loading by the IPC samples increased in the non-zero strain-rate tests showing that such a material exhibits strain-rate-dependent mechanical characteristics.

From the stress-strain curves of the compression tests, the deformation energy absorbed in a sample was determined. To enable a comparison among all the groups of the specimens and levels of the strain rates, only the deformation curves up to 21 % were considered. The comparison is presented in **Table 1**.

**Table 1:** Comparison of absorbed deformation energies
**Tabela 1:** Primerjava absorbirane energije deformacije

| | Strain-energy density ($J cm^{-3}$) |
|---|---|
| Open-cell foam; quasi-static test | 0.339 ± 0.014 |
| Open-cell foam; drop test | 0.327 ± 0.043 |
| IPC; quasi-static test | 0.452 ± 0.051 |
| IPC; drop test | 0.711 ± 0.078 |

## 4 CONCLUSIONS

A comparative study on the strain-rate effects of the polymeric filling in an open-cell aluminium foam was performed. Deformation behaviour was assessed with quasi-static and moderate strain-rate compression tests. The results showed an increase in the absorbed impact energy in the case of the IPC, while the impact energy absorbed by the plain aluminium foam remains un-

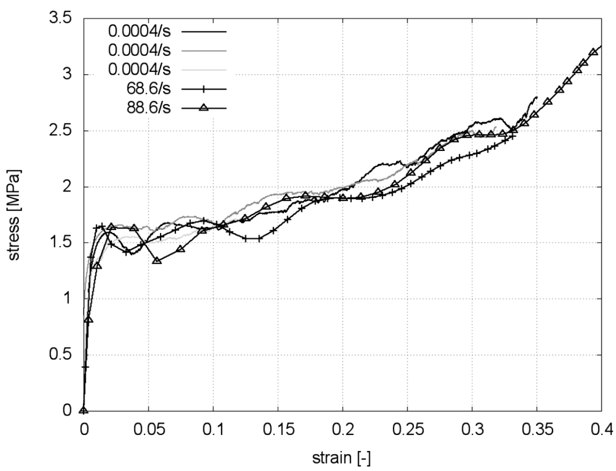


**Figure 3:** Stress-strain diagrams of open-cell aluminium foam – comparison of quasi-static and dynamic loading tests
**Slika 3:** Obremenitveni diagrami odprtocelične aluminijeve pene – primerjava kvazistatične obremenitve in dinamičnih preizkusov obremenitve

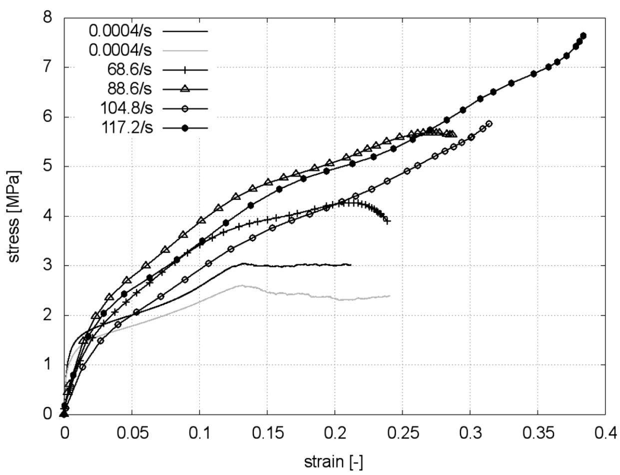


**Figure 4:** Stress-strain diagrams of open-cell aluminium foam filled with thixotropic polyurethane putty – comparison of quasi-static and dynamic loading tests
**Slika 4:** Obremenitveni diagrami odprtocelične aluminijeve pene, napolnjene s tiksotropičnim poliuretanskim kitom – primerjava kvazistatične obremenitve in dinamičnih preizkusov obremenitve

changed at the increasing strain rates. According to the comparison, the deformation energy absorbed by the IPC showed a 57 % increase at higher strain rates, while in case of the unfilled foam the deformation energy remained unchanged. We can conclude that to exploit the strain-rate-sensitive nature of the IPC, the density of the filling material should be optimized in order to improve its strength-to-mass ratio. In order to describe the strain-rate-dependent behaviour in a wider range of strain rates, the drop tower is not sufficient and a different technique, e.g., the Split-Hopkinson pressure bar should be employed in further investigations.

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