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DETERMINATION OF ELASTIC-PLASTIC PROPERTIES OF ALPORAS FOAM AT THE CELL-WALL LEVEL USING MICROSCALE-CANTILEVER BENDING TESTS

DOLOČANJE ELASTIČNIH IN PLASTIČNIH LASTNOSTI PENE ALPORAS NA RAVNI CELIČNE STENE Z UPOGIBNIMI PREIZKUSI Z MIKROSKOPSKO IGLO

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The presented paper is focused on determining the mechanical properties of the Alporas closed-cell aluminium foam. To utilise the favourable properties of cellular metals (e.g., high strength-weight ratio, energy absorption or insulation capabilities) a detailed description of the mechanical properties is required. Cellular metals exhibit heterogeneity at several scale levels. The contribution of the internal structure to the overall mechanical properties may not be in detail evaluated utilizing only the macroscopic testing. On the other hand, the compact material of cell walls is influenced by its composition (titanium- and calcium-rich regions are present in aluminium). Therefore, localised testing techniques with a small region of interest (e.g., indentation methods) may neglect the inhomogeneity along the cell walls. Hence, a testing of isolated cell walls was performed. A custom-developed modular loading device (based on precise linear bearing stages) was assembled to enable cantilever bending tests. The load was applied with a stepper motor and the loading force was measured with a micro-scale load cell with a loading capacity of 2.25 N. Displacements of the samples were measured optically. Several points along the longitudinal axis of a sample were tracked using the Lucas-Kanade tracking algorithm and the obtained displacements were compared to the analytically prescribed deflection curve. Based on the obtained deflections and measured forces, a stress-strain diagram was constructed and the constants of the elastic-plastic material model were evaluated.

Keywords: aluminium foam, cantilever bending, micromechanics, optical strain measurement

Članek obravnava določanje mehanskih lastnosti aluminijaste pene Alporas z zaprtimi porami. Za uporabo ugodnih lastnosti celičnih kovinskih materialov (npr. visoko razmerje med trdnostjo in maso, absorpcija energije ali izolacijske zmožnosti), je potrebeno poznati mehanske lastnosti. Celični materiali kažejo heterogenost, če jih opazujemo pri različnih merilih velikosti. Podrobna ocena notranje zgradbe in njen prispevek k mehanskim lastnostim ni mogoč zgolj z uporabo makroskopskega preizkušanja. Po drugi strani pa zgradba vpliva na kompakten material celičnih sten (v aluminiju je mogoče najti področja, ki so bogata s titanom in kalcijem). Zato je mogoče, da preveč lokalizirano preizkušanje (npr. metoda za določanje trdote) zanemari nehomogena področja na stenah celic. Zato je bilo izvršeno preizkušanje posamezne celične stene. Sestavljena je bila modularna obremenitvena naprava, ki omogoča natančne stopnje linearne obremenitve, da so mogoči upogibni preizkusi z mikroskopsko iglo. Vzorec je bil obremenjen s koračnim motorjem, pri čemer je bila sila obremenitve izmerjena z mikroskopsko merilno celico z nosilnostjo 2,25 N. Premik vzorcev je bil izmerjen optično. Nekaj točk ob vzdolžni osi vzorca je bilo spremljano s sledilnim algoritmom Lucas-Kanade, ugotovljeni premiki pa so bili primerjani z analitično določeno krivuljo deformacije. Na podlagi ugotovljenih deformacij in izmerjenih sil je bil postavljen diagram odvisnosti med obremenitvijo in deformacijo. Ocenjene so bile konstante elastično-plastičnega modela materiala.

Ključne besede: aluminijska pena, upogibanje igle, mikromehanika, optično merjenje deformacije

1 INTRODUCTION

Aluminum foams are lightweight materials with a favourable combination of mechanical properties, e. g., a high strength-to-weight ratio. This material, widely used in damping applications as an impact-energy absorbent and as a thermal or acoustic insulation, was studied in detail at the macroscopic level[1,2]. Moreover, models for predicting the macroscopic deformation behaviour were developed[3].

To enable the exploitation of the favourable properties of aluminium foams for structural applications, a detailed description of their deformation behaviour is required. Due to complex inner structures of closed-cell foams, exhibiting a significant inhomogeneity at the cellular level[4] (in terms of the size and shape of the cells as well as the thickness of cell walls), an analysis of the deformation response of a cellular structure requires a complex mathematical description and modelling. The numerical models of metal foams have to reflect both the geometry of the cellular structure and the mechanical properties of the base material.

Since the cell-wall material contains residuals of the foaming agents (calcium and titanium) and micropores are present after the foaming process, the mechanical properties should not be measured solely with direct localized measurement techniques (e.g., the nanoindentation where the measured properties have to be processed with a homogenization procedure[5]).

To provide a more complex description of the foam's deformation response a microstructural numerical model of a representative volume element was developed in our recent study based on X-ray imaging and tomographic reconstruction[6]. However, the parameters of the constitutive material model that was necessary in the finite-element simulation have to take into consideration also the material properties at the level of cell walls.

In this study, a micromechanical testing methodology was employed to determine the mechanical properties of the base material of the Alporas aluminium foam. A cantilever arrangement of the loading test was used to ensure a simple description of the boundary conditions for both analytical and numerical evaluations of the experiments.

2 MATERIALS AND METHODS

2.1 Specimen preparation

The specimens were prepared from the Alporas closed-cell aluminium foam (Shinko Wire, Inc, Japan). Flat cell walls were identified in the cellular structure. The cells containing such walls were carefully extracted using a hand-operated micro-lathe (Dremel FortiFlex, Bosch GmbH, Germany). To protect the base cell-wall material against a plastic deformation the specimens were embedded into rosin (with a high purity and transparency and a melting point not exceeding 80 °C) during every distinct step of the preparation procedure. A specimen's shape was finalized by precise grinding and polishing using an oscillation grinding machine, TegraPol (Struers, A/S, Denmark).

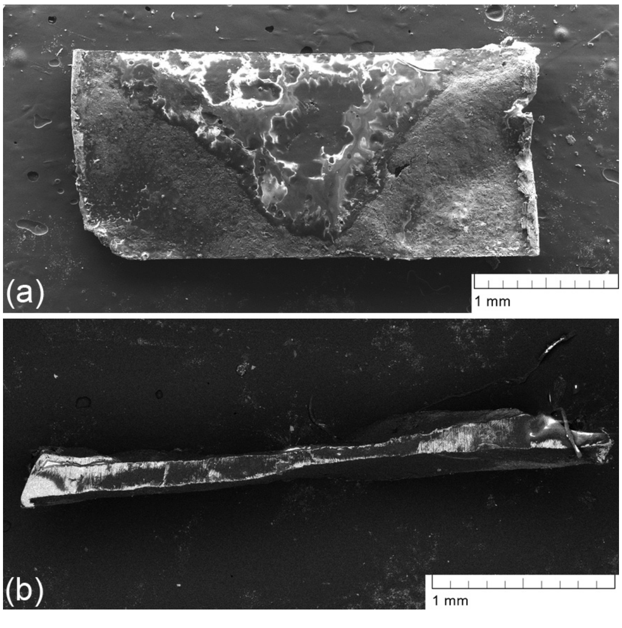

Figure 1: a) Specimen extracted from the cellular structure of Alporas aluminium foam, b) cross-section (SEM)

Slika 1: a) Vzorec, izrezan iz celične stene aluminijske pene Alporas, b) prečni prerez (SEM)

2.2 Sample-volume description

To determine the geometrical characteristics required for evaluating the bending tests (i.e., the distance between the clamp and the loading point and the cross-sectional characteristics) a set of projections of each specimen was acquired with a scanning electron microscope (SEM) (Mira II, Tescan, s. r. o., Czech Republic). Since the specimens had a metallic nature, the secondary electron probe was employed for the scanning. The obtained projections provided a resolution of 2 μm per pixel. For each specimen three projections were acquired, a floor plan (normal to the loading direction, **Figure 1a**) and two longitudinal faces (parallel to the in-plane loading, **Figure 1b**). A volumetric model of each specimen was developed using a custom-assembled image-processing procedure developed in the language of computational environment MatLab (Mathworks, Inc., USA).

2.3 Experimental set-up

For the loading test an in-house loading set-up was designed and assembled. The set-up was based on linear bearing stages (Standa Ltd, Lithuania) with a resolution of 1 μm and a travel range of up to 50 mm. The motion of the loading point was provided with a precise linear bearing stage, UMR 9.0 (Newport, Ltd, USA) with a resolution of 0.1 μm and a travel range of 5 mm, which was driven by a stepper motor (Microcon, s. r. o., Czech Republic). The reaction force at the loading point was measured with a miniature load cell in the cantilever arrangement (FPB350, Futek Inc., USA) with a loading capacity of 2.25 N and a read-out unit, OM911 (Orbit Merret, s. r. o., Czech Republic) with a sampling rate of

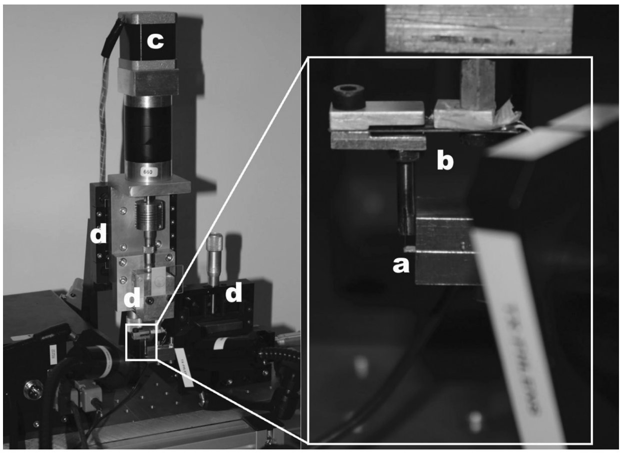

Figure 2: Experimental set-up for micro-scale loading tests: a) specimen, b) load cell, c) stepper motor, d) linear bearing stages

Slika 2: Eksperimentalni sestav za preizkuse obremenitve na mikroskopski ravni: a) vzorec, b) merilna celica, c) koračni motor, d) nastavljanje linearnih obremenitev

100 Hz. A detailed description of the loading set-up is depicted in **Figure 2**.

2.4 Loading procedure

The loading was performed in the cantilever arrangement in order to overcome the issues of low stiffness of the supports and the eccentricity of the loading point that occurred during our previous studies where the three-point bending arrangement was used. The clamp was implemented by placing a specimen between two prisms connected together with a pair of screws (**Figure 2**).

The loading tests were displacement controlled. The synchronization of the loading and force logs was ensured with the custom software based on an open-source LinuxCNC project and real-time Linux kernel. The loading rate was set to 1 μm s^{-1}.

2.5 Strain measurement

Due to a high compliance of the load cell (even higher than the deflection of the loaded point of a specimen) the strain could not be determined directly from the displacement prescribed by the linear bearing stage. Instead, the displacements were measured optically from a set of projections of the loading scene captured with a CCD camera (Manta G504B, Allied Vision Technologies, GmbH, Germany) with a resolution of 2452 px × 2056 px attached to a light microscope (Navitar Imaging, Inc., USA) that provided a magnification of up to 24×. The acquisition of the projections was controlled by in-house-built software based on the OpenCV[7] (Open Source Computer Vision) library and Python programming language. The acquisition rate of the camera was 2 fps, which enabled an identification of a sufficient number of points on the force-displacement curve. A selected loading scene is depicted in **Figure 3**.

2.6 Strain-stress curve evaluation

From the sets of projections, displacements were determined using a digital-image-correlation (DIC) software tool[8] based on the Lucas-Kanade tracking algorithm[9]. The points on the specimens' surfaces were selected along their longitudinal axes and the displacements of each point were tracked by searching for the highest correlation coefficient between the two consequent projections.

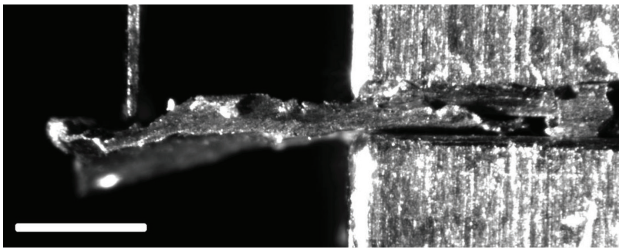

Figure 3: Loading scene of a clamped specimen (image acquired with a CCD camera and light microscope, the bar corresponds to 1 mm)
Slika 3: Obremenjen vzorec (posnetek narejen s CCD-kamero, dolžina traku ustreza 1 mm)

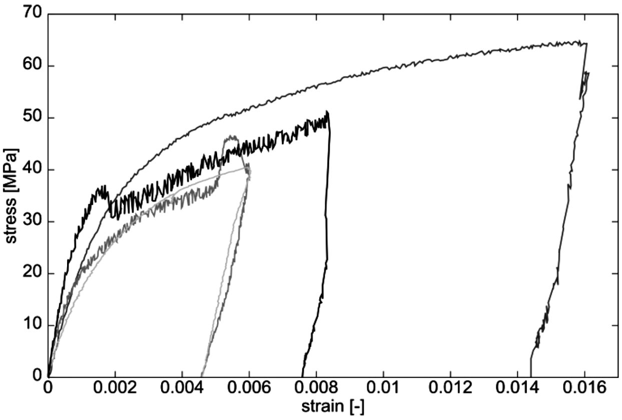

Figure 4: Stress-strain curves of the tested specimens
Slika 4: Krivulje napetost – raztezek preizkušanih vzorcev

The engineering stress (σ) and strain (ε) values were determined from the geometrical properties of a tested specimen and optically measured displacements of the loading point using Equations (1) and (2):

$$\varepsilon = \frac{3uh}{2l^2} \quad (1)$$

$$\sigma = \frac{Flh}{2I_Z} \quad (2)$$

Here u denotes the displacement of the loading tip, h is the height of a specimen, F is the loading force, l is the distance between the clamp and the loading point and I_Z is the axial quadratic moment of inertia of the loaded cross-section. From the slope of the unloading phase, the Young's modulus was determined and the yield point was estimated using the offset method at a 0.2 % strain level.

3 RESULTS AND DISCUSSION

Deformation behaviour of the isolated cell walls was described using micro-scale cantilever measurements. The obtained stress-strain curves are presented in **Figure 4** (selected curves only). The curves exhibit similar slopes in their initial parts as well as in their unloading phases. Different portions of the plastic strain are caused by the non-uniformity in the specimens' dimensions due to a highly irregular geometrical arrangement of the cellular structure. The obtained values of the Young's modulus are (36.7 ± 5.23) GPa, the yield stress reached (39.0 ± 9.7) MPa and the yield strain reached (0.279 ± 0.044) %.

4 CONCLUSIONS

Based on a series of the cantilever bending tests of the isolated cell walls of the Alporas aluminium foam elastic and plastic mechanical properties were determined. The obtained results scatter slightly among the measured sets, which might be caused by a highly irregular nature of the tested material in terms of its geometrical arrangement. This issue may be overcome using an inverse numerical evaluation of the measured results in conjunction with the precise geometrical models obtained with the X-ray tomography.

The obtained results may serve as the parameters for the constitutive material models for microstructural numerical models. The conjunction of the material properties of the foam's base material and the microstructural models (e. g., developed by X-ray computed micro-tomography) will provide a more detailed description of the mechanical behaviour of the metal foam.

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