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Compression of Open-Cell Aluminium

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The paper presents compression test results of self-made open-cell aluminium which was produced by the investment casting method. Two groups of samples were studied: prototype samples containing some structural imperfections (apparent density 0.485 g/cm^3) and regular samples without visible mistakes (apparent density 0.312 g/cm^3). Performed experimental research covered quasi-static compression tests with one hysteresis loop. Based on experimental results, new measures to help material characterisation were proposed: instant and average loop secant gradients ($E^{**}_{\text{inst.sec}}$ and $E^{**}_{\text{av.inst.sec}}$) and average linear loop gradient ($E^{**}_{\text{av.lin}}$).

Key words: open-cell aluminium, compression test, loop gradient.

1. INTRODUCTION

Porous metals are a wide class of materials, constantly developing and finding new applications – from automotive and aircraft industry, through biological implants to space engineering or, finally, military use (*e.g.* [1–3]). Features, which guarantee such a broad scope of applications, are, among others: small weight of the materials combined with relatively good structural properties, high impact energy absorption capacity and large specific surface with conductive properties at the same time.

There are many publications which treat about production routes of the mentioned materials, for example [4–6]. The referred works give complete classifications of porous metals and their manufacturing methods. Also, it is worth denoting that skeletons of the discussed materials can be made of various metals and alloys – from aluminium, copper, titanium to steel.

An interesting and relatively new subgroup of porous metals is: open-cell metals. The authors would like to present here self-made open-cell aluminium and some of its properties in compression.

2. Material and samples

Samples for the research were produced by the investment casting method. The main idea of this method comprises in a few steps. First, one takes a polymer open-cell foam precursor, which is then cast with a ceramic slurry. Secondly, thermal processing is applied – the ceramic hardens and the polymer is burned out, leaving open canals in the ceramic form. Then, a molten metal is cast into the canals and, finally, after the metal hardens, the ceramic form is removed. Successful production depends on proper adjusting of many parameters, like: the ceramic slurry ingredients, the temperature and duration of the thermal processing, the alloy composition *etc.* Some of the performed calibration details are to be presented in [7].

In result of manufacturing calibration attempts, two series of material samples were produced: the prototype samples (denoted here with the letter 'P') and – after the calibration – the regular samples ('R'). Samples of the prototype series had a few structural imperfections, such as: some of the cells were half-closed and filled with aluminium drops and in some cells there remained entrapped small amounts of foreign materials used in the manufacturing process. On the other hand, the series named 'R' did not show visible structural mistakes. Photos are presented in Fig. 1.

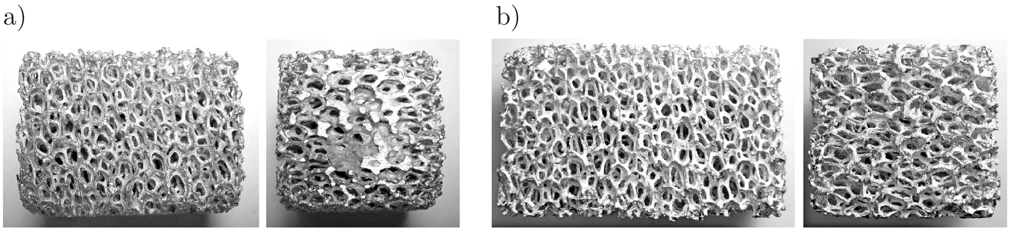

Fig. 1. Samples of open-cell aluminium: a) a sample of the type 'P', b) a sample of the type 'R'.

The material had open-cell, orthotropic, stochastic structure. The obtained PPI was from 5.4 to 6.2. Presence of structural mistakes was revealed by the higher apparent density of samples 'P'. Characteristics of the produced samples are shown in Table 1.

Table 1. Basic specifications of the produced open-cell aluminium.

Feature	Value or description
Average PPI	According to anisotropy: $5.4 \div 6.2$
Average sample size, P [mm]	$53.0 \times 39.5 \times 39.0$
Average sample size, R [mm]	$62.8 \times 39.5 \times 38.0$
Average apparent density, P [g/cm^3]	0.485 ± 0.010
Average apparent density, R [g/cm^3]	0.312 ± 0.006

3. Compression tests

Cellular metals require specific way of conduct regarding compressive experiments. Methodology directions can be found *e.g.* in [8] and standards [9, 10]. A proposition of experimental procedures for cellular metals is to be presented in [7].

The experiments were performed using Zwick 1455 20 kN machine and Test-Expert II computer application. Assumed experimental conditions: initial force 5 N, data acquisition frequency 100 Hz and strain speed $0.5\% \cdot L_0$ [mm/s] (where L_0 was the initial length). The hysteresis loop started at stress 0.25 MPa, the reversing point was at 0 MPa and then there was re-loading. The hysteresis loop starting and reversing points were not in consistence with directions from the mentioned standards; however, it was assumed that the set limits would allow for better observation of the initial region.

4. Experimental results and discussion

In publications [8–10] there are proposed some measures which can be determined from compression tests of porous metals and then used as material characteristics; these publications also give hints how to perform the measures' evaluation. An example can be: the slope of a hysteresis loop secant and its assessment method. However, in the performed compression experiments the obtained loop region results (see Fig. 3a) did not allow one to find the loop secant without question. Since the straight forward determination of this characteristics was impossible, alternative measures were proposed and calculated (Subsec. 4.2).

4.1. Results

A graph showing plots of stress-strain curves for all the samples can be seen in Fig. 2. Apparent densities of specimens are also depicted in this figure. The difference between the ‘P’ group (solid lines) and the ‘R’ group (dashed lines) in terms of the compressive response is quite distinct. One can notice that the smaller the apparent density of a sample, the flatter the stress-strain curve. It can be inferred hence that the production process calibration led to manufacturing of samples which gave a more uniform response to compression and thus to a better quality product.

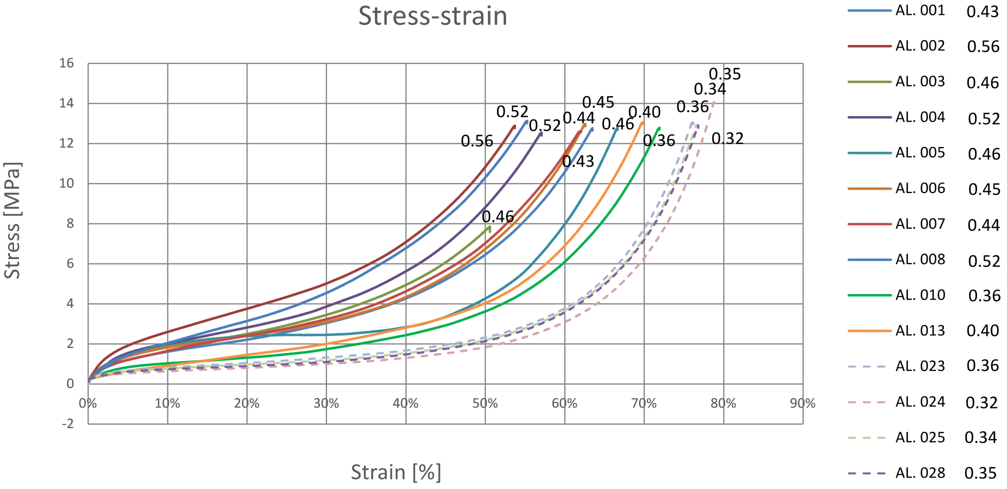

FIG. 2. Stress-strain plots. Solid lines are for the ‘P’ group, dashed lines are for the ‘R’ samples. The numbers by samples and their plots are apparent densities in [g/cm^3].

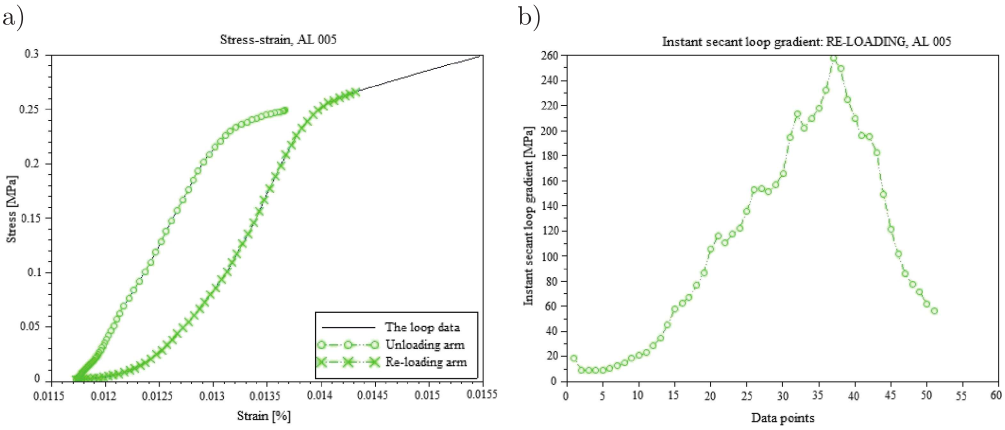

FIG. 3. Results for exemplary sample AL 005: a) loop region; b) instant loop secant gradient (re-loading).

4.2. Proposed material characterisation measures

Data from the experiments were analysed in terms of determination of loop secant slope. Results for all samples could be generalised among the ‘P’ and ‘R’ groups due to similar characteristics among those specimen sets.

The loop shape (see Fig. 3a) made the secant calculation questionable. Results analysis led to the hypothesis that the loop-region material characteristics might be in this case more conveniently approximated by other measures. Three measures to help characterisation of open-cell metals were proposed: instant and average loop secant gradients ($E^{**}_{\text{inst.sec}}$ and $E^{**}_{\text{av.inst.sec}}$) and average linear loop gradient ($E^{**}_{\text{av.lin}}$). Detailed analysis and calculation procedures are to be presented in [7], while here only averaged results to comment the proposed measures concepts are communicated (Table 2).

Table 2. Averaged loop gradients for the open-cell aluminium.

Sample group	av. $E^{**}_{\text{av.inst.sec}}$ [MPa], unload	av. $E^{**}_{\text{av.inst.sec}}$ [MPa], re-load	av. $E^{**}_{\text{av.lin}}$ [MPa], unload	av. $E^{**}_{\text{av.lin}}$ [MPa], re-load
P	193.03	227.04	195.36	228.12
R	175.05	215.02	181.38	219.44

Instant loop secant gradient ($E^{**}_{\text{inst.sec}}$) was defined as the slope of a secant through every two consequent data points of the loop, separately for unloading and re-loading loop arm. Those are green points in Fig. 3b.

Average loop secant gradient ($E^{**}_{\text{av.inst.sec}}$) was defined as the arithmetic mean of a chosen subset of instant loop secant gradients for a given sample. The subset choice was based on checking consequent series of at least 10 points and taking the one with the least coefficient of variation.

Finally, average linear loop gradient ($E^{**}_{\text{av.lin}}$) was defined as the slope of the straight line led through a loop arm. The slope was determined by linear regression. The choice of data points for the regression was according to examining correlation coefficient of consequent series of at least 10 points and taking the series with the highest correlation coefficient.

5. Conclusions

Two main conclusions were drawn based on the results. Firstly, the difference between the ‘P’ and ‘R’ groups was visible, so the calibration of the production method improved samples’ quality significantly. Secondly, due to the fact that the instant secant loop gradient was not a constant value for a given sample but had a non-linear plot with a distinct maximum, the hypothesis was formulated that the loop region might not be best approximated by a straight line, but the proposed measures (instant or average secant or linear gradients) might be more exact characteristics.

Further research on a larger group of the 'R' type samples and with different loop starting and reversing points could lead to verification of the proposed hypothesis. Theoretical approach for the description of the observed results should be developed.

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