# CHARACTERISATION OF STRUCTURAL AND COMPRESSIVE PROPERTIES OF ALUMINUM FOAM ALPORAS

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**Abstract**

Metallic foams are very perspective candidates for light-weight applications in automotive, aerospace, naval and construction industry. However their mechanical properties are very sensitive, different density regions and structural anisotropy can significantly affect the resulting mechanical properties of products. In this study the compressive properties of samples excised out from different parts of relatively large block of Al foam ALPORAS have been measured. The effect of structural parameters, density and strain rate sensitivity were discussed.

**Keywords:** Aluminum foam, density, compression, strain rate

## 1. INTRODUCTION

Closed cell Al foams, having closed pores distributed inside are very light material. They are highly evaluated for their good kinetic energy absorption and their applications to automobile vehicles, aircraft, naval and many others are expected. However, inhomogeneities in the structure cause anisotropy and significant dispersion of the mechanical properties if the effects of the manufacturing parameters on the foam structure are not considered. The result is foams with low industry acceptance despite their long existence. During the production of larger aluminum foam parts, the formation of inhomogeneities in the structure is also affected by the precursor distribution in the mould and the heating conditions [1-5]. Despite the considerable efforts of researchers and manufacturers, it has not yet been developed a technique for production of Al foams, which would ensure full homogeneity and pore distribution in products with large dimensions. In this study the compressive properties of samples excised out from different parts of relatively large block of Al foam ALPORAS have been measured. The effect of different sample location (distance from the mould surface) on the porosity, density and compression properties was examined. The impact of different strain rates was also investigated.

## 2. EXPERIMENT

Closed-cell aluminum foam for testing and evaluation was provided by UMMS SAV Bratislava. It was processed by modified ALPORAS process by adding about 2 wt.% Ca (to enhance the viscosity) and 1.5 wt.% $TiH_2$ particles (as foaming agent) and fan cooled. A macroscopic view of the provided material 168 x 100 x 213 mm, which was carved from the middle part (without contact with side walls) of a larger block of foam is shown in **Figure 1**. One side of this block consisted of continuous Al sheet (without pores), because this part was in the contact with the bottom of the mould during foaming and solidification. Cylindrical test samples 22 mm in diameter and 33 mm long were electrodischarge machined from block of Al foam. The one part of samples was machined from the area near contact with mould (distance about 25 mm from edge), the second part of samples was machined from the central area (distance about 80 mm) and the last part of samples was machined from area with the most distance from the area with contact with mould (about 150 mm). Demonstration of the sample for testing is shown in **Figure 2a**. All samples were subjected to the apparent density measurements by weighting using analytical balance and accurate dimensions measurement. Relative density ($\rho_{rel}$) was calculated by dividing the density of samples ($\rho$) and density of Al alloyed with 2 wt.% Ca ($\rho_{teo}$ = 2.66 g·cm$^{-3}$) by the equation:

$$\rho_{rel} = \frac{\rho}{\rho_{teo}} \tag{1}$$

For the determination of porosity and pore distribution of the machined samples was used automatic image analysis with using optical macroscopic view and the almost same procedure was used as described in [6]. Demonstration of the determination of individual pores in the sample is shown in **Figures. 2b** and **2c**. The second method of porosity determination was based on the results of the relative densities. From the relative density is possible to easily calculate the total porosity according to the equation [7]:

$$\theta = (1 - \rho_{rel}) \times 100, \tag{2}$$

where $\theta$ denotes the total porosity percentage and $\rho_{rel}$ relative density. Chemical composition and microstructure were investigated by scanning electron microscopy in the mode of back-scattered electrons (BSE) and secondary electrons (SE) using microscope QUANTA FEG450 equipped with an energy dispersive spectrometer EDAX (EDS).

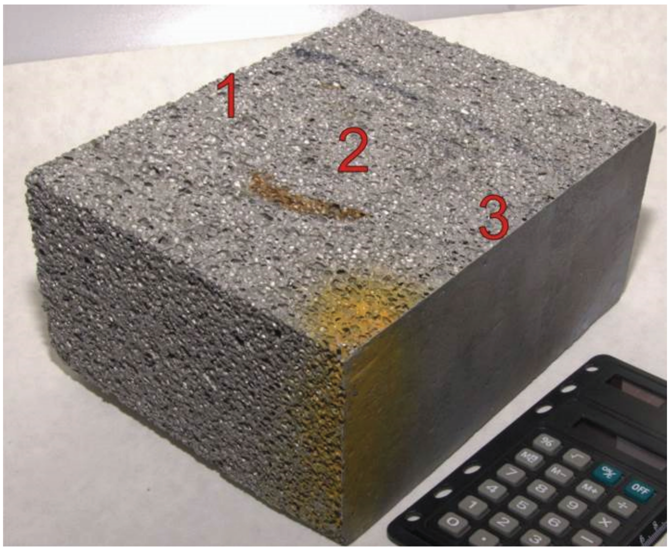


**Figure 1** Macroscopic view of provided Al foam ALPORAS with the designation of individual areas

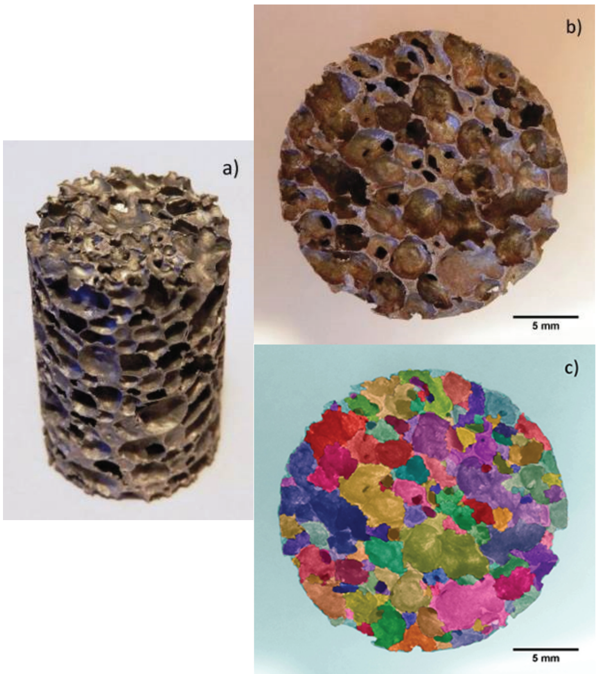


**Figure 2 a)** Electrodischarge machined sample for compression testing; **b)** Foam structure; **c)** Demonstration of the determination of individual pores

High-speed test equipment Zwick/Roell Z150 was used for mechanical compression testing. Mechanical compression testing was performed under four different strain rates: 0.85; 0.57; 0.057 and 0.0057 s$^{-1}$. The resulting mechanical properties were deducted from diagrams showing the relationship between strain and stress. The degree of deformation was determined by proportion between the change in length of the specimen during the pressure test and its initial length. The first peak of the deformation curve, often defined as an upper yield stress, was used as a compressive strength value $\sigma_c$.

## 3. RESULTS AND DISCUSSION

The **Table 1** shows the results of EDS analysis in individual areas of Al foam. The resulting composition exhibits a relatively small deviation from the nominal composition (nominal composition Al - 2 wt.% Ca) and individual parts of Al foam exhibit between themselves no appreciable deviations. **Figure 3** shows the typical microstructure of Al foams formed by relatively large pores and a thin metal layer, which separates the individual pores. On this image can be seen bright fine particles existing on a surface of each pore. A more detailed image of the particles at a higher magnification is shown in **Figure 4**. The identified chemical composition of these particles is listed in **Table 2**. As can be seen in this table, the particles contain mostly Ca and O and only very low amount of Al. According to the results of EDS chemical composition analysis can be concluded that these particles are oxides of Ca, which was added to the material to increase the viscosity and which, because of its high affinity to oxygen during the heat treatment, create oxides CaO.

**Table 1** Determined chemical composition in individual areas by EDS (wt.%)

| | **Results of EDS analysis** | |
|---|---|---|
| Area | Al | Ca |
| 1 | 97.5 ± 0.4 | 2.5 ± 0.4 |
| 2 | 98.0 ± 0.6 | 2.0 ± 0.6 |
| 3 | 97.9 ± 0.9 | 2.1 ± 0.9 |

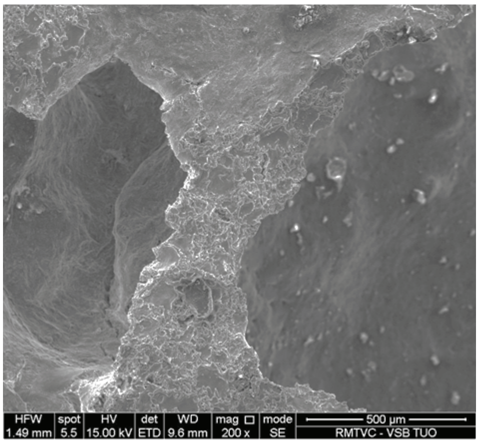


**Figure 3** SE image of surface of Al foam (area 1)

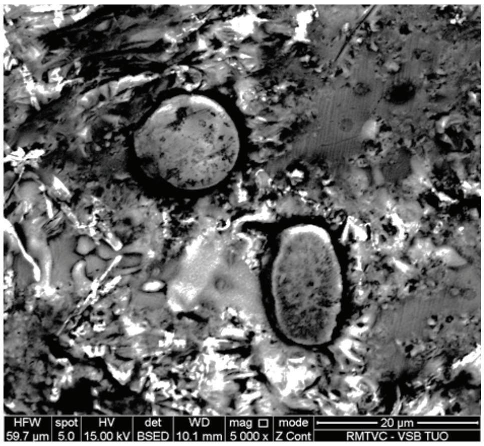


**Figure 4** BSE image of CaO particles (area 3)

**Table 2** Average chemical composition of the particles shown in **Figure 4** (EDS)

| **Element** | **wt. %** | **at. %** |
|---|---|---|
| O | 47.3 ± 19.5 | 66.1 ± 20.0 |
| Al | 3.2 ± 2.5 | 3.0 ± 2.8 |
| Ca | 49.5 ± 18.2 | 30.9 ± 17.8 |

The values of density, porosity and average pore size for individual areas are shown in **Table 3**.These values are in good agreement with typical values for the Al foams of the type ALPORAS as mentioned e.g. Hamada, which reported a density of about 0.3 g·cm$^{-3}$ and an average pore size ranging from 2.35 to 2.96 mm [5], or Ramamurthy [8]. As appears from **Table 3**, the value of the relative densities showed significant differences and with increasing distance from the point of contact with the mould showed a falling trend. Porosity values calculated from relative density ($\theta$) are with good agreement with porosity values identified by automatic image analysis ($\theta_{ia}$) and as well as the average value of the pore size ($S$) with increasing distance from the point of contact with the mould showed increasing tendency. This can be explained by non-uniform pore nucleation and growth, which is affected by heat conduction.

**Table 3** Density and porosity for individual areas of Al foam

| Area | $\rho$ (g·cm$^{-3}$) | $\rho_{rel}$ | $\theta$ (%) | $\theta_{ia}$(%) | $S$ (mm$^2$) |
|---|---|---|---|---|---|
| 1 | 0.293 ± 0.003 | 0.110 ± 0.001 | 88.9 ± 0.7 | 89.2 ± 0.6 | 3.3 ± 0.2 |
| 2 | 0.337 ± 0.007 | 0.127 ± 0.002 | 87.3 ± 0.4 | 88.2 ± 0.4 | 2.9 ± 0.3 |
| 3 | 0.358 ± 0.005 | 0.135 ± 0.001 | 86.7 ± 0.3 | 86.7 ± 0.3 | 2.3 ± 0.3 |

**Figure 5** shows the relationship between the distance from the wall of the mould and average relative density. This figure clearly shows that relative densities exhibited significant differences and with increasing distance from the point of contact with the mould showed a falling trend.

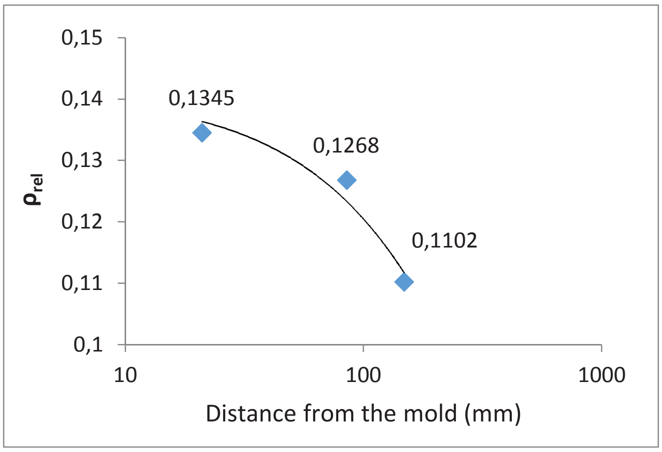


**Figure 5** Dependence of the average relative density in the individual areas of Al foam on the distance from the mould wall

**Figure 6** shows the statistically processed data describing the relative frequency and cumulative frequency for each class of pore size for the area 1 and for the area 3. For better clarity was area of identified pores converted to circle diameter (D) whose area corresponds to the area of the individual pores identified according to the equation:

$$d = \sqrt{\frac{4S}{\pi}}, \tag{4}$$

where $S$ is the area of the identified pores. As can be seen in this graph in area 3 which was close to the mould during foaming is higher proportion of pore diameter smaller than 0.75 mm. The following class from 0.75 to 1.5 mm, which was for both areas characterized by the highest relative frequency, the difference in the frequency is lower and a higher proportion of pores identified in this class is in region 1 as well as for a class from 1.5 to 2.25 mm. For other classes is a difference in the relative frequencies minimal. From the obtained data follows that lower porosity at region 3, determined by the density measurement or by image analysis and a lower average pore size is related to the higher relative frequency of fine pores (diameter 0-0.75 mm) which is more fully appear in the Al foam near the mould. In remote areas, the frequency of these fine pores was lower, which is probably related to the increased interaction of the individual gas bubbles between them, and their linking into larger size bubbles.

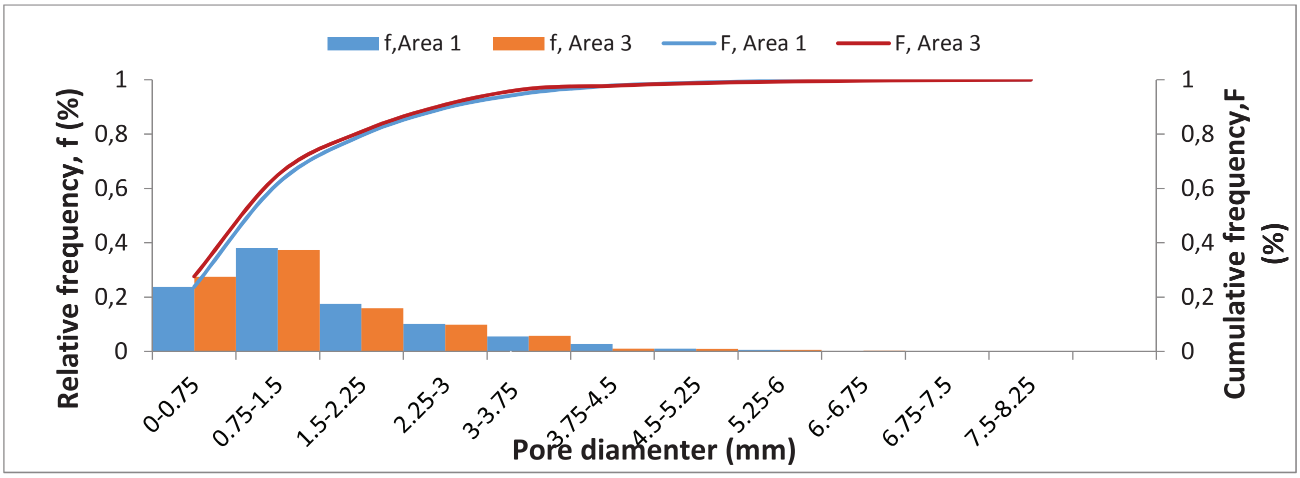


**Figure 6** The relative frequency and cumulative frequency for individual classes of pore size

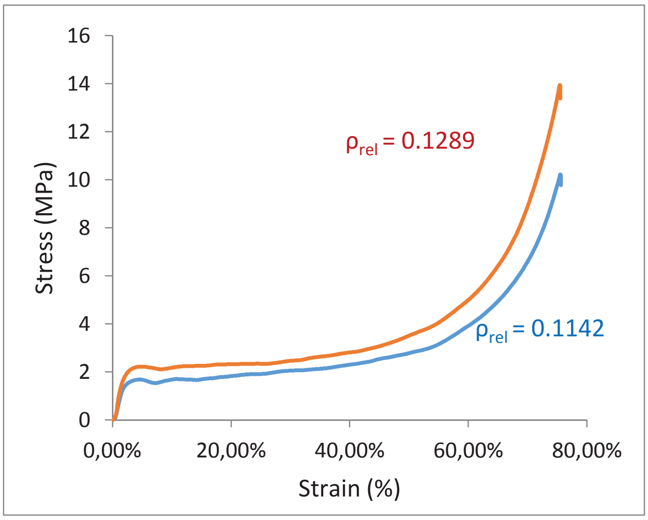


**Figure 7** Deformation curves of two samples with different density

**Figure 7** shows a graph with two curves expressing the stress-strain dependence during uniaxial compression test at room temperature with a strain rate of 0.057 $s^{-1}$. Each sample corresponds to the Al foam with different relative density. The values of relative densities for a specific sample are indicated in the graph. As may be seen in this graph, stress-strain curves show the typical shape characteristic for Al foam and comprise of three regions: (i) elasto-plastic deformation region, (ii) an extended plateau region, (iii) rapidly increasing stress region [4, 9]. Stress values reach values of about 2 MPa, which is typical for this type Al foams and their shape shows no significant oscillations and for the majority of tested samples, the first characteristic peak was not observed or was not too pronounced. This indicates that the cell walls are ductile and predominant deformation mechanism is bending of cell walls, which is typical for Al foams with good ductility [9]. This graph shows also significant dependence of the mechanical properties of Al foam on the density, which usually with increasing tendency achieve higher stress values. In addition, some publications reported a significant impact of different strain rates [8]. **Figure 8** shows the relation between the relative density and stress $\sigma_c$ for all tested samples and for all used strain rates. For all strain rates the stress $\sigma_c$ increase with increasing relative density. It is also possible observe the effect of different strain rates. The highest values of $\sigma_c$ were observed in samples of similar density deformed with the highest strain rates 0.85 $s^{-1}$, lower during strain rates of 0.57 $s^{-1}$ and lowest at slow strain rates 0.057 and 0.0057 $s^{-1}$.This effect is in good agreement with results of Hamada [5], who reported that stress during the compression tests are dependent on strain rate and stress increased by the increase of the strain rate in closed cell Al foams, but the strain rate dependency of stress is small and higher influence on the stress values has the density.

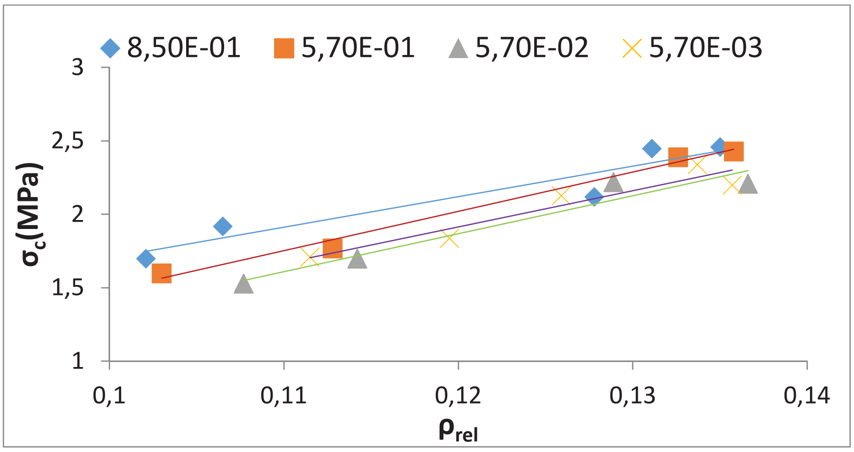


**Figure 8** Dependence between the density and stress $\sigma_c$ for all tested samples and for all used strain rates

## 4. CONCLUSIONS

It has been shown that Al foam is not completely homogeneous and relative densities exhibited significant differences and with increasing distance from the point of contact with the mould showed a falling trend. Differences in relative density then cause a significant difference in stress values during compression tests. It was also confirmed the effect of strain rates on the mechanical properties of Al foams, but strain rate dependency of stress is compared to density smaller. However, this phenomenon shows that the Al foams of this type can absorb higher energy at higher strain rates and hence will be very useful in protecting against impact, wherein the strain rate tend to be very high.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] YI, F. Strain rate effects on the compressive property and the energy-absorbing capacity of aluminium alloy foams. *Materials Characterization*, 2001, vol. 47, pp. 417-422.

[2] NOSKO, M. Reproducibility of aluminium foam properties: Effect of precursor distribution on the structural anisotropy and the collapse stress and its dispersion. *Materials Science and Engineering A*, 2010, vol. 527, pp. 5900-5908.

[3] BANHART, J. Manufacture, characterisation and application of cellular metals and metal foams. *Progress in Materials Science*, 2001, vol. 46, pp. 559-632.

[4] KOZA, E. Compressive strength of aluminium foams. *Materials Letters*, 2003, vol. 58, pp. 132-135.

[5] HAMADA, T. Effect of the strain rate and alloying on the compression characteristics of closed cell aluminium foams. *Materials Transactions*, 2009, vol. 50, pp. 1418-1425.

[6] POHLUDKA, M. Porosity of $Ni_3Al$ based alloys prepared by gravity and centrifugal casting. In: *Metal 2012: 21st International Conference on Metallurgy and Materials*. Ostrava: TANGER, 2012, pp. 1547-1553.

[7] LIU, P.S. *Porous Materials: Processing and Applications*. Elsevier, 2014, 576 p.

[8] RAMAMURTY, U. Strain rate sensitivity of closed-cell aluminium foam. *Materials Science and Engineering A*, 2000, vol. 281, pp. 1-7.

[9] FLOREK, R. Compression test evaluation method for aluminium foam parts of different alloys and densities. *Powder Metallurgy Progress*, 2010, vol. 10, pp. 207-212.