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Mechanical Properties of Aluminium Foam Derived From Infiltration Casting of Salt Dough

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Abstract This paper addresses the mechanical properties of Corevo® aluminium foam. The effective Young's modulus, Poisson's ratio, and material yield stress are determined. To this end, samples are tested using uni-axial compressive testing. In addition, micro-computed tomography data of the complex material geometry are obtained and converted into finite element calculation models. The numerical analysis further enables the testing of mechanical material anisotropy and plastic deformation within the material's meso-structure.

Keywords Cellular metal, mechanical properties; compressive testing; finite element method

Cellular metals combine a range of attractive properties. Due to their high porosity they are relatively light whilst maintaining a high level of strength [1]. Furthermore, they can be used for the damping of structural and acoustic vibrations [2]. Their versatile thermal properties make them especially attractive for use in thermal conductivity enhancement [3] or heat exchangers [4]. Finally, cellular metals exhibit controlled deformation behaviour under compressive loading making them optimum materials for plastic energy absorption applications [5, 6]. Corevo® aluminium foam is a novel type of cellular metal consisting of an aluminium matrix and an interconnected pore network. In this paper and for the first time, its mechanical properties are characterised using experimental and numerical methods.

Corevo® foam is manufactured by a replication process based on salt dough as a spacer material [7]. Salt dough pellets are manufactured with sizes ranging from 2 to 10mm (dictating the final pore size of the foam) and compressed into a preform (the compression step dictates the final foam porosity ranging from 70% to 80%). Aluminium is then infiltrated inside the preform by a low pressure die casting process. After this step, the salt is rinsed away to obtain the final foam. This process is quite versatile, allowing for foam parts with various shapes and sizes as well as the integration (one shot during casting or by integration of external elements at the preform stage) of dense metal parts.

Finite element analysis of models based on micro-computed tomography (μ CT) data is now an established tool for the numerical analysis of cellular metals and their complex meso-structures [8, 9]. It enables mechanical testing of materials without destroying samples, the study of anisotropy, strain rate dependency and the visualisation of stresses within the material [10]. Furthermore, geometric modifications of the models enable the virtual study of material defects or the improvement of materials [11].

a)

b)

Fig. 1 Corevo® aluminium foam cylinder ($d=h=25\text{mm}$): a) photograph of sample #3, b) μ CT reconstruction of sample #3 sliced along its centre

Figure 1 shows a light photograph and μ CT reconstruction of one of the tested cylindrical Corevo® foam samples. A total of four cylindrical samples have been used for the mechanical characterisation of Corevo® aluminium foam. These samples are analysed using experimental and numerical testing to determine their effective Young's modulus, Poisson's ratio and yield strength.

A total of four samples have been tested in the experimental analysis. Prior to uni-axial compression, samples 2 and 3 were scanned using μ CT imaging for additional numerical analysis. The voxel size in both scans was 36.25 microns. All samples exhibited a cylindrical shape (diameter and height $d = h = 25\text{mm}$). The masses m of each sample are listed in Table 1. The sample porosity p was calculated in two steps. First, the metal volume V_m was obtained by dividing the mass by the density of the aluminium alloy (i.e. $\rho_{Al} = 2670 \text{ kg/m}^3$ [12]). The combined volume of the pores is then the metal volume V_m subtracted from the cylinder volume $\pi d^2 \cdot h / 4$. Subsequent normalisation of the pore volume with the cylinder volume yields the porosity p . For samples 2 and 3 where μ CT data were available the specific internal surface area S_i was determined. In the first step the μ CT data was segmented by identifying the metallic phase using the software ImageJ. The segmentation threshold was adjusted iteratively until the segmented metal volume corresponded to the calculated metal volume V_m . Next, a fine STL surface mesh was generated that encloses the segmented metal volume using the commercial software Mimics 10. The area of the surface mesh was divided by the cylinder volume in order to calculate the specific internal surface area S_i . The values indicated homogenous geometric properties of the samples considered.

Nr	m [g]	p [%]	S_i [mm ² /mm ³]
#1	9.165	71.7	-
#2	8.900	72.6	1.48
#3	8.970	72.4	1.49
#4	8.875	72.6	-

Table 1 Samples' characteristics

Compressive testing was performed on a Shimadzu50 kN uni-axial testing machine. The speed of the machine crosshead was 0.5 mm/min (quasi-static compression). Compressive forces F were measured using a 50 kN load cell. Displacements u were obtained using a novel optical measurement system that provides superior accuracy (resolution 3.4 microns) at small displacements and machine crosshead displacement data at large displacements. Images were recorded with a frequency of $1s^{-1}$. The force-displacement curve obtained was transformed into engineering stress-strain data using the initial cylindrical cross section A_0 and height h_0 , i.e. $\sigma = F/A_0$ and $\varepsilon = \Delta u/h_0$. A total of four specimens were tested with the results being shown in Fig. 2. The effective Young's modulus (z -direction) is identical to the initial slope of the stress-strain curve. The corresponding values are $E_1 = 7.15$ GPa, $E_2 = 6.52$ GPa, $E_3 = 5.38$ GPa, and $E_4 = 6.29$ GPa where the subscript indicates the sample ID. Furthermore, the 0.2% offset yield strength $\sigma_{0.2}$ was determined and similar values were found for all samples ($\sigma_{0.2,1} = 11.2$ MPa, $\sigma_{0.2,2} = 11.0$ MPa, $\sigma_{0.2,3} = 11.2$ MPa, and $\sigma_{0.2,4} = 12.4$ MPa). The densification strain was defined as the strain where stress first exceeds 20 MPa. The corresponding values are $\varepsilon_{d1} = 0.59$, $\varepsilon_{d2} = 0.55$, $\varepsilon_{d3} = 0.43$, and $\varepsilon_{d4} = 0.60$. It is interesting to note that the onset of densification occurs earlier in Sample 3.

Fig. 2 Stress-strain data of the experimental measurement

Segmented micro-computed tomography data were converted into high resolution finite element calculation models that accurately capture the complex meso-structure of the

material. In the first step, two non-intersecting cubes with a side length of 10 mm were extracted from each of the two cylindrical μ CT data sets of samples 2 and 3. Mixed meshes containing tetrahedral, pentahedral and hexahedral elements exhibit minimum element distortion and thus superior numerical accuracy [13] and were used in the present analysis. Preliminary mesh refinement analysis indicates a minimum of 710 000 nodes per model for numerical convergence. Analogous to the experimental testing, uni-axial compressive loading was simulated. To this end, a time-dependent compressive boundary condition was prescribed at one surface of a cube whilst the opposing surface was constrained in its normal direction. By alternating the orientation of these planes, material anisotropy was tested. All other surfaces remained unconstrained. For the subsequent calculation of Poisson's ratio, averaged displacements of the nodes within the free surfaces were used. The chemical composition of the metallic base material corresponds to AIS7G06. Accordingly, the following base material properties were used in the numerical analysis: Young's modulus $E=72.4\text{GPa}$, Poisson's ratio $\nu=0.33$, and initial yield stress $\sigma_0=241\text{ MPa}$. Plastic hardening was modelled using a tangent modulus $T=2.3\text{ GPa}$ to match the ultimate yield stress $\sigma_u=310\text{ MPa}$ at $\varepsilon_u=0.03$ [12].

A user-supplied subroutine was applied to log the total nodal reaction force F and nodal displacement Δu . Based on these values and identical to the procedure used in experimental testing, engineering stresses σ and strains ε were calculated. The numerical stress-strain data were used to extract the effective material properties of Corevo® aluminium foam. Figure 3 shows the effective Young's modulus and initial yield stress. Young's modulus ranges from 3.4 to 7.7 GPa and a distinct elastic anisotropy was found. The effective Young's modulus was relatively consistent in the x and y -directions. However, in the casting (i.e. z) direction distinctly higher values were found. Especially the extracted cubes #2b and #3a showed excellent agreement with experimental results. The initial yield stress (see Fig. 3b) is the macroscopic stress at the instant when plasticisation first occurs within the numerical calculation model. The material property follows the anisotropy found for Young's modulus. This material property can only be determined in numerical analysis and limits the range of purely elastic deformation.

*Fig. 3 Results of the finite element analyses:
a) Effective Young's modulus, b) Initial yield stress*

Poisson's ratio ν (see Table 2) was calculated by dividing the average length change $\Delta u_{\perp}$ perpendicular to the loading direction by the average length change $\Delta u_{\parallel}$ parallel to the loading direction, i.e. $\nu = -\Delta u_{\perp}/\Delta u_{\parallel}$. The orientation of Poisson's ratio is indicated by its subscripts with the first subscript indicating the loading direction and the second subscript the transverse direction. The results are summarised in Table 1 and show values between 0.17 and 0.36. Minimum values are found for compression in the x or y -directions and transverse deformation in the z -direction, i.e. ν_{xz} and ν_{yz} . This can be explained by the relatively high Young's modulus in the z -direction (see Fig. 3a).

	#1	#2	#3	#4	Average
ν_{xy}	0.31	0.26	0.31	0.30	0.30
ν_{xz}	0.17	0.18	0.18	0.20	0.18
ν_{yx}	0.36	0.32	0.31	0.30	0.32
ν_{yz}	0.19	0.17	0.20	0.19	0.19
ν_{zx}	0.32	0.26	0.23	0.30	0.28
ν_{zy}	0.24	0.25	0.32	0.30	0.28

Table 2 Poisson's ratio

Furthermore, finite element analysis allows the visualisation of the deformation mechanism within the material's meso-structure. Figure 4 shows the distribution of equivalent plastic strain at a macroscopic compression of 10%. It can be observed that plastification is concentrated in thin struts parallel to the loading direction. This behaviour is observed for all (i.e. x , y , and z) loading directions.

Fig. 4 Distribution of equivalent plastic strain (sample #2a).

This paper addressed the mechanical properties of Corevo® aluminium foam. Combined experimental and numerical analysis allowed the determination of the effective Young's modulus, Poisson's ratio, initial yield strength and 0.2% offset yield strength. The elastic anisotropy was found with Young's modulus ranging from an average of 3.9 GPa in the x - y plane to 5.9 GPa in the z -direction. Similar behaviour was found for the initial yield stress (x - y plane 0.6 MPa and 1.14 MPa in the z -direction). Good agreement between experimental and numerical results for Young's modulus was found. Experimental analysis further indicated values of the 0.2% offset yield strength between 11.0 MPa and 12.4 MPa. The densification strain (i.e. the strain where 20 MPa is first exceeded) was found to range from 0.43 to 0.60. Finally, numerical analysis indicates that initial plasticisation was concentrated in thin struts of the meso-structure parallel to the macroscopic loading direction.

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