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Geometrical and mechanical analysis of various types of cellular metals

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Abstract

The paper gives a short overview of geometrical characterization, experimental testing, computational modelling and finite element analysis of various cellular metals: Advanced Pore Morphology (APM) foam, open-cell aluminum foam, Metallic Hollow Sphere Structure (MHSS) and cellular metals with uni-directional pores (UniPore). The geometrical analysis and characterization is based on the analysis of micro computed tomography scans and proper recognition of their internal cellular structure, taking into account statistical distribution of morphological and topological properties. The results of conducted geometrical analysis provided means to develop methodology for proper 2D and 3D geometrical modelling of irregular cellular structures and consequent formation of computational models. These were used to study the compressive and bending behavior of analyzed cellular structures by means of quasi-static and dynamic nonlinear computational simulations (using engineering codes ABAQUS and LS-DYNA), validated by experimental tests.

Keywords: cellular metals; mechanical characterization; geometrical analysis; advanced pore morphology (APM) foam; metallic hollow sphere structure (MHSS); UniPore structure.

1. Introduction

A cellular/porous material is made of an interconnected network of solid struts or plates which form the cell's edges and faces [1,2]. Their mechanical behavior mainly depends on the relative density (the density of the cellular structure, divided by the base material density) and the base material which can be either metal, polymer, glass or ceramics. The other important parameters of the cellular structures are morphology (open or closed cells, size and shape of cells), topology (regular or irregular cell structure) and possible filler type. To achieve adequate properties of the cellular material, the base material has to be carefully chosen regarding to its mechanical (strength, stiffness) and thermal properties (thermal conductivity). The advantages of cellular materials in general are low density (light-weight structures), high acoustic insulation and damping, high energy absorption capabilities, durability at dynamic loadings and recyclability [1-3].

Cellular materials have a characteristic stress-strain relationship in compression, which is characterized by large strains at almost constant stress in plastic region (stress plateau) until the cells completely collapse (densification) [1,4-6]. With the strain increase, the cells become oriented with the loading direction, increasing the stiffness of the cellular material until the tensile failure. The mechanism of cell deformation and collapse also depends on the cellular's structure relative density.

The micro- and macroscopic properties of cellular materials make them very attractive for use in automotive, rail, naval and aerospace industry as heat

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exchangers, filters, bearings, acoustic dampers, core material in sandwich structures, bio-medical implants and elements for energy absorption. To further expand their application potentials the cellular materials are often used as parts or cores in composite structures, e.g. sandwich structures, foam filled tubes [7-9]. Sandwich structures are usually comprised of two face sheets with cellular material as a core in between. Such sandwich structures have an increasing relevance in various engineering applications due to their high stiffness, strength and reduced mass (light-weight). In some cases single cellular material elements (metallic hollow sphere structures, advanced pore morphology foam) are joined together using different technologies such as sintering, soldering and adhering. Adhering provides the most economical way of joining and allows for further cost reduction and therefore the expansion of potential applications.

The understanding of cellular material behavior under quasi-static and dynamic loading is valuable for engineering applications such as those related to mechanical energy absorption through deformation [10,11]. Proper characterization of all influential parameters is particularly important and can be best achieved through combination of dedicated experimental testing program and computational simulations. However, the structure of industrial cellular materials in terms of shape, size and distribution of pores cannot be fully controlled with existing mass production technologies. The structural characterization techniques significantly contributed to describe such complex structures (pore morphology and topology) [12-14]. Random pore geometry can result in a certain scatter of mechanical and thermal characteristics of these materials and their components. Some recently developed fabrication methods of cellular metals result in more homogeneous pore structures [15-19].

This paper provides a short overview of mechanical and geometrical characterization of different types of cellular materials based on experimental testing, computational simulations and computed tomography.

2. Unidirectional cellular structure - UniPore

Some innovative manufacturing approaches have been investigated recently in search of cellular materials with more regular distribution of pores, constant wall thickness and pore sizes. One such an approach is explosive compaction of thin-walled tubes, which after treatment form a cellular structure with straight unidirectional pores – the UniPore structure [20,21]. This manufacturing procedure results in making a cellular material with perfectly parallel unidirectional pores (Fig. 1). The advanced geometrical properties of the UniPore structure assure wide opportunities for its application due to its unique mechanical and thermal properties (e.g. heat sinks using phase change materials [22]). Mechanical behavior of the UniPore structure with unidirectional pores can be influenced by size, thickness and base material of original tubes.

Fig. 1. UniPore samples with different porosities (p = 0.32, 0.49, 0.58).

The compressive mechanical properties of UniPore structure have been investigated by means of experimental (two specimens for each loading direction, Fig. 2) and parametric computational simulations considering various materials and geometrical parameters using the LS-DYNA finite element system [23]. The engineering stress has been calculated by dividing the reaction force with the maximal cross-section area.

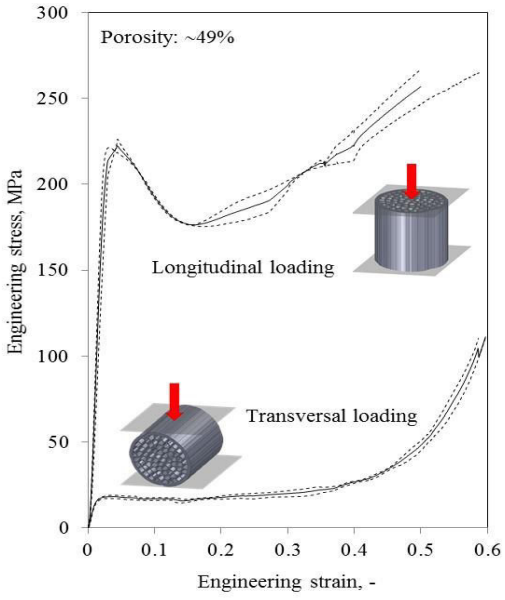
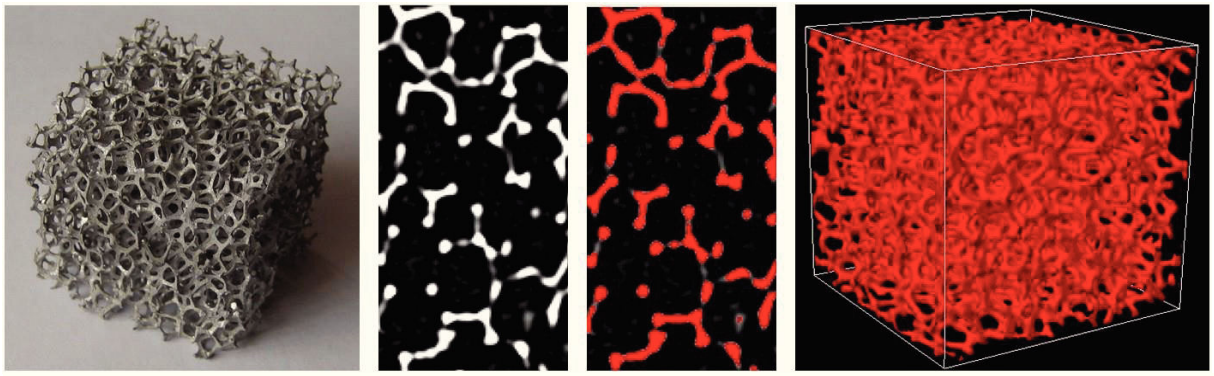


Fig. 2. Longitudinal and transversal compressive behavior of UniPore structures [20].

The results have shown that the UniPore structures exhibit characteristic cellular material behavior in the transversal direction, i.e. onset of yielding after the initial elastic response which is then manifested in a typical stress plateau followed by the final densification.



a) b) c) d)

Fig. 3. Open-cell foam (a) sample; (b) CT scan; (c) virtual reconstruction; (d) solid CAD model.

3. Open-cell aluminum foam

The open-cell foam specimens are manufactured using an investment casting process. Starting point is a cellular polymer precursor. The pores are filled with a fire-resistant slurry that is dried and burned. The precursor pyrolises during the burning, while the slurry hardens and forms the mould for subsequent investment casting of the metallic matrix. The final step is the removal of the moulding material resulting in a cellular metallic geometry that closely resembles the polymer precursor [24]. The base material of the open-cell foam is Al99.7% and the relative density of the structure is 6.1 % (porosity is 93.9 %). Its average pore size is 20 pores per inch (ppi).

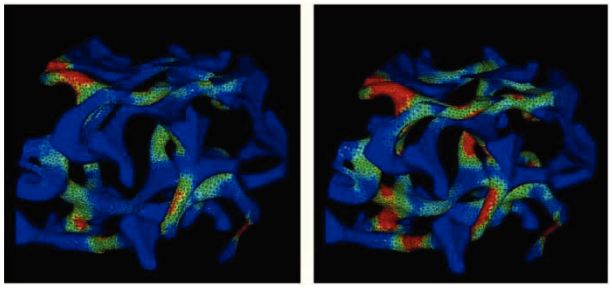


Fig. 4. Stress concentrations of the aluminum foam by structural computer analysis.

The cube shaped aluminum foam samples (Fig. 3a) with dimensions 40 x 40 x 40 mm were scanned with computed tomography (CT) at the Department of Radiology, University Medical Centre Maribor. The CT images were then used for appropriate geometrical statistical analysis and virtual reconstruction (Fig. 3) [10,25]. The reconstructed models have been discretized with solid finite elements and used for explicit dynamic finite element analysis using the finite element code LS-DYNA. The results of computer simulations are shown in Fig. 4, in which the local stress concentrations during loading can be clearly observed. The results of the structural analysis of this irregular cellular material also correspond to a typical compressive stress-strain behavior of the cellular structures.

4. Advanced Pore Morphology (APM) Foam

Advanced pore morphology (APM) foam consists of sphere-like metallic foam elements (Fig. 5) of sizes ranging from 5 to 15 mm in diameter. The APM spheres can be used individually or bonded with a matrix as fillers of hollow engineering parts, as core layers for sandwich structures or other composite materials [26-31]. They have a characteristic stress-strain behavior under compressive loading (Fig. 6) [16]. Since the APM foam manufacturing procedure has been developed only recently, the mechanical characterization of these materials is still limited.

Fig. 5. APM foam element.

Single APM elements have a characteristic cellular material behavior under compressive loading where the

larger foam elements experience lower densification strain, which corresponds to their observed higher inner porosity. The use of IR thermography has demonstrated the importance of studying the heat generation as well due to the fast plastic deformation during dynamic loading. The yielding starts at the contact between the loading/support plate and the APM element and then propagates through the sphere in a shear band, finally resulting in a fully compressed APM foam element. The study of single APM elements provided valuable mechanical properties and the basic knowledge for an efficient composition of composite APM structures [15,16].

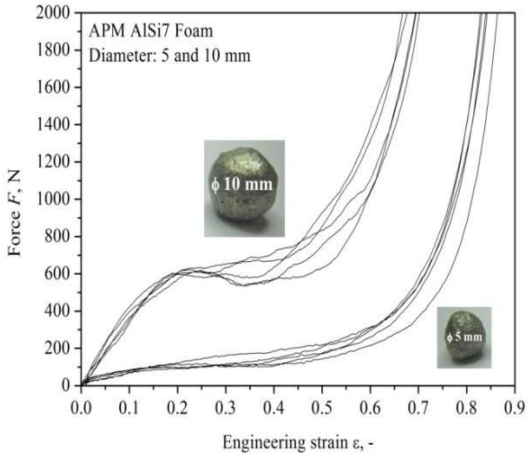


Fig. 6. Behavior of APM foam elements under compressive loading [16].

A recent structural analysis of APM foam elements using micro computed tomography (μCT) revealed different levels of porosity (Fig. 7). The pore size from micro level (several micrometers in diameter) up to macro level (several millimeters in diameter) can be found resulting in a high total number of pores in each APM foam element [14,32].

5. Metallic Hollow Sphere Structures (MHSS)

The mechanical behavior of MHSS [16,33-35] has been simulated by novel computational models describing irregular MHSS structures (random sphere packing) discretized by the shell finite elements, as shown in Fig. 8. Most of the computational simulations of MHSS structures so far have considered only a regular structure, discretized either with shell or solid finite elements [36] or irregular structure, discretized only with the volume finite elements. Using shell instead of solid elements significantly decreases the total number of elements and consequently yields much shorter computational times while providing the same computational accuracy level. The shell MHSS models with random topology were assembled and generated by a self-written sphere packing code. The uniaxial compressive response of generated shell MHSS models with random (irregular) topology was computationally estimated and finally compared to experimental results, with excellent agreement (Fig. 9).

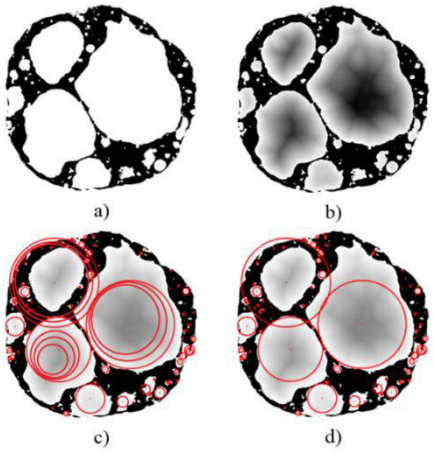


Fig. 7. Pore search process based on the μCT figures and the distance transform algorithm [14,32].

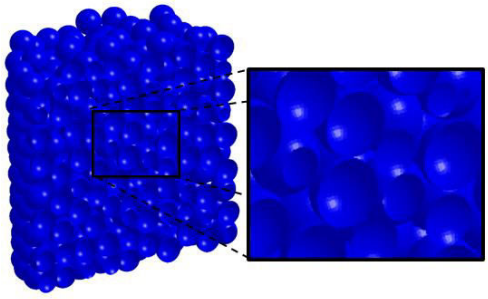


Fig. 8. Shell finite element model of MHSS with random distribution of metallic hollow spheres.

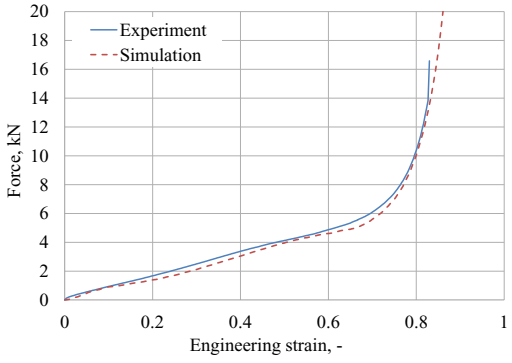


Fig. 9. Comparison between experimental and computational results.

6. Conclusions

As the cellular/porous materials are directly applicable in contemporary industry it is necessary to better understand their mechanical response. Therefore, the knowledge about their morphology, topology and mechanical properties is of crucial importance. They can be defined by geometrical characterization based on micro computed tomography, experimental testing and computational simulations within the finite element method. New computational models and carefully characterized properties of cellular materials allow for parametric computational simulations, with the aim to define the most suitable design parameters of parts made of cellular materials for a given application.

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