Computational modelling and simulations of cellular materials

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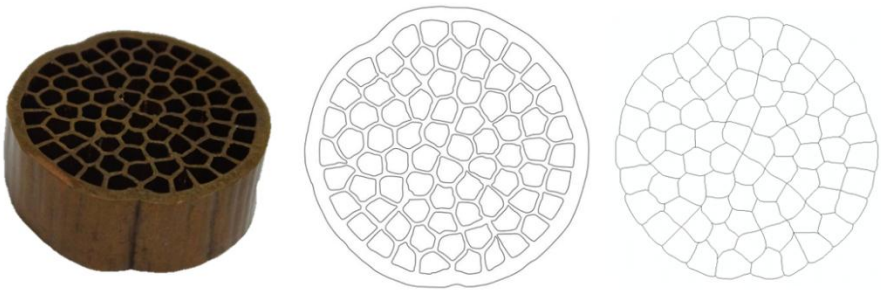
1. Introduction

Cellular structures have an attractive combination of mechanical properties and are increasingly being used in modern engineering applications [1]. Consequently, the research of their behaviour under quasi-static and dynamic loading is valuable for engineering applications such as those related to mechanical energy absorption through deformation [2, 3]. However, the structure of industrial cellular materials in terms of shape, size and distribution of cellular pores cannot be fully controlled with existing mass production technologies. This results in a certain scatter of mechanical and thermal characteristics of these materials and their components. Some recently developed fabrication methods of porous metals result in more homogeneous pore structures [4-7]. This paper focuses on reconstruction and computational modelling of different types of porous materials. Their mechanical properties were determined with combination of experimental tests and computational simulations using ABAQUS and LS-DYNA.

2. Unidirectional porous 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 approach is explosive compaction of thin-walled tubes, which are being compressed together and thus form a cellular structure with straight unidirectional pores – the UniPore structure. UniPore material was recently developed at Shock Wave and Condensed Matter Research Center at Kumamoto University in Japan. The advanced geometrical properties of the UniPore structure assure wide opportunities for its application due to its particular and unique mechanical and thermal properties. This research focuses on mechanical behaviour of the UniPore structure with unidirectional pores under dynamic loading.



a) b) c)

Figure 1. UniPore sample and reconstruction of its structure: a) UniPore specimen, b) CAD reconstruction, c) mid-surface representation

This manufacturing procedure results in making a porous material with perfectly parallel unidirectional pores (Fig. 1a). The computational model of the cellular structure was based on realistic (reconstructed) irregular geometry of the manufactured specimens (Fig. 1b and Fig. 1c). The outer and inner pipes were made of phosphorus deoxidized copper (Cu 99.98 % and P 0.02 %). The compressive mechanical properties of UniPore structure have been investigated by means of parametric computational simulations considering various materials and geometrical parameters using the LS-DYNA [8].

The simulations have shown that the UniPore structures exhibit characteristic cellular material behaviour, i.e. onset of yielding after the initial elastic response which is then manifested in typical stress plateau followed by the final densification (Fig. 2) .

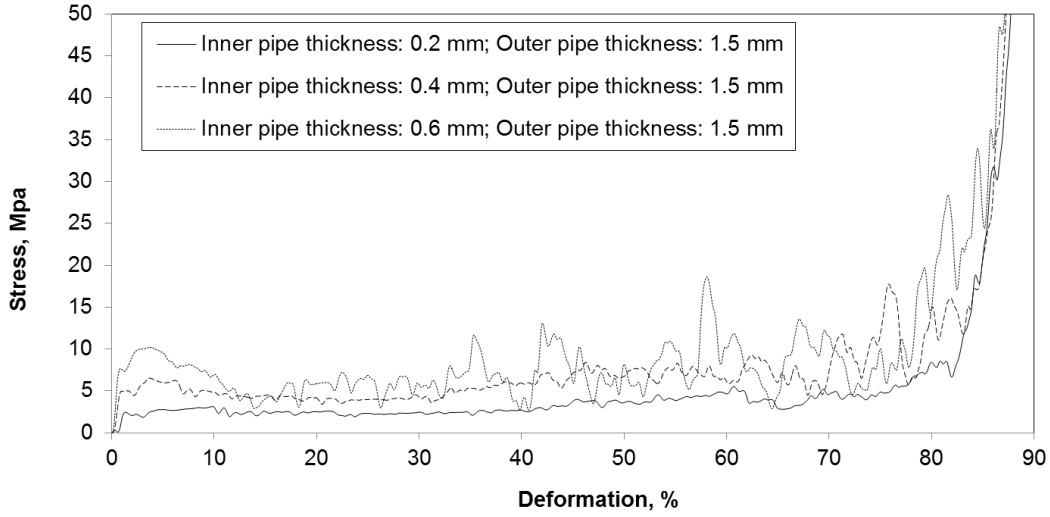
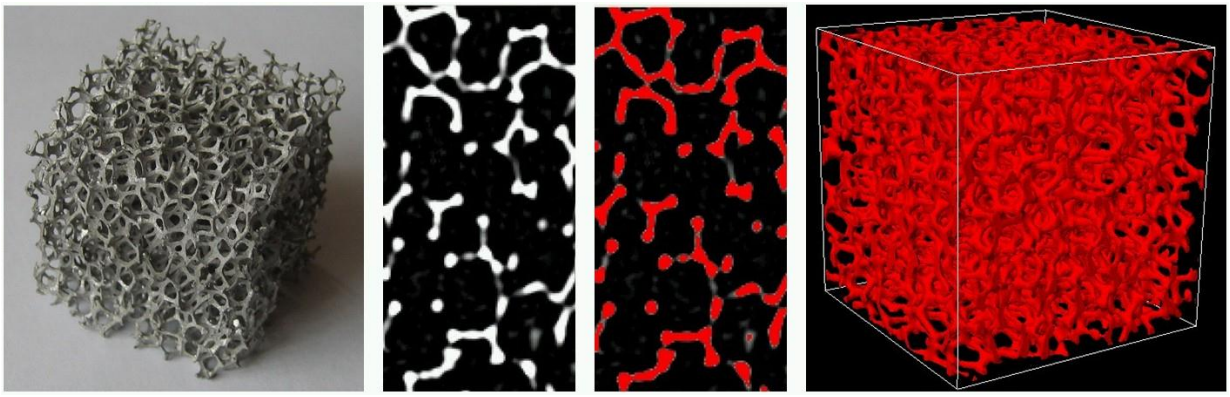


Figure 2. Influence of the inner pipe thickness on the compressive behaviour of UniPore structure at strain rate of 100 s^{-1}

3. Open-cell aluminium foam - m.pore

The open-cell foam specimens are manufactured using an investment casting process. Starting point is a porous polymer precursor. The pores are filled with a fire-resistant slurry that is dried and burned. During the burning the precursor pyrolises 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 porous metallic geometry that closely resembles the polymer precursor [9]. 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 %). Their average pore size is 20 pores per inch (ppi). The aluminium foam (Fig. 3a), cube shaped with dimensions 40 x 40 x 40 mm, was scanned at the Department of Radiology, University Medical Centre Maribor. The CT images were then using recognition software segmented and virtually reconstructed (Fig. 3) [2, 10].

Finally the reconstructed models have been meshed with solid finite elements. Explicit dynamic finite element analysis was performed using the engineering code LS-DYNA. The results of the structural analysis in the form of cellular material deformations are shown in Fig. 4, in which the stress concentrations during loading can be clearly observed.



a) b) c) d)

Figure 3. Alluminium cellular material (a); CT scan (b);
virtual reconstruction (c); solid CAD model (d)

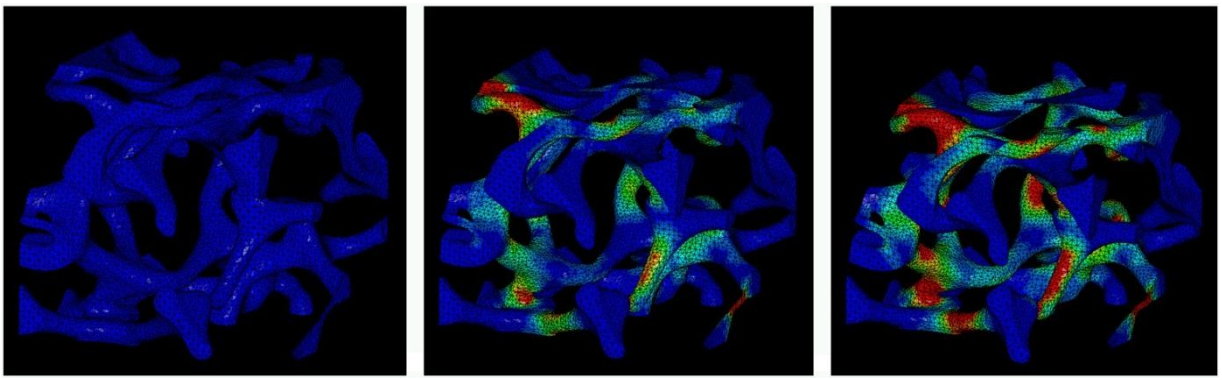


Figure 4. Structural analysis of the aluminium cellular material

The results of the structural analysis of this irregular cellular material indicate a typical compressive stress-strain behaviour of the cellular structures.

4. Advanced Pore Morphology (APM) Foam

Advanced pore morphology (APM) foam (Fig. 5), consisting of sphere-like metallic foam elements (from 5 to 15 mm in diameter), proves to have advantageous mechanical properties and unique application adjustability [11-14]. The APM spheres (Fig. 1) can be used individually, as fillers of engineering parts, as core layers for sandwich structures or bonded with a matrix as composite materials. Since the APM foam manufacturing procedure has been fully developed only recently, the mechanical characterization of these materials is still limited.

Figure 5. APM foam element (left) and the CT scan (right)

The computational simulations were based on the three-dimensional CT scan reconstruction modelling technique. The single APM elements showed a characteristic cellular material behaviour [15]. It has been observed that 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 also the heat generation due to 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 plastically 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].

A recent structural analysis of APM foam element using micro computed tomography revealed different levels of porosity (Fig. 6). Pore size from micro level (several micrometres in diameter) up to macro level (several millimetres in diameter) can be found resulting in high total number of pores in only one APM foam element.

Figure 6. μCT scan of the APM foam element

5. Conclusions

Computational models of some different novel types of cellular materials have been presented. In spite of complex and irregular geometry of the cellular structure, it is possible to build appropriate computational models by using some porous structure reconstruction techniques. The use of computational simulations consequently allows for faster characterization and unique insight in the deformation mechanics and behaviour of novel cellular materials under different types of loading.

6. References

[1] Ashby, M.F., Evans, A., Fleck, N.A., Gibson, L.J., Hutchinson, J.W. and Wadley, H.N.G. (2000), *Metal foams: a design guide*, Burlington, Massachusetts, Elsevier Science.

[2] Vesenjak, M., Veyhl, C. and Fiedler, T. (2012) *Analysis of anisotropy and strain rate sensitivity of open-cell metal foam*, Mater. Sci. Eng. A, 541, 105-109.

[3] Vesenjak, M., Krstulović-Opara, L. and Ren, Z. (2012) *Characterization of photopolymer cellular structure with silicone pore filler*, Polymer Testing, 31(5), 705-709.

[4] Körner, C. and Singer, R.F. (2000) *Processing of Metal Foams - Challenges and Opportunities*, Adv. Eng. Mater., 2(4), 159-165.

[5] Vesenjak, M., Fiedler, T., Ren, Z. and Öchsner, A. (2008) *Behaviour of Syntactic and Partial Hollow Sphere Structures under Dynamic Loading*, Adv. Eng. Mater., 10(3), 185-191.

[6] Nakajima, H. (2007) *Fabrication, properties and application of porous metals with directional pores*, Prog. Mater. Sci., 52(7), 1091-1173.

[7] Fiedler, T., Veyhl, C., Belova, I.V., Tane, M., Nakajima, H., Bernthaler, T., et al. (2012) *On the anisotropy of lotus-type porous copper*, Adv. Eng. Mater., 14(3), 144-152.

[8] Hallquist, J.O. (2006), *LS-DYNA theoretical manual*, Livermore, California, Livermore Software Technology Corporation.

[9] Hipke, T., Lange, G. and Poss, R. (2007), *Taschenbuch für Aluminiumschäume*, Düsseldorf, Alu Media.

[10] Vesenjak, M., Matela, J., Young, P. and Said, R. (2009) *Imaging, virtual reconstruction and computational material (tissue) testing*, Acta medico-biotechnica, 2, 19-30.

[11] Hohe, J., Hardenacke, V., Fascio, V., Girard, Y., Baumeister, J., Stöbener, K., et al. (2012) *Numerical and experimental design of graded cellular sandwich cores for multi-functional aerospace applications*, Mater. Design, 39(0), 20-32.

[12] Lehmhus, D., Baumeister, J., Stutz, L., Schneider, E., Stöbener, K., Avalle, M., et al. (2010) *Mechanical Characterization of Particulate Aluminum Foams—Strain-Rate, Density and Matrix Alloy versus Adhesive Effects*, Adv. Eng. Mater., 12(7), 596-603.

[13] Avalle, M., Lehmhus, D., Peroni, L., Pleteit, H., Schmiechen, P., Belingardi, G., et al. (2009) *AlSi7 metallic foams – aspects of material modelling for crash analysis*, Int. J. Crashworthiness, 14(3), 269 - 285.

[14] Stöbener, K., Lehmhus, D., Avalle, M., Peroni, L. and Busse, M. (2008) *Aluminum foam-polymer hybrid structures (APM aluminum foam) in compression testing*, Int. J. Solids Struct., 45(21), 5627-5641.

[15] Vesenjak, M., Gačnik, F., Krstulović-Opara, L. and Ren, Z. (2012) *Mechanical Properties of Advanced Pore Morphology Foam Elements*, Mech. Adv. Mater. Struc., accepted for publication.

[16] Vesenjak, M., Gačnik, F., Krstulović-Opara, L. and Ren, Z. (2011) *Behavior of composite advanced pore morphology foam*, J. Compos. Mater., 45(26), 2823-2831.