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Modelling of cellular materials by a microsphere-based material model

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Metal foams are a very interesting class of cellular materials which, due to their structure, can be used both for lightweight construction and for the absorption of kinetic energy. They have a microheterogeneous structure, which makes it difficult to simulate these materials efficiently. Although microstructure models are very precise in terms of strut size and pore geometry, they are very computationally intensive due to their high resolution and therefore do not allow the simulation of entire components. While continuum models that do not resolve the specific microstructure are very efficient, they do not allow the influence of variations in strut size, strut geometry or pore size to be modelled directly by the simulation. Therefore, simulation approaches such as microsphere models are necessary, which combine the macroscopic component scale with the microscopic microstructure.

1 Microsphere modelling approach

The microsphere modelling approach is a special case of the microplane theory of Bažant et al. [1]. The model is based on micro-macro bridging by introducing a unit sphere with a certain number of defined directions, the so-called microsphere, at each integration point of the macro model. The microsphere directions are defined as line elements from the center of the unit sphere describing the microsphere and the surface of the microsphere. At the microsphere for each direction a 1D constitutive law is attached. A deformation of the unit sphere applied in the reference configuration leads to an ellipsoid in the current configuration. While the microplane theory uses both kinematic projections in normal direction as well as in tangential direction to the specific directions of the microsphere and hence also stresses in normal direction and tangential direction, the microsphere theory [2] uses only the normal direction and thus only normal stresses.

This paper describes a microsphere model for the scale-bridging simulation of open-cell aluminium foams. The specific directions of the microsphere model are interpreted as orientations of individual struts in the macroscopic foam sample (see Figure 1). 42 directions are used for the discretisation of the microsphere following Bažant et al. [3]. For each direction a 1D elastic constitutive law derived from uniaxial tensile tests and uniaxial compression tests will be applied [4]. The macroscopic stress of a foam sample under loading then results based on the equality of the stress power of the material point in the finite element macro model (FE) and the sum of the stress power of the uniaxial stresses of the individual directions of the microsphere according to equation (1),

$$\mathbf{S} = \sum \omega_i \, S_i \, \mathrm{d}\mathbf{X_i} \otimes \mathrm{d}\mathbf{X_i}. \tag{1}$$

$\mathbf{S}$ is the homogenised macroscopic second Piola-Kirchhoff stress tensor, ω_i are weight factors taken from Bažant et al. [3] for a microsphere with 42 directions. $\mathrm{d}\mathbf{X_i}$ represents the line element in the reference configuration and S_i are the individual microscopic stresses for each direction i of the microsphere.

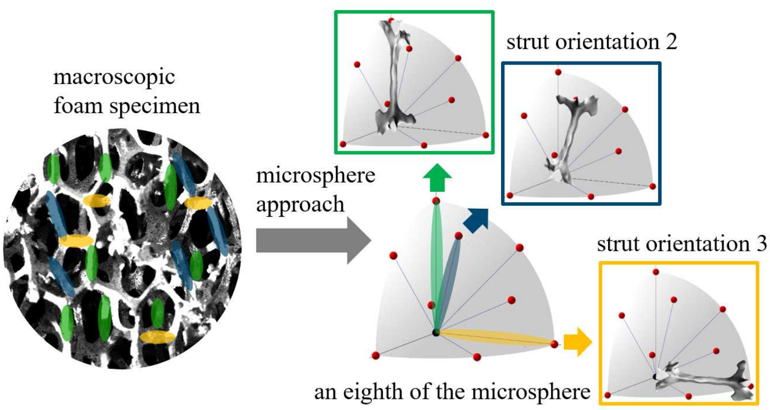

Fig. 1 Proposed microsphere approach for open-cell metal foams. Each strut represents a microsphere at a material point. The microsphere directions correspond to specific strut orientations in the macroscopic foam. Three different directions are exemplarily shown including its orientation in an eighth of the microsphere.

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2 Macro and micromechanical compression and tensile experiments on metal foams

Microtensile and microcompression experiments on individual struts of 10 ppi aluminium foams ($AlSi_7Mg_{0.3}$, from Celltec Materials GmbH (Dresden, Germany), were performed to provide the 1D constitutive laws used in the microsphere simulation. The struts were carefully extracted from the entire foam without a pre-damaging and than tested using a custom-made microtesting device developed by Jung et al. [5]. Three struts for each loading condition were characterised for sake of statistics. More details e. g. on the experimental setup and clamping can be found in a previous work [6].
Macroscopic uniaxial compression and tensile experiments on entire foam specimens of cuboid shape ($40 \times 40 \times 80\,mm^3$) were performed for validation of the proposed microsphere-based material model. The specimens were investigated using an ElectroPuls 10000 Instron ® universal testing machine (Pfungstadt, Germany) at a strain rate of $10^{-3}\,s^{-1}$ with the larger specimen dimension in loading direction.

3 Results and discussion

The received stress-strain diagrams from the microtensile and microcompression experiments were piecewise fitted by a linear interpolation resulting in six 1D constitutive laws for tensile loading and six constitutive laws for compresion loading as function of the applied strain. Figure 2 compares the homogenised macroscopic strain of the microsphere-based model with the macroscopic stress-strain curves from the uniaxial compression and tensile experiments of the macroscopic foams specimens. For both loading states, there is a very good correlation between the experimental and the numerical results. The simulation perfectly fits the experimental curve under tensile loading up to the failure of the foam. The following peaks in the simulated stress curve results from the subsequent failure in different directions of the microsphere model. In addition, also the compression tests can be perfectly described by the proposed microsphere model up to the plastic collapse stress of the foam, where the first pore layer collapses. However, the simulation is not able to account for the osscilations resulting from the successive collaps of the pore layers in the foam. The simulation gives a good correlation with the mean plateau stress but is not able to account for the transition between plateau stress and densification.

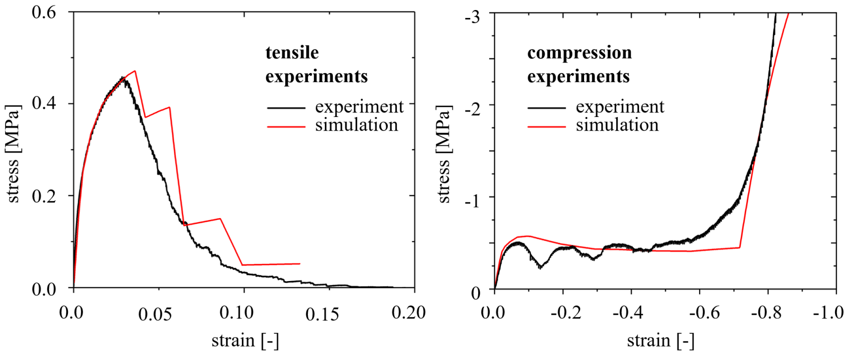

Fig. 2 Comparison of macroscopic experimental tensile (left) and compression (right) tests on open-cell 10 ppi aluminium foams with simulations using the microsphere-based modelling approach based on microtensile and microcompression experiments on individual foam struts.

4 Conclusion and future work

The proposed macroscopic microsphere-based material model is able to describe the material behaviour of macroscopic foams by simply using micromechanical experiments on individual struts. Hence, the model directly connects the real microstructure with the macroscopic foam behaviour. In contrast to conventional macro models, the presented model offers the advantage that it only requires uniaxial microtensile and microcompression experiments on single struts in order to take into account the influence of the microstructure. This leads to a drastic reduction in material costs and experiment time compared to the otherwise required macroscopic experiments, which all have to be repeated for each change of the microstructure. In future work, the model will be extended by 1D elastic-plastic laws to improve the model. Furthermore, a statistical analysis of the length and orientation of the struts in the foam will be performed to introduce additional microstructural information into the model by using the propability of the occurence of an orientation in the foam as weight factors ω_i in the microsphere model.

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