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Microstructural characterisation and experimental determination of a multiaxial yield surface for open-cell aluminium foams

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ABSTRACT

Metal foams are bio-inspired microheterogeneous materials, which exhibit a strong structure-property relationship. Their global mechanical properties depend strongly on the local micromechanical properties of the struts and on the pore geometry of the foams. A solid micromechanical and macromechanical understanding of the yield behaviour of the foams under realistic complex stress states is essential in order to be able to design components made of foams. However, up to now, experimental yield surface data for foams are very limited.

The present contribution deals with the structural characterisation of open-cell aluminium foams of different pore sizes by X-ray computed tomography (CT). The strut geometry e.g. regarding cross-sectional shape and the mass distribution along the struts is evaluated from the CT data. Yield surfaces for 10, 20 and 30ppi foams are experimentally probed by performing uniaxial tensile and compression tests, pure torsion as well as combined compression-torsion and tension-torsion tests. This results in one of the most comprehensive experimental data sets in the literature ever reported for open-cell aluminium foams. The shape of the yield surface and its degree of asymmetry were connected to the geometric data from the structural characterisation. It provides a deeper understanding of aluminium foams under complex multiaxial stress states.

1. Introduction

Cellular materials such as metal foams are an interesting class of bio-inspired microheterogeneous materials. They mimic natural materials such as trabecular bone, wood, cork, sponge, and coral [1] and consist of a 3D porous structure of stochastically distributed interconnected pores. Cellular materials have a great potential for application as light-weight construction elements or as energy absorbers [1–3].

The concept of scale separation, also known as the MMM principle says that microheterogeneous materials can be separated into different hierarchical levels, whereas foams are usually separated into three levels [4,5]. The macro scale comprises the entire component with application-oriented sizes, while the meso scale is governed by individual pores or a small number of pores, especially by the geometry, distribution and size of the pores. Finally, the micro scale is the lowest level and deals with individual struts, which are characterised by their composition, grain structure, grain size and inclusions. Due to their hierarchical design, cellular materials exhibit a distinct structure-property relationship, where the global mechanical properties of such materials display a strong morphological sensitivity. The global properties depend on the geometric constitution of the meso scale (morphology, pore size, pore geometry and distribution) [6–9], on the local micromechanical properties and geometry of the micro scale (strut material, grain size, strut geometry) [10–13] as well as on the relative density [1,14]. Grenestedt et al. [15] have proved the influence of wavy imperfections in cell walls and corrugated struts, while Gradinger et al. [16] and Li et al. [17] have studied the effect of density variations on the mechanical properties. Brothers et al. [18] and Jung et al. [19] have investigated so-called density-graded foams.

Evans et al. [20] have already stated in 2001 that establishing/determining relationships between the morphology and the mechanical properties of cellular materials is a challenging research area. Since then, a lot of research has been done with focus on the experimental and numerical characterisation of the mesostructure and its connection to the mechanical properties. Due to the limited possibilities to produce cellular materials with geometric variations, most of the work concentrates on numerical studies, where, e. g., the strut geometry including the mass distribution along the struts was changed [21,22] or variations in the cross-sectional shape on the global properties were investigated [8,17,23].

Experimental analysis of structural and geometrical effects were directly connected to X-ray computed tomography (X-CT) measurements. Comprehensive analysis on geometric dimensions and mass distributions along the struts of open-cell polymeric foams can be found

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by Gong et al. [7] and Jang et al. [8], while Jang et al. [24] and Maire et al. [25] provide a comprehensive analysis of aluminium foams.

The macroscopic experimental characterisation of foams has in great part be done by performing uniaxial compression testing and uniaxial tensile testing (e. g. [26–30]). However, foams are usually subjected to more complex multiaxial stress states in their applications than simple uniaxial compression or tension [31,32]. Yielding in homogeneous metals can be described by the von Mises yield criterion, which is independent from the hydrostatic component of stress. The yield surface in the deviatoric-hydrostatic stress space is given by two parallel lines to the hydrostatic stress axis. Yielding occurs only when the deviatoric stress reaches the yield line. As a result, a single experiment, such as a uniaxial experiment excluding hydrostatic stress, is sufficient to describe the complete yield surface of a bulk metal. Yielding in foams is not independent of hydrostatic stress due to the change in volume during external loading. This compressibility results in closed and convex yield surfaces [33–35]. Therefore, a single experiment is not enough to completely characterise the yield surface of foams [36]. Gioux et al. [31] found for closed-cell aluminium foams that uniaxial loading induces bending in the cell edges, while hydrostatic loading induces stretching. As a consequence, the plastic strength under uniaxial loading is much less than that of hydrostatic compressive loading. Similar results were obtained by Deshpande & Fleck [33], who concluded from experimental tests as well as simulations that the hydrostatic yield strength is about 20% larger than the uniaxial yield strength. Another feature that is often found in the yield surfaces of metal foams is a tension-compression asymmetry, where the yield surface is shifted in direction to the compressive quadrant. In sum, this clearly shows the need for multiaxial testing of foams.

A typical yield surface for a foam consists of a convex envelope in the deviatoric-hydrostatic stress space [37]. The foam remains (pseudo-)elastic within the yield surface and outlines plastic yielding by the successive pore collapse on the yield surface. A detailed understanding of the yielding and failure of foams under complex multiaxial stress states is necessary in order to be able to produce lightweight structures or energy absorbers made of foams with optimal design [38]. Although the mechanical behaviour of foams under simple uniaxial loading has been studied extensively, experimental studies investigating the failure and the yield behaviour of foams under multiaxial loading are limited due to the complexity of performing multiaxial experiments on foams. Hence, most works on yield surfaces focus only on theoretical models but are not experimentally validated (e. g. [32,39-45]).

The exploration of a full yield surface for solid foams requires a series of uniaxial as well as multiaxial tests under tension, compression, shear and hydrostatic loading. In particular, the experimental testing under multiaxial loads is a very challenging task. The majority of studies on yield surfaces of foams covers only a small part of the yield surface as a result of the variety of different experimental test methods needed for probing a yield surface. Especially multiaxial stress states with superimposed tensile axial stress are very limited [46]. Most of the known yield surfaces consist of only 10 to 15 yield points, which have been compared with different theoretical yield models (e. g. [31,47-50]).

Some of the first multiaxial experiments on open-cell aluminium foams were conducted by Triantafillou et al. [51] using a combination of axial tension and radial compression. The experiments have been used to validate the failure surface developed by Gibson et al. [39]. Deshpande et al. [33] experimentally investigated the yield behaviour of open-cell and closed-cell aluminium foams under uniaxial and hydrostatic loadings as well as under proportional axisymmetric load conditions. They developed two phenomenological models for the initial yield surface and its evolution under successive loading. Further triaxial compression tests on aluminium foams were conducted by Ruan et al. [37].

Additional yield data for open-cell and closed-cell aluminium foams under a variety of biaxial, shear and axisymmetric loading were reported by Gioux et al. [31]. Öchsner et al. [52] as well as Ehlers et al. [35] developed new devices for the investigation of cellular solids under biaxial stress states. Some studies were performed on polymer foams [53–55] as well as aluminium foams [48,50,56-58] using the Arcan method. Taher et al. [54] developed a modified Arcan fixture in order to investigate the tensile and compression region of the yield surface. The normal Arcan fixture, however, can only be used for combined shear-tensile loading. Further combined shear-compression tests on open-cell aluminium foams were carried out by Jung et al. [59] using a commercial shear load frame with superimposed compression loading.

Finally, shear loading and combined shear-tensile/shear-compression loading of polymer foams [47,49,60] and aluminium foams [31,46,61] can be realised by torsion testing with and without superimposed axial loads. Torsion testing of closed-cell PVC foams was conducted by Christensen et al. [47] using an axial-torsion biaxial test device. PU foams were investigated by Chuda-Kowalska et al. [62].

Hanssen et al. [61] were the first to investigate the multiaxial failure behaviour of closed-cell aluminium foams and to validate a constitutive model by applying a multitude of different experimental methods. Reyes et al. [63] developed a symmetric yield surface using the multiaxial experimental data determined for aluminium foams by Hanssen et al. [61]. Peroni et al. [36] conducted one of the most detailed studies on the multiaxial characterisation of closed-cell aluminium foams by performing uniaxial tensile and compression tests, torsion tests, hydrostatic tests as well as hydro-compression tests. Up to now, the most recent experimental work providing the most comprehensive data set on yield surfaces ever produced for any foam was done by Shafiq et al. [64]. They investigated PVC foams by using a new costum-built multiaxial testing apparatus, that covers the entire range of multiaxial loads from hydrostatic compression to hydrostatic tension. Like to Deshpande & Fleck [34], they used so-called 'maltese-cross specimens', which are of complex shape and not easy to manufacture but provide accurate results under different loading conditions. The yield surface for the PVC foams was of elliptic shape and shifted in direction to the tension-tension quadrant. Additionally, Shafiq et al. [64] gave a detailed review on yield surfaces of foams and the probing of these.

An elliptical yield surface in the deviatoric-hydrostatic stress space was found in most investigations for aluminium foams [39,61] and for polymer foams [49,51,64,65]. Deshpande & Fleck [33,34] as well as Christensen et al. [47] extended the elliptical yield surface by a cut-off tensile stress criterion. Ayyagari et al. [66] developed a multiaxial yield surface of elliptical shape based on the experimental results found by Shafiq et al. [64] for transversely isotropic foams. Unlike the majority of yield surfaces in the literature, similar to Miller et al. [32] they account for the tension-compression difference in the yield behaviour. The main hypothesis in the model of Ayyagari et al. [66] is that the yielding in the foam is driven by the total strain energy density.

The present contribution deals with the structural characterisation of aluminium foams of different pore sizes by X-CT. The cross-sectional shape and the mass distribution along the struts as well as the strut length and the critical buckling force are evaluated from the CT data. Furthermore, the macroscopic material behaviour is investigated by uniaxial compression and tensile tests as well as by pure torsion tests and torsion loading with superimposed uniaxial tensile or compression loading. This study offers one of the most comprehensive experimental data sets in the literature ever reported for open-cell aluminium foams. Yield surfaces are probed for 10, 20 and 30 ppi (pores per inch) foams, where significant changes occur in the shape and size of the closed yield surface. These changes were directly correlated to the geometrical characteristics determined from the CT measurements.