Correlation between fracture behaviour and ductility of the cell strut material in case of metallic foams

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ABSTRACT

The aim of this paper is to report on the characterization of the influences of foam homogeneity and the cell strut material on the mechanical behaviour and the fracture mode of metallic foams. For two open-cell foams with identical cell geometries produced in the same precision casting process but using different cell strut materials, the stress-strain behaviour and the evolution of damage until fracture is compared. To account for effects arising from a change in the geometry of the cell structure and the resulting homogeneity of the foam, the main characteristics of fracture for the group of closed-cell foams were included in this study. Monotonic tests carried out in compression revealed that foam homogeneity is the major factor with respect to the formation of deformation bands in metallic foams. The influence of the cell strut ductility is particularly pronounced in monotonic tension where the fracture mode changes from extremely brittle fracture to strongly plastically deformed cells, with substantial fracture elongation. In tension-tension fatigue as well as under symmetric push-pull loading conditions, damage is governed by a combination of cyclic creep and fatigue crack propagation through the specimen. From a mechanistic point of view no fundamental differences between the three foams tested were detected for these loading conditions. However, in compression-compression fatigue the same dependencies in terms of homogeneity and ductility influence the mechanisms of strain evolution that are active in monotonic compression.

1 INTRODUCTION

In the last few years much effort has been placed on the development of numerous processing routes for closed-cell and open-cell metallic foams with the objective to improve the homogeneity of their structure. Now, several foams with outstanding properties are available, which fulfill the needs of industrial applications. The low cost closed-cell aluminium foams have been established as crash energy absorbing materials in technical components such as bumpers of railway trains, cars or nuclear waste containers. Open-cell metallic foams exhibit even better homogeneity, the processing by precision casting is complex though and therefore open-cell foams are expensive. Reasonable applications have to make use of the special multifunctional properties of the open-cell structure taking particular features into account, such as the permeability for fluids or the enormous strut surface for catalytic applications. The mechanical behaviour of metallic foams in the case of monotonic compression is quite well understood (e.g. [1-3]) and can be controlled by adjusting the porosity of the foam and the microstructure of the cell-wall material. However, for more advanced structural and functional applications not only the monotonic but also the cyclic loading behaviour and the influence of cyclically fluctuating temperature (thermomechanical fatigue, TMF) has to be taken into account.

2 EXPERIMENTAL

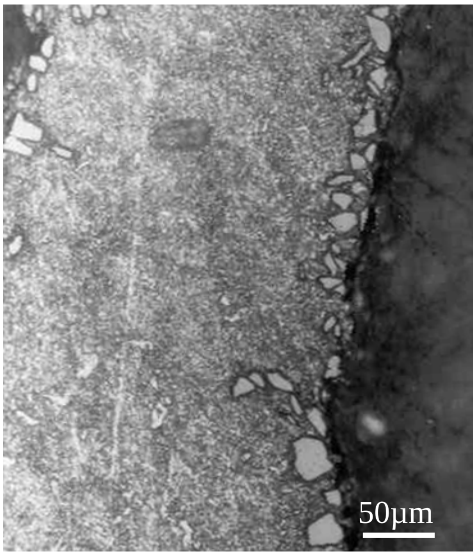
Mechanical testing of the foam specimens was performed under monotonic loading conditions as well as under fatigue loading conditions using servohydraulic testing systems. Since the compressive strength of all tested foams is not sufficiently high for clamping the specimen directly with hydraulic grips, the samples were glued to special gripping mounts. The gluing with an epoxy resin was arranged in the testing system itself to achieve an excellent alignment of the specimen and preventing residual stresses arising from the gripping. In order to measure the integral strain of the specimen, adapter plates were screwed to the gripping mounts on which an extensometer was attached. For monotonic compression tests the specimens were deformed between two steel plates which were polished to minimize the influence of strain constraints due to friction. Monotonic tensile and compression tests were carried out in displacement control applying constant deformation rates. Fatigue tests were performed using closed-loop load control with a triangular wave shape of the control signal.

3 RESULTS AND DISCUSSION

3.1 Materials and microstructure

The mechanical properties of three different materials were examined taking into account the microstructures. One of them was the closed-cell aluminium foam HAL 175/4/1 (HAL) of composition AlSi7Mg produced following a melt route [4] with an addition of 15 Volume-% of silicon carbide particles in order to stabilize the foam which is produced by means of the introduction of compressed air into the melt. These particles tend to gather on the surface of the cell walls and decrease the surface tension [3,4]. Besides the foam-stabilising effect the addition of SiC particles comes along with some detrimental influences concerning the fracture behaviour. First of all, an increase in the Young`s modulus can be observed that is due to the high elastic modulus of the ceramic particles, which on the other hand are responsible for the transition of the fracture behaviour towards brittle failure. With respect to cyclic loading conditions a second effect of the particles plays an important role. As mentioned before, the particles tend to occupy the surfaces of the cell walls. Moreover, they are prevalently sticking out of the surface (see figure 1) making the surface extremely rough. The stress concentration arising from the outsticking SiC particles facilitates the initiation of fatigue cracks.

In comparison to the closed-cell foam two materials representing the group of open-cell metallic foams were tested. Both foams were provided by Gießerei-Institut Aachen (technical university) and manufactured by a precision casting process [5] reproducing a very regular polymer precursor foam on the basis of polyurethane. The resulting metallic foam structure features the same homogenous and regular structure as the precursor foam. Depending on the alloy chosen, some microstructural peculiarities can result from the casting process. As shown in Fig. 2 the microstructure of the tested open-cell foam of composition AlSi9Cu3 exhibits an extremely coarse grain structure with grains extending over the entire cell strut diameter. As a result of the high silicon content of the aluminium alloy, the formation of silicon precipitates at the grain boundaries [6] can be observed. At the surface of the cell struts, these brittle precipitates are attacked by the high pressure water jet which is required to remove residues of the ceramic filler, used for the casting process, leaving notch-like defects. Starting from those notches cracks can initiate and easily propagate along the grain boundaries that are weakened by persistent paths of silicon precipitates. As a second open-cell metallic foam material, α-brass was employed. The microstructure of this foam is much less critical with respect to mechanical loading, because grain sizes are much smaller and no brittle precipitates are present.



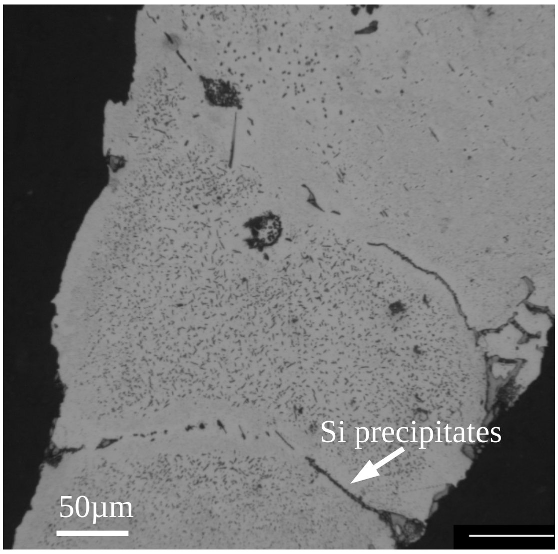


Fig. 1: SiC particles occupying the surface of a cell wall of a closed-cell foam

Fig. 2: Coarse grain within the cell struts of open-cell aluminium foam

3.2 Monotonic tests

The mechanical response during monotonic compression of all metallic foams is dominated by an expanded stress plateau in the stress-strain curve that follows a short region of quasi elastic deformation [3,4]. Within this stress plateau, macroscopic damage is caused by the collapse of particularly weak cells leading to the formation of deformation bands. The ductility of the cell strut material as well as the homogeneity of the structure primarily determines the processes operative in this region. In order to compare the stress level despite the different densities of the three materials, in Fig. 3 the specific stress is plotted normalizing the stress with respect to density. Obviously, the closed-cell aluminium foam (HAL) exhibits a much higher specific strength than the open-cell foams and thus, its capability for crash energy absorption is superior. The addition of silicon-carbide particles enhances the effective properties of the cell wall material like its strength and its resistance against buckling [3]. On the other hand, additional mechanisms such as decohesion or fracture of particles lead to a more complex fracture behaviour. As a result of brittle fracture behaviour in combination with an insufficient homogeneity of the cell geometry, pronounced oscillations in the stress-strain response can be observed for the closed-cell foam. For a distinction between the influence of material`s ductility and the influence of foam homogeneity, stress-strain curves of two open-cell foams were compared. Both foams exhibit identical cell geometries and a good homogeneity and, hence, stress oscillations are smaller as compared to the closed-cell foam. The deformation distribution becomes more uniform with enhanced homogeneity and the tendency to form deformation bands is reduced. However, the stress-strain curve of the extremely ductile brass foam is found to be even smoother, because fracture of cell struts plays a minor role.

The significance of the ductility of the cell strut material becomes evident from the stress-strain response in monotonic tension (see Figure 4). Whereas in compression strong plastic deformation for all types of foams prevails, the fracture elongation in tensile testing is reduced to values of about ε=1% in the case of the brittle cell strut materials. Both the closed-cell and the open-cell aluminium foam present a macroscopic brittle fracture mode without any indication of deformation within the cell geometry. In contrast to this, the cell struts in the open-cell brass foam show massive plastic deformation after unloading during the tensile test. The elastic region for the brass foam ranges up to a specific stress of about 2MPa/(g/cm^3) in tension as well as in compression. In compression, further loading causes instabilities in terms of buckling of cell struts establishing a nearly horizontal stress-strain curve. Exceeding the yield strength in tension leads to the formation of plastic hinges in the cell struts and work hardening increases the load response.

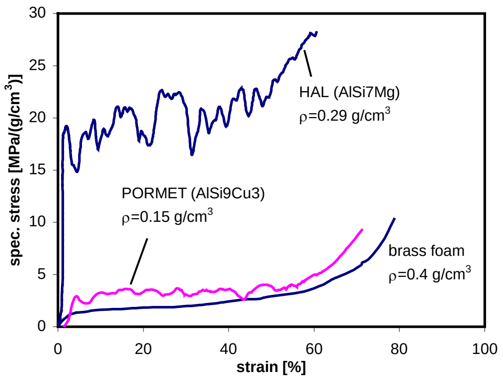


Fig. 3: Stress-strain behaviour under monotonic compression of metal foams

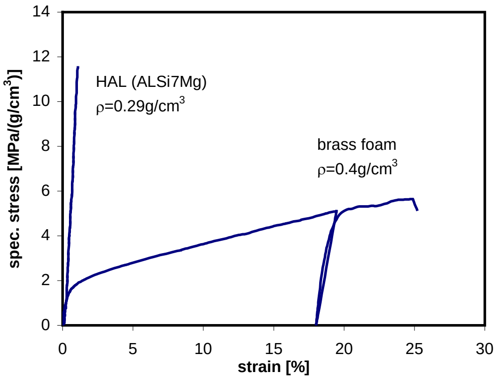


Fig. 4: Tensile behaviour of metal foams

3.3 Cyclic loading conditions

Since significant differences in the mechanical behaviour of foams under monotonic loading conditions depending on their ductility and homogeneity were observed, similar relationships were expected to manifest themselves under cyclic loading.

Compression-compression fatigue tests revealed a deformation mechanism very similar to that found in monotonic compression for the brittle closed-cell aluminium foam. If the applied load amplitude is sufficiently high, the evolution of strain for the closed-cell foam as depicted in Fig. 5 shows a stepwise progression. Deformation of the specimen is strongly localised in deformation bands while other regions of the specimen remain completely undeformed (see also [7]). Every step in the strain evolution is related to the formation and the subsequent collapse of one single deformation band. Already the collapse of a first deformation band may separate the specimen into two parts. Microscopic observations of the fracture surfaces show massive destruction of the cells in the region of a deformation band.

With increasing homogeneity of the foam the appearance of deformation bands becomes less pronounced. Only slight steps in the progression of strain can be found for the open-cell aluminium foam. The ductile open-cell brass foam finally exhibits a uniform strain distribution where no abrupt collapse of deformed cells takes place. Consequently, the strain evolutes nearly linear (Fig. 6) up to a total strain of about ε=40%. At higher deformations global densification sets in, when cell struts get in contact with their neighbouring cells and the strain rate decreases [8].

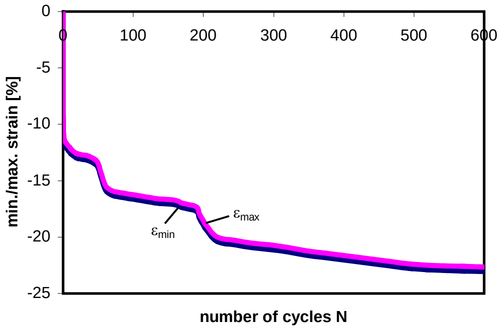


Fig. 5: Strain evolution in compression-compression fatigue of a closed-cell aluminium foam (HAL)

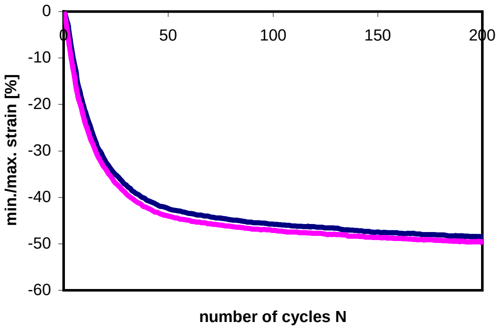


Fig. 6: Strain evolution in compression-compression fatigue of an open-cell brass foam

In tension-tension fatigue as well as under symmetric loading conditions damage evolution is governed by cyclic creep in the first stage of a fatigue test. Progressive lengthening of the specimen can be attributed to an alignment of the cell struts into the direction of the applied load. In a later stage fatigue cracking of cell struts becomes dominant [9] and leads to the formation of a macroscopic fatigue crack. Propagation of the macroscopic crack increases the compliance of the specimen in the tensile regime where fractured cell struts do not contribute to the stiffness. Compressive stresses force the fractured struts to get in contact again and thus the stiffness in compression remains nearly unaffected. Fig. 7 depicts the evolution of the last hysteresis loops prior to failure for a fatigue test of the PORMET foam. Typically, the fatal crack that finally causes failure is running through weak regions of the specimen. Especially in the case of the closed-cell aluminium foam, particularly huge pores were observed on the fracture surface as it is illustrated in Fig. 8.

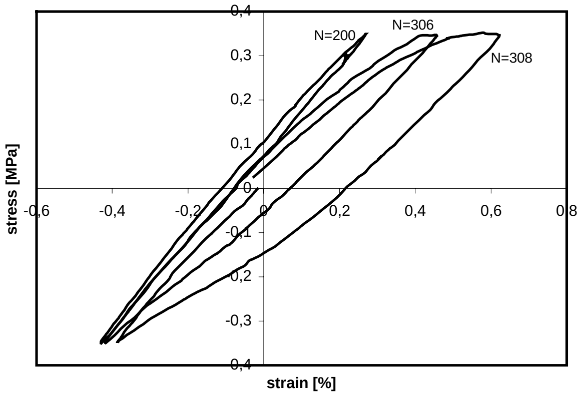


Fig. 7: Evolution of the last stress-strain hysteresis loops prior to failure (PORMET)

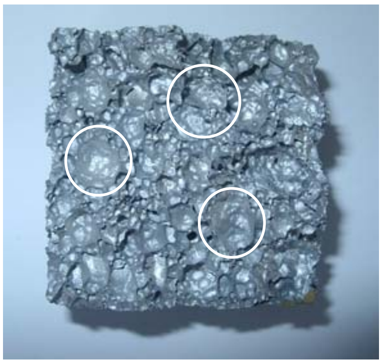


Fig. 8: Particularly huge pores on the fracture surface of a HAL foam after fatigue testing

4 CONCLUSIONS

The mechanical response and the fracture behaviour of metallic foams are strongly influenced by the homogeneity of the cell structure on the one hand and by the ductility of the cell strut material on the other hand. Inhomogeneous foams show a distinct localisation of deformation in deformation bands if they are loaded in compression. The collapse of foam cells is the main reason for a permanent oscillation of the stress in the plateau regime during monotonic compression. When the homogeneity is enhanced, these stress oscillations disappear and the tendency for the formation of deformation bands decreases. In case of the ductile and homogeneous open-cell brass foam a uniform distribution of deformation was found.

The effect of enhanced ductility of the cell strut material becomes obvious for monotonic loading conditions. Whereas brittle fracture with fracture elongations of about $\varepsilon=1\%$ prevails for the open-cell aluminium foam, the brass foam featuring identical cell geometries reaches fracture elongations of up to $\varepsilon=25\%$ with strongly deformed cells.

Fatigue loading in tension-tension as well as under fully reversed loading conditions is generally connected to a combination of cyclic creep and fatigue crack propagation. With respect to damage mechanisms and fracture no significant differences for all three foams tested became apparent for fatigue under tension-tension and under fully-reversed loading conditions. In compression-compression fatigue, however, the closed-cell aluminium foam exhibits a pronounced localisation of damage in deformation bands and, thus, a stepwise evolution of the strain in the progression of the fatigue test is evident. The homogeneous and ductile brass foam in contrast features a nearly linear evolution of strain and uniform deformation.

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