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Fatigue behaviour of aluminium foams

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Aluminium-silicon foams were characterised under uniaxial static and cyclic loading. The static compression tests were used to obtain values for the compression strength. Fatigue tests on foam samples were then carried out in compression at maximum stress levels ranging from 50 to 80% of the static compression strength. The failure of the foams was monitored and a Wöhler-like diagram was constructed. Difficulties arising in the measurements are discussed.

Introduction

In the past few years there has been a considerable increase in interest for metal foams especially of aluminium or aluminium alloys. The reason for this are recent process developments which promise a better quality of the foamed material [1-5]. There are many possible applications for aluminium foams ranging from lightweight construction, sound and heat insulation to energy absorption applications. Structural light-weight applications make use of the high specific stiffness of foams. Especially sandwich structures consisting of a foamed layer and massive metallic face sheets are attracting the automotive and aerospace industry [6].

Quite some work has been carried out in characterising static mechanical properties of metal foams - e.g. the compression strength, Young's modulus, mechanical damping, or bending strength [7-11] and in discussing the data in terms of theoretical models [12]. However, only very little is known about the behaviour of metal foams under cyclic loading (see Ref. 13, e.g.). Therefore, measurements were carried out to obtain some first data which can be used in the design of light-weight structures. As the main interest is currently concentrating on aluminium foam sandwich panels [6] manufactured using a powder metallurgical route, samples made by means of this method were used. The test specimens were chosen to be as close as possible to the foams used in these applications with respect to their density and alloy composition.

Sample preparation

Metal foam samples were produced by the powder metallurgical Fraunhofer-process [3]. According to this process aluminium powder (purity 99.5) was mixed with 7 wt.% silicon powder (purity 98.5) and 0.5% titanium hydride (TiH_2) powder. The mixture was hot extruded to rectangular bars. In the resulting composite the blowing agent TiH_2 was homogeneously distributed within a dense, virtually non porous heterogeneous Al+Si matrix. Pieces of this composite were placed inside a simple closed mould of cylindrical shape (h=60mm, d=44mm). The actual foam was then obtained in a second step by heating the mould up to about 700° C. During this step the metal melted and at the same time the blowing agent slowly released hydrogen. The metal turned into a semi-solid, slowly expanding foamy mass. The aluminium and silicon powders form an alloy during this process. Foaming was stopped by simply cooling down the mould. The density of the foams was controlled by inserting a certain quantity of the foamable material into the given volume. Foams of 3 different densities were manufactured this way: 0.55, 0.63 and 0.94 g/cm^3 (±0.1 g/cm^3).

The resulting foamed samples had a closed outer skin (Figure 1). When a sample was cut apart, the highly porous structure became visible (Figure 2).

Quasi-static compression tests
Quasi-static tests were performed on a number of samples to obtain the compression strength of the foams which should be used as a reference strength in the fatigue tests. All foams whatever material they are made of show the universal deformation behaviour which is depicted in schematical form in Figure 3: for small compressions one observes an increase which changes into a regime of very strong plastic deformation after a few percent deformation. Sometimes an upper and lower yield point is observed [7]. After a phase of strong deformation the foam is densified and the stress levels grows very quickly.

The definition of compression strength, is not unambiguous. Some of the various possibilities to define this quantity are shown in Figure 3. In the present study we chose the extrapolation method („3") to determine the compression strength of the foams.

Compression strengths were determined for 5 samples of each of the three densities investigated (Table 1). The averaged value for each density was used as reference compression strength σ_{qs} in the fatigue tests. As only in the case of the two lower densities the statistical variation of the strength was acceptable, fatigue measurements were only carried out for these densities.

Fatigue tests
Cylindrical foam samples were exposed to the cyclic, purely compressional loading defined in Figure 4. The stress was varied between an upper bound σ_u and lower bound σ_l with an amplitude of $2\sigma_a$. A load ratio $\sigma_u/\sigma_l=10$ was chosen. Stresses are calculated assuming a constant apparent area of the sample all through the experiment. The testing frequency was 3 to 10 Hz. Because the onset of compression is somewhat undefined due to the not exactly planar faces of the sample and owing to some initial settling in the foam, all samples were pre-loaded with an initial stress of 0.1 MPa.

All samples were cycled up to $3{\cdot}10^6$ times. The maximum stresses were chosen to be between 50 and 80% of the measured averaged compression strength σ_{qs}. During cycling the strain was constantly monitored. The gradual deformation under cyclic compression is shown in Figure 5.

One sees that a similar failure pattern is observed in all cases. The initial deformation due to pre-loading is about 1 mm. One observes a very gradual compaction for some 10^4 or 10^5 cycles. Then within a few hundred cycles the foam starts to yield strongly and is strained by a few millimetres. After this initial yielding the rate of straining decreases but the destruction of the foam continues.

It is very difficult to detect the features leading to fatigue failure in the foam because already the unloaded foam is full of cracks and crack propagation is hard to observe. The foams seem to fail in a similar way under static and cyclic loading: certain regions with an unadvantageous cell wall arrangement, or possibly holes or cracks in their walls collapse first, causing the subsequent failure of neighbouring cells. Finally, deformation planes are formed in the foam. Figure 6 shows one such example.

One can somewhat arbitrarily define a failure criterion and determine the number of cycles up to failure for various maximum stresses in order to obtain a Wöhler-like curve for the foam. One such diagram is shown in Figure 7. Failure was assumed after more than 2 mm (3%) deformation (including the initial deformation due to pre-loading).

One sees that most foam samples failed between 10^4 and $2{\cdot}10^5$ cycles for the stresses applied. The scatter of the results is considerably higher than for the quasi-static tests as one expects. Only in two cases the samples survived the maximum number of cycles ($3{\cdot}10^6$) at stress levels between 50 and 60% of the quasi-static compression strength. From the results obtained one can not derive an endurance limit in a reliable way but it can be estimated that it is below 50% of the static compression strength.

These findings differ from what other authors have found in preliminary tests [13]. Tests on aluminium foams which were made using the same powder-metallurgical route yielded endurance limits ranging from 75 to 95% of the compression strength. Possible reasons for this difference include a different definition of the failure criterion, possible differences in the definition of compression strength and the different alloy composition of the samples used. Moreover, samples without face skins were used.

Conclusions

In trying to characterise the fatigue behaviour of foams one encounters various difficulties:

– the static compression strength varies even when the density of various foams is the same,
– this applies even more to fatigue failure because fatigue properties depend more sensitively on cell arrangements or crack densities in the foam,
– having to relate stresses in fatigue tests to static compression stresses one even combines the two sources of error.

One can therefore draw the conclusion that one needs more samples (perhaps 100 or more) to obtain reliable estimates for the endurance limit, many more than used in the present study. If one thinks of studying effects of density, alloy composition, heat treatment or pore morphology on fatigue properties, one immediately realises that this can be a formidable task.

References

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Tables and Figures

density ρ [g/cm^3]	av. strength σ_{qs} [MPa]	variation $\Delta\sigma_{qs}$ [MPa]
0.55	7.1	$\pm$ 0.2
0.63	8.8	$\pm$ 0.2
0.94	19.4	$\pm$ 2.4

Table 1: Results of quasi-static compression tests

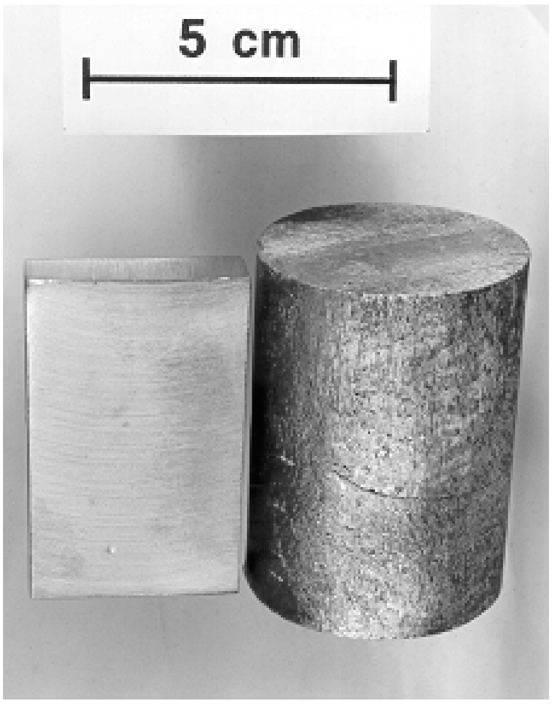

Figure 1: Left: unfoamed aluminium alloy precursor material, right: corresponding foamed part as used for the tests.

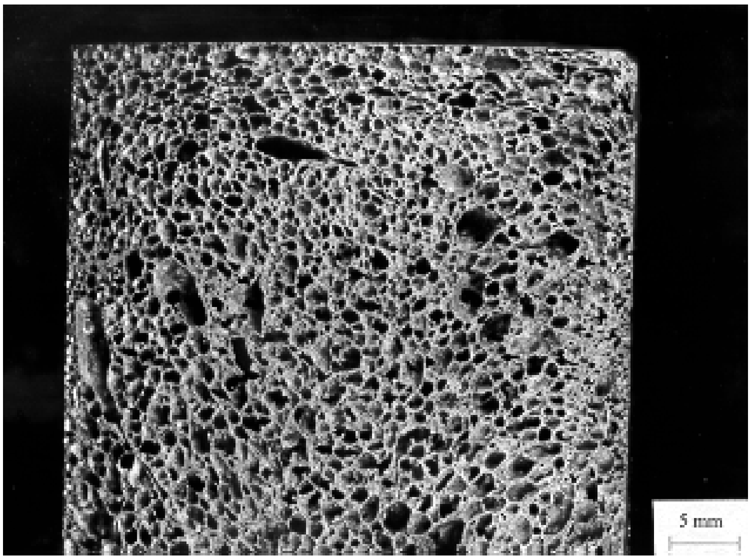

Figure 2: Pore structure of a metal foam sample as shown in Figure 1 (density 0.55 g/cm^3).

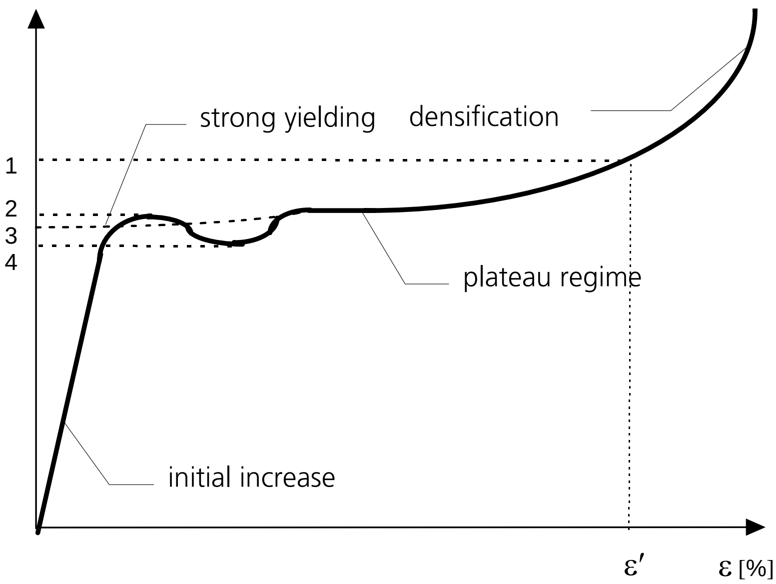

Figure 3: Schematical stress-strain diagram of a foam. The numbers denote the various compression strengths. 1: compression under a given load, 2: upper yield strength, 3: strength extrapolated to ε=0 from the stress-strain curve in the plateau regime, 4: lower yield strength.

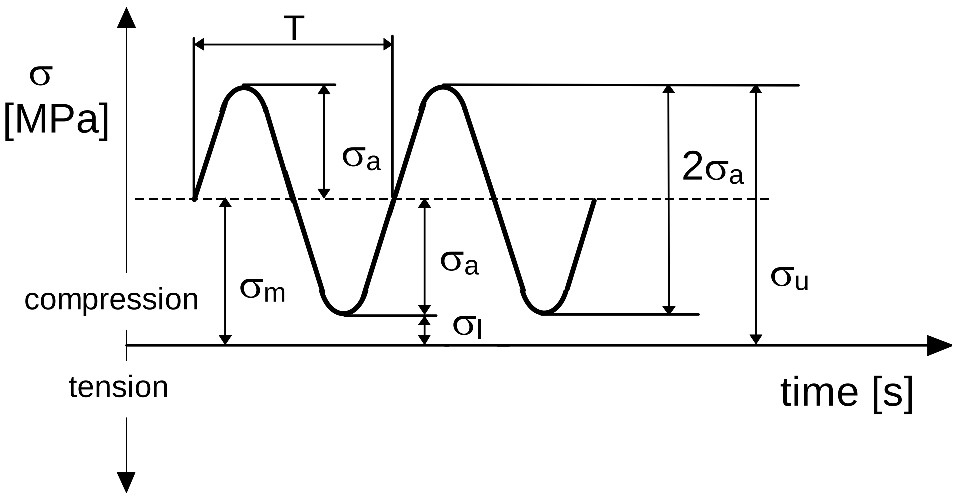

Figure 4: Definition of forces applied in fatigue tests.

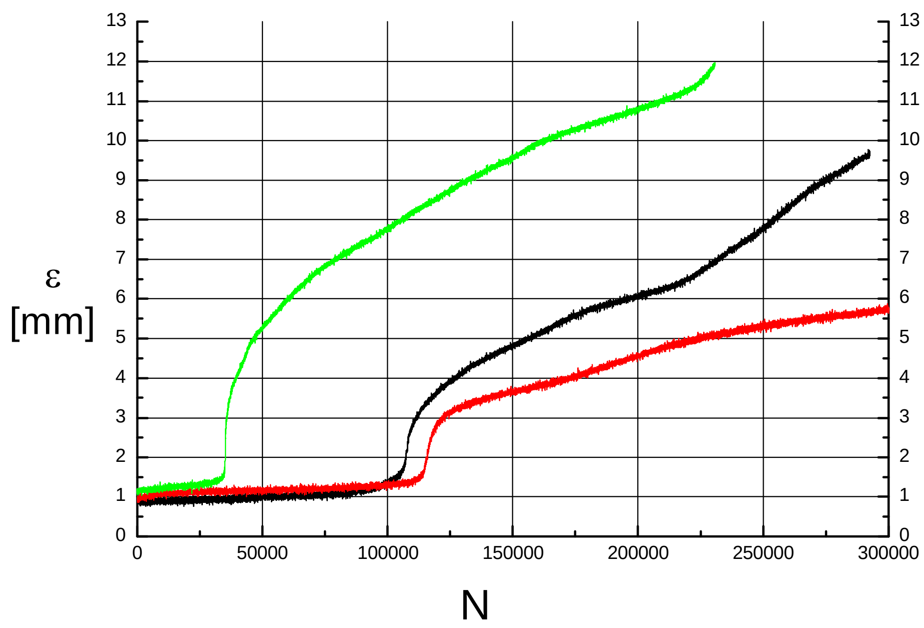

Figure 5: Deformation of AlSi7 foams (density $0.55 g/cm^3$) under cyclic loading with σ_u= 4.6 MPa.

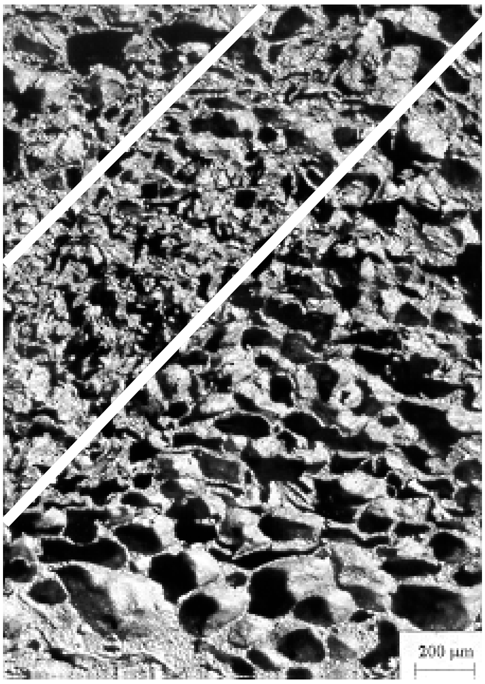

Figure 6: AlSi7 foam after 50% deformation. White lines indicate the boundary of a deformation plane.

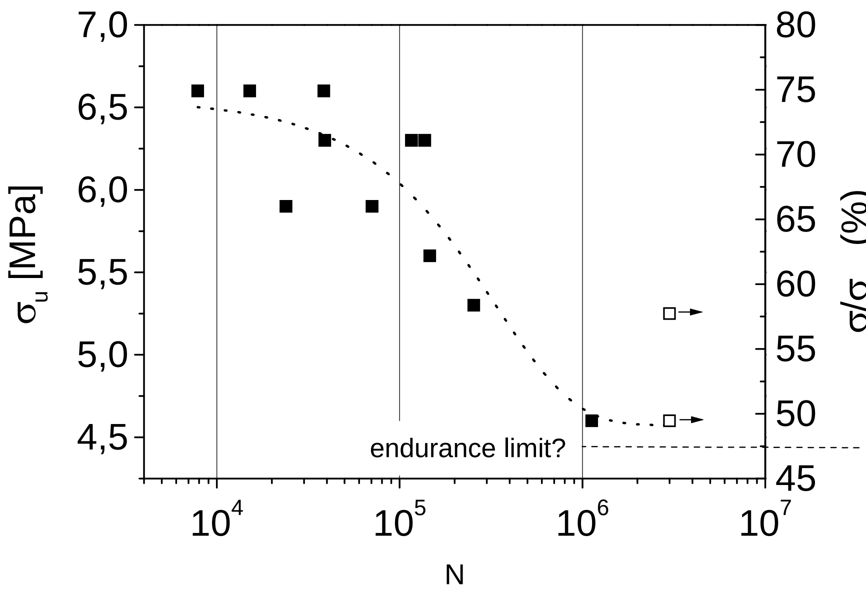

Figure 7: Results of fatigue tests on AlSi7 foams with density 0.63 g/cm^3. Full squares: <$3{\cdot}10^6$ cycles, open squares: no failure after $3{\cdot}10^6$ cycles.