Influence of heat treatment on fatigue phenomena of aluminium foams under compressive loading

D. Lehmhus, C. Marschner, J. Banhart, Fraunhofer Institut für Fertigungstechnik und Angewandte Materialforschung (IFAM), Bremen; **H. Bomas**, Institut für Werkstofftechnik, Universität Bremen

Abstract

Metal foam specimens are produced by means of the powder-metallurgical method. The foams were made of a wrought aluminium alloy similar to AA 6061 and were subjected to a precipitation hardening treatment after foaming. Fatigue tests of the specimens were carried out under compressive loads. The compression vs. cycle number curves and the observed failure patterns are assessed. Values for fatigue strength are obtained and compared to the static strength found for corresponding specimens.. As a reference alloy with a different failure mode aluminium foam based on the cast aluminium alloy AlSi7 is examined which is known to exhibit a more brittle failure.

1. Introduction

Within the last few years renewed interest in fields like light-weight construction has fuelled many efforts to improve processing techniques for metallic foams. While these efforts continue, the recent achievements in processing have created a situation in which knowledge of materials properties becomes vital: although characterisation of cellular metals began as soon as the first laboratory samples had been produced the data base so far available is by no means comparable to the broad range of knowledge gathered over the decades for conventional but nevertheless competing materials. It is mostly a lack of knowledge rather than an assumed inferiority of properties that still keeps metal foams off the market. In order to improve this situation the determination of properties and the development of ways to adapt them is of primary importance for raising the acceptance of an unconventional class of materials. Among these properties, fatigue is of paramount importance. This is exemplified by the different studies that dealt with this subject in the past. They are dedicated to the evaluation of tension-compression (1), tension-tension (2) or compression-compression (3) load cycles and shed light on such parameters as matrix alloy (4) or foam density (3). Investigation of failure mechanisms for a number of these combinations has begun. In addition to these studies others have shown the potential of heat treatment for adapting and improving properties of aluminium foams as shown in static tests (5,6). The aim of this study is to extend the latter ones to the realm of fatigue loading conditions.

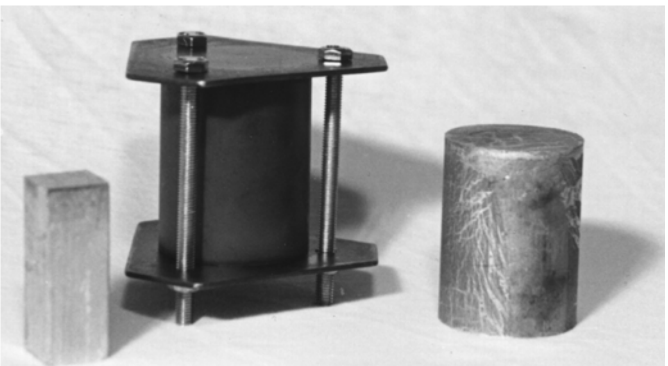

Fig. 1: Precursor material, foaming mould and foam sample

2. Experimental

2.1. Sample preparation

The study compares Al foam samples produced by means of the IFAM process (7,8). The dimensions of these samples are: diameter 44.2 mm, height 60 mm. Fig. 1 gives an impression of the foam samples, the corresponding precursor material and the mould that was used to make the foams. As a matrix alloy AlMgSi1Cu in a composition similar to AA 6061 was chosen. The samples made from this alloy are tested in an “as foamed” and a precipitation hardened state. AlSi7 samples were also tested for matters of comparison and data from a previous publication was included (3). The density of the foamed specimens was 0.6 ± 0.03 g/cm^3 for the AlMgSiCu samples and 0.6 ± 0.05 g/cm^3 for the AlSi7 samples.

The heat treatment of the samples is a conventional precipitation hardening cycle. As such, it consists of three steps, namely *solution heat treatment*, *quenching* and *ageing*. In this case, warm ageing was chosen. The parameters used as well as a representation of the principle are shown in Fig. 2.

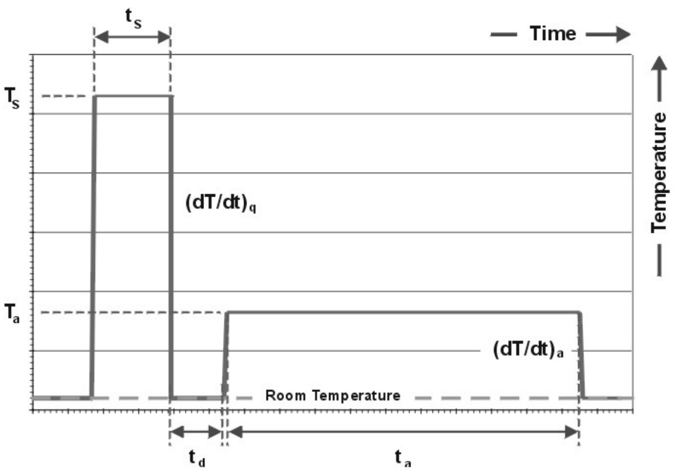

Fig. 2: Heat treatment temperature cycle and parameters

Heat treatment parameters can in general be taken from sources dedicated to the heat treatment of conventional Al parts, e.g. Ref. 9. Special attention must be paid to the question whether the parameters given in such compilations are actually sufficient to achieve the required quenching rates within all sections of an aluminium foam sample. This question will be discussed in more detail elsewhere (10).

2.2. Testing procedures

<u>*2.2.1. Static tests*</u>

The tests for establishing static strength values for the foam samples were carried out using a Zwick model 1474 testing machine. They were performed as quasi-static tests with a constant global strain rate of 5 mm/min. Single tests were either stopped at 80 % deformation or when reaching a force of 95 kN, corresponding to an overall stress level of approximately 62 MPa.

In static compression tests performed on aluminium foams, two fundamental failure modes are observed. Brittle failure is supposedly controlled by breaking of cell walls and struts, while ductile failure is based upon bending rather than breaking of these basic structural elements. Stress-strain curves representing these failure modes are fundamentally different in the lower strain range and thus require a close look at what is actually meant by the term “compressive strength” in different cases. Fig. 3 illustrates both the different failure modes and a number of definitions of the material’s strength.

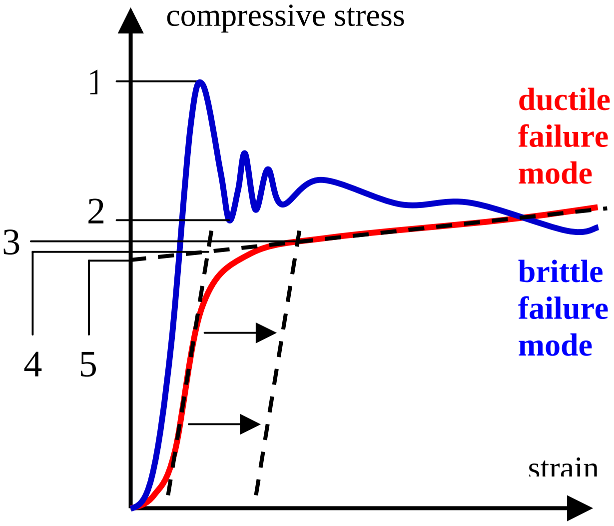

Fig. 3: Failure modes and common strength definitions for metal foams

Within the scope of this study, the upper yield strength (1) was chosen to describe foams failing in the brittle mode, while in the other cases strength values measured at 5 % strain were chosen (similar to definition no. 3 - total deformation taken as a basis).

2.2.2. Fatigue tests

Fatigue tests were carried out using a hydraulic testing machine in which the samples were clamped as shown in Fig. 4. Each load cycle lay completely within the range of compressive stresses. Thus the lower stress level σ_l, represents the highest load in this case. For the initial series of samples, its level was chosen slightly below the static strength of the samples. Further series were tested at reduced stress levels. The number of samples per series was at least three for the AlMg1SiCu foams. The actual numbers for all material and stress levels are given in Tab. 1.

σ_l [MPa]	**4.3**	**4.9**	**5.3**	**6.3**	**6.6**	**7**	**7.7**	**8**	**8.3**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
AlMg1SiCu (σ_{static} = 18.5 MPa)	-	-	-	-	-		-	3	-	3	3	5	3	3	3	3
AlMg1SiCu (σ_{static} = 12.19 MPa)	-	-	-	-	-	4	5	-	4	4	5	3	3	-	-	-
AlSi7 (σ_{static} = 8.15 MPa)	5	3	2	2	3	-	-	-	-	-	-	-	-	-	-	-

Tab. 1: Number of samples tested at different stress levels for each material, static strength in brackets.

The amplitude of the load cycles was not kept constant for the different values of σ_l. Instead, the load ratio R between σ_u and σ_l was set to 0.1 for all the tests.

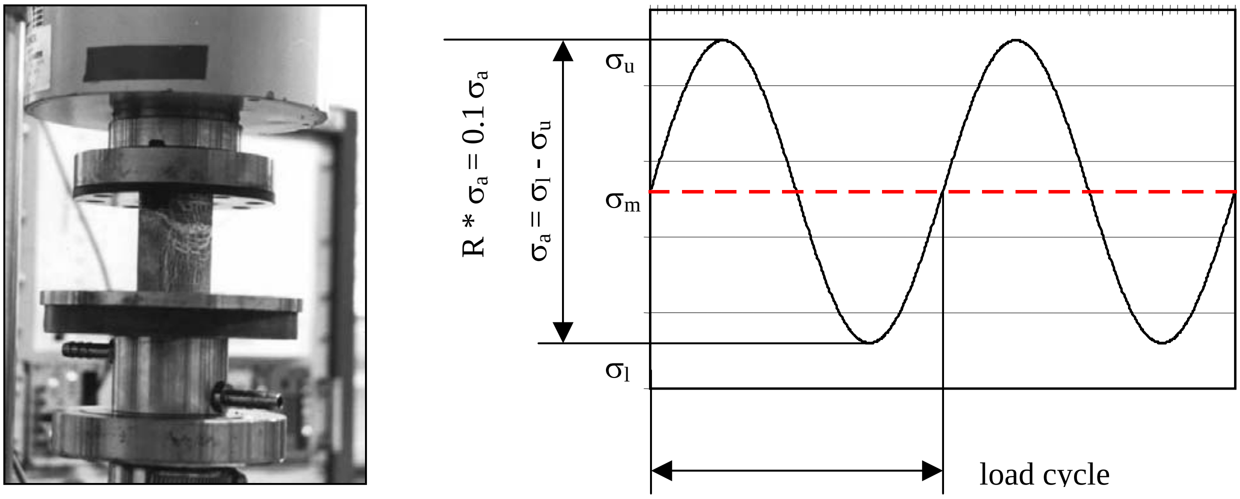

Fig. 4: Test setup and general concept of fatigue tests

Most of the tests took place within the low cycle fatigue regime. As a failure criterion 3 mm (or 5 % deformation) were chosen. For practical reasons the tests were stopped when a sample reached $N_{max}=3\cdot 10^6$ load cycles. For 3 samples that had not failed up to this margin, the test was continued until $N_{max}=10^7$ load cycles were reached.

3. Results

3.1. Static tests

As had been shown before (5), precipitation hardening treatments of foamed AlMgSiCu alloys produces a significant increase in static strength (see Fig. 5).

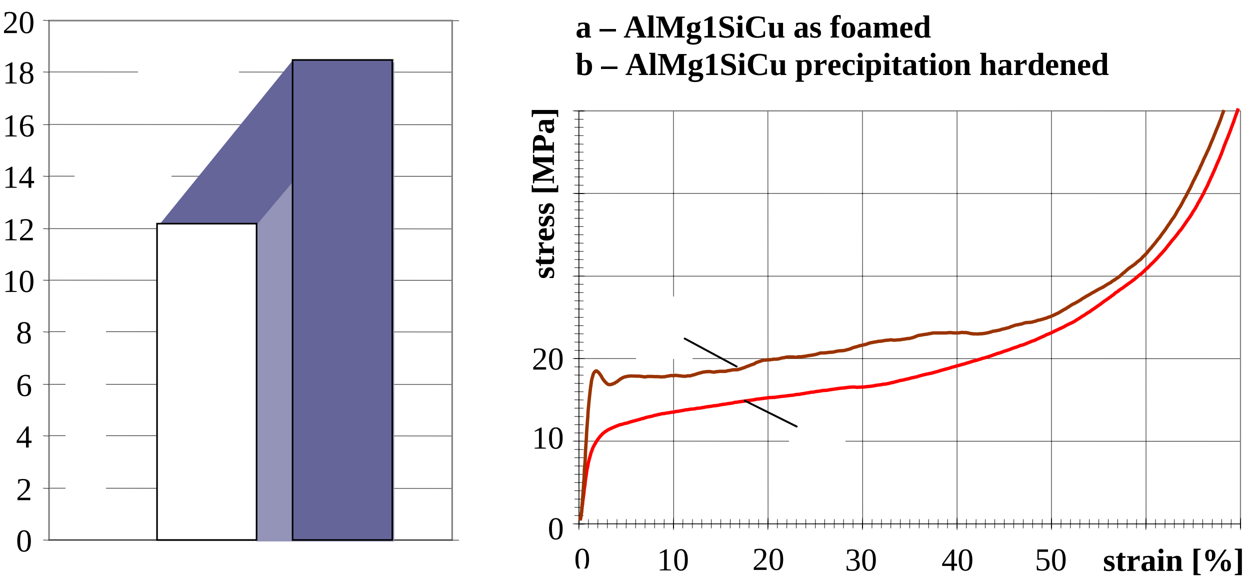

Fig. 5: Static strength and stress-strain curves for “as foamed” and precipitation hardened AlMg1SiCu foam, density 0.6 ± 0.03 g/cm^3 (average of 4 measurements)

This increase in strength is accompanied by a change in failure mechanisms. Fig. 5 displays the average stress-strain-curves obtained for the precipitation hardened specimens and those without heat treatment. Comparison of these curves to the principle representations given in Fig. 3 clearly exhibits the said change. Brittle failure modes are commonly associated with casting alloys, ductile ones with wrought alloys (11). However, it has been shown that even wrought alloys may switch failure modes after having been subjected to a precipitation hardening treatment (5).

As a result of the static tests, the following values for the static strength of the different samples were found:

- AlMg1SiCu, precipitation hardened, density 0.6 ± 0.03 g/cm³: 18.50 MPa
- AlMg1SiCu, without heat treatment, density 0.6 ± 0.03 g/cm³: 12.19 MPa
- AlSi7, without heat treatment, density 0.6 ± 0.05 g/cm³: 8.15 MPa

3.2. Fatigue tests

Fig. 6 and 7 summarise the results obtained during fatigue testing. In Fig. 6 a comparison between precipitation hardened and “as foamed” AlMg1SiCu foam is given. Stress levels are displayed as absolute stresses in this case.

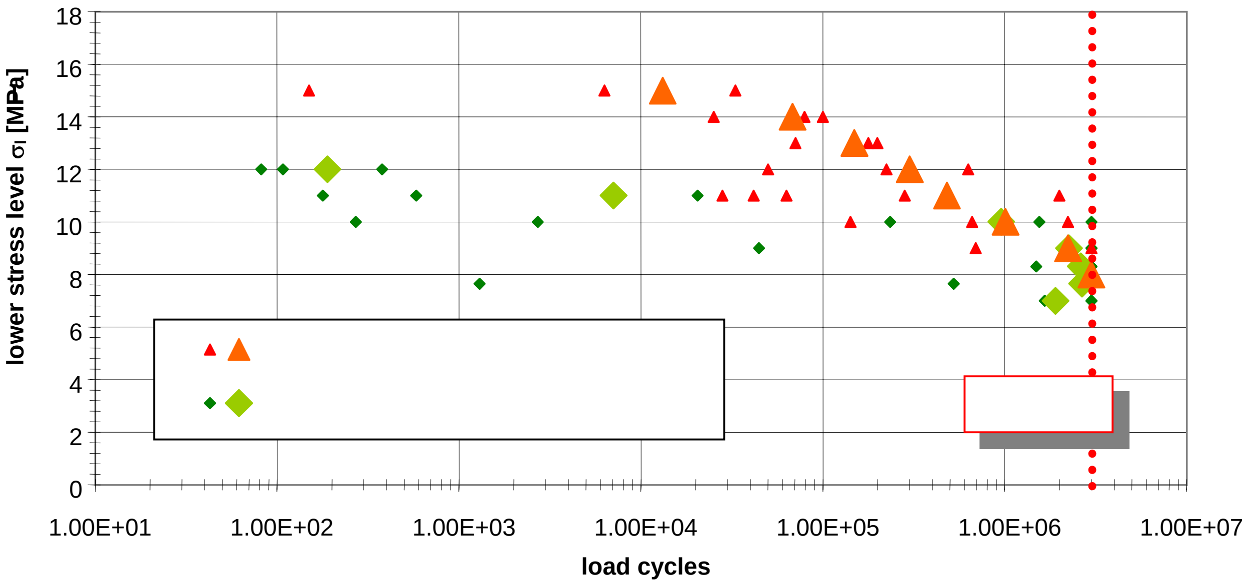

Fig. 6: Results of fatigue tests for AlMg1SiCu (absolute stress values given)

The diagram clearly indicates higher strength levels for the precipitation hardened material only for a very high stress range, which is above the static strength of the competing foam without heat treatment. Both curves begin to move closer to each other at about 10 MPa, which is 82 % of the static strength for “as foamed” but only 54 % of static strength for precipitation hardened material.

This observation is further underlined by the fact that at this stress level there is already one sample of the “as foamed” material that reached the somewhat artificial limit of $N_{max}= 3 \cdot 10^6$ MPa. Assuming that those samples that reached this limit might have sustained additional load cycles, all average values calculated for stress levels were samples survived have to be seen critically – in reality, they are, or would have been, higher than is indicated in figures 6 and 7. This remark is supported by the observations made when two precipitation hardened samples (stress levels 8 and 9 MPa) and one “as foamed” sample (stress level 7 MPa) were kept in the test until 10^7 load cycles were reached: All three of them survived this extended test, too.

For the “as foamed” material, samples surviving 3 x 10^6 load cycles were seen at several stress levels, namely 10 MPa (1 of 5 samples tested at this level, 82 % of static strength),) 9 MPa (2/4, 74 %), 8.3 MPa (3/4, 68 %), 7.65 MPa (3/5, 63 %) and 7 MPa (3/4, 57 %). At none of these stress levels, all samples survived. In contrast to this, the first sample that withstood $3{\cdot}10^6$ load cycles was not found until the stress level was reduced to 9 MPa or 49 % of the static strength for the precipitation hardened foam. At this stress level, 2 of 3 samples survived. After a further reduction down to 8 MPa or 43 % of the static strength, all of the three samples tested survived.

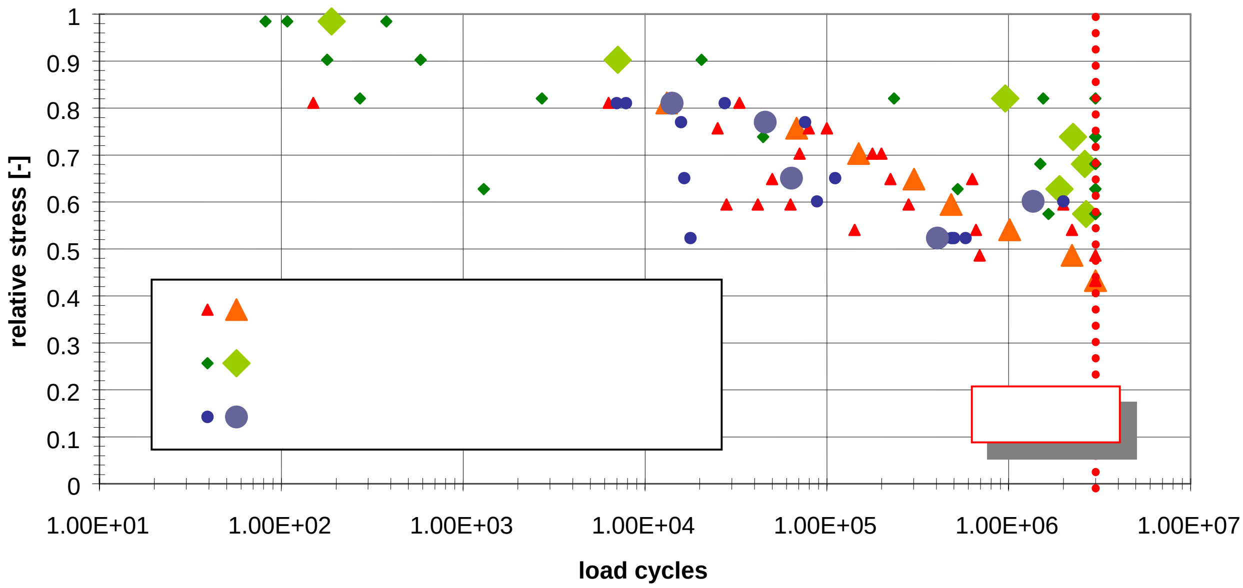

Fig. 7: Results of fatigue tests for AlMg1SiCu and AlSi7 (relative stress values given)

The impression given by the relative numbers quoted above is confirmed by Fig. 7. In this diagramme, relative stresses, that is, the absolute stress level σ_l at which a test was performed divided by the static strength of the respective material, are given.

4. Conclusions

Heat treatments of the precipitation hardening type yield a significant increase in the static compressive strength of aluminium foams when compared to the state of the material directly after foaming. This effect, however, is not reflected in the fatigue strength. In contrast, especially in a load range associated with low cycle fatigue (LCF), foams subjected to such a heat treatment exhibit lower strength values. This phenomenon becomes even more apparent when relative strength values are considered: Under cyclic loading conditions precipitation hardened foams fail at stress levels that represent a lower fraction of their static strength than those relative levels at which “as foamed” material fails.

Based on this observation we assume that it is primarily the failure mode already known from static tests that determines the fatigue behaviour of metal foams. In static tests, a distinction between brittle and ductile failure modes is well established. In fatigue tests, such a distinction can be seen, too: Precipitation hardened AlMgSiCu and AlSi7 are both known to fail in a brittle way in static tests, while the same tests suggest “as foamed” AlMg1SiCu to be a ductile material. Static tests to which the materials were subjected during this study confirmed this assumption, while fatigue tests establish a similar distinction: Here, too, precipitation hardened AlMg1SiCu and AlSi7 foams show a comparable results which in turn differs from that obtained for AlMg1SiCu without heat treatment. The implication of the failure modes is different for fatigue conditions in comparison to static tests. Ductile failure means higher number of load cycles to be endured at the same relative stresses. Furthermore, the deviation seen between individual measurements in fatigue tests is lower for brittle material. Once again, this is in contrast to results from static tests.

An explanation of these observations may be based on fracture mechanics. Foams produced by means of the IFAM process are usually described as having a closed porosity. Although this may be correct from a general point of view, many cell walls are characterised by cracks, which either occur during foaming in the liquid state or during cooling and solidification of the material (12). Propagation of these cracks is facilitated in brittle materials. However, to come to final result explaining the actual mechanisms that determine failure on a microscopic level, further investigations are needed.

References

(1) O.Schultz et. al.: “Metal Foams and Porous Metal Structures”, Editors. J. Banhart, M.F. Ashby, N.A. Fleck, MIT-Verlag, Bremen (1999), p. 379

(2) O. B. Olurin, N. A. Fleck, M. F. Ashby: “Metal Foams and Porous Metal Structures”, Editors. J. Banhart, M.F. Ashby, N.A. Fleck, MIT-Verlag, Bremen (1999), p. 365

(3) J. Banhart, W. Brinkers, J. Mater. Sci. Lett. **18** (1999) 617

(4) B. Zettl, S. Stanzl-Tschegg: “Metal Foams and Porous Metal Structures”, Editors. J. Banhart, M.F. Ashby, N.A. Fleck, MIT-Verlag, Bremen (1999), 373

(5) D. Lehmhus, J. Banhart, C. Marschner: “Metallschäume”, Editor: H.P. Degischer, Wiley-VCH, Weinheim (2000), p. 474

(6) J. Banhart, J. Baumeister, J. Mater. Sci. **33,** 1431 (1998)

(7) J. Banhart, J. Baumeister: MRS Symp. Proc. **521,** 121 (1998)

(8) J. Baumeister, German Patent DE 40 18 360 (1991)

(9) J.R. Davies [Ed.]: Aluminum and Aluminum Alloys, Materials Park, 1993

(10) D. Lehmhus, J. Banhart, Acta Materialia (submitted, 2000)

(11) H.P. Degischer et. al.: “Metallschäume”, Editor: J. Banhart, MIT-Verlag, Bremen (1997), 79

(12) B. Zettl, S. Stanzl-Tschegg, Mat.-Wiss. u. Werkstofftechnik **31**, 484 (2000)