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Influence of heat treatment on compression fatigue of aluminium foams

D. LEHMHUS, C. MARSCHNER, J. BANHART
Fraunhofer Institut für Fertigungstechnik und Angewandte Materialforschung, Bremen, Germany
E-mail: dl@ifam.fhg.de

H. BOMAS
Institut für Werkstofftechnik, Stiftung Bremen, Germany

Metal foams were produced by means of the powder compact melting technique. Specimens were made of a wrought aluminium alloy similar in composition to AA 6061. A part of the samples was subjected to a precipitation hardening treatment after foaming, others were left in the state "as foamed". Cyclic tests were then carried out under compressive stresses. S-N curves of untreated and heat-treated foams are compared. Values for fatigue strength were estimated and compared to the static strength found for comparable specimens. As a reference system with a brittle failure mode foams based on the aluminium casting alloy AlSi7 are examined.

1. Introduction

Within the past few years renewed interest in lightweight 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 material 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 for many conventional materials. It is mostly a lack of this 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 this 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, e.g., to the evaluation of tension-compression [1], repeated tension [2, 3] or repeated compression [3, 4] load cycles and try to clarify the influence of parameters such as foam density [4] or alloy composition [5]. Investigation of failure mechanisms for a number of these combinations has begun [6], see also a recent review [7]. In addition to these studies others have shown the potential of heat treatment for adapting and improving properties of aluminium foams under quasi-static conditions [8–10]. The aim of this study is to extend the scope of the latter ones to the realm of fatigue loading conditions.

2. Experimental

2.1. Sample preparation

Aluminium alloy foam samples were produced by means of the powder compact melting process, which comprises mixing aluminium alloy and titanium hydride powder, compacting the mix and foaming the compact thereafter within a closed mould [11, 12]. The resulting foams had closed pores and a densified outer skin. The dimensions of these samples were: diameter 44.2 mm, height 60 mm. As a matrix alloy AlMgSi1Cu in a composition similar to AA 6061 was chosen—due to the added foaming agent, an increased Ti content was observed. This alloy leads to quite high strengths when heat treated due to its copper and combined magnesium and silicon content but requires fast quenching after solution heat treatment, which might be a disadvantage. The samples made from this alloy were tested in an "as foamed" and a precipitation hardened state. AlSi7 samples of the same dimensions were tested in a previous study [4]. The density of the foamed specimens was 0.60 ± 0.03 g/cm^3 for the AlMg1SiCu alloy and 0.60 ± 0.05 g/cm^3 for AlSi7, the relative densities being 0.22 ± 0.01 and 0.22 ± 0.02 accordingly. Removal of the densified outer skins formed during foaming was considered, but not performed for these tests. Components made of aluminium foam will exhibit a similar skin, and it is their properties at which the results of this study should hint. Size effects are likely to occur, but these are common for non-porous materials, too.

Heat treatment of the samples followed a conventional precipitation hardening cycle. As such, it consisted of three steps, namely *solution heat treatment,* *quenching* and *ageing*. In this case, warm ageing was chosen. Heat treatment parameters can in general be taken from sources dedicated to the heat treatment of conventional Al parts, e.g., [13]. Special attention must be paid to the question whether the parameters given in such compilations are actually achieved within all sections of an aluminium foam sample. This question will be discussed in more detail elsewhere [14]. In the present study we solution heat treated the foams at 530°C for 100 minutes and quenched them in water at room temperature. Warm ageing was done at 165°C for 10 hours.

2.2. Testing procedures
2.2.1. Quasi-static tests
The tests for establishing values for the static strength of 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. For both AlMg1SiCu type samples, four of these tests were carried out to define the average strength.

In static compression tests on aluminium foams two fundamentally different failure modes are observed: brittle failure is supposedly caused by breaking of cell walls and struts, while ductile failure is based on bending rather than breaking of these basic structural elements. Kriszt *et al.* claim that in foams produced by the PM method, wrought alloys as matrix lead to a densification based on plastic deformation until total collapse of cells is reached. In contrast, failure of foams based on cast matrix alloys is characterised by propagation of cracks on a macroscopic scale through several pores [15]. Stress-strain curves representing these failure modes are fundamentally different in the lower strain range and within the plateau region seen in stress-strain curves. Thus a close look is required at what is actually meant by the term "compressive strength". Fig. 1 illustrates both the different failure modes and a number of possible definitions of the material's strength.

Within the scope of this study, the upper yield strength (1) was chosen for describing foams failing in the brittle mode, while in the other cases strength values measured at 5 % total strain were chosen (definition (3), with total deformation taken as a basis). The static strength values derived for the three different sample types are based on four tests for each type.

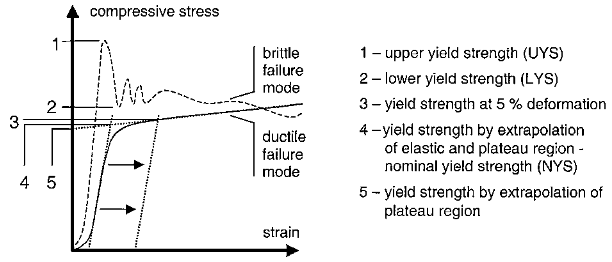

Figure 1 Failure modes and common strength definitions for metal foams.

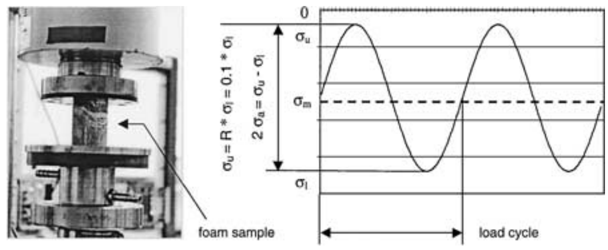

Figure 2 Test set-up and general concept of fatigue tests—note that the compressive stress range is examined, for which negative stress values are commonly used.

2.2.2. Fatigue tests
Fatigue tests were carried out using a hydraulic testing machine (PSA 100) in which the samples were arranged as shown in Fig. 2. Each load cycle lay completely within the range of compressive stresses. In this paper, compressive stresses will be measured in positive numbers. The maximum compressive load is σ_L, the minimum compressive stress level σ_u. The load ratio $R = \sigma_u/\sigma_L$ between these stress levels was set to 0.1 for all tests.

For the first series of samples, $\sigma_{c,max}$ was chosen slightly below the static compressive strength σ_s of the samples. Further series were then 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 Table I. At the beginning of each test, the load amplitude was steadily increased until the nominal stress level given for each test was reached after about 100 cycles. Thus samples that did not sustain these first 100 cycles must be considered as having failed immediately.

Most of the tests took place within the low cycle fatigue regime. As a failure criterion 3 mm or 5 % deformation was chosen, and most experiments were stopped as soon as this limit was reached. For practical reasons all tests were stopped after $N_{max} = 3 \times 10^6$ load cycles. An exception was made for 3 samples that had not failed up to this margin. For these the test was continued up to $N_{max} = 10^7$ load cycles were reached.

3. Results and discussion
3.1. Static tests
Precipitation hardening treatment of foamed AlMg1SiCu alloys produces a significant increase in static strength [10]. This increase in strength is accompanied by a change in failure mechanism. Fig. 3 displays averaged stress-strain-curves obtained for 4 precipitation hardened specimens and 4 others without heat treatment. Comparison of these curves to the principle representations given in Fig. 1 clearly exhibits the said change. Brittle failure modes are commonly associated with casting alloys, ductile ones with wrought alloys [16]. However, it has been shown before that even wrought alloys may switch failure modes after having been subjected to a precipitation hardening treatment [10]. The quasi-static tests yielded the strength values given in Table I.

3.2. Fatigue tests
Figs 4 and 5 summarise the results obtained in the cyclic tests. Fig. 4 gives absolute stresses, whereas in

TABLE I Static compression strength and number of samples tested at different stress levels for each material (A1Si7 taken from [4])

Alloy heat treatment	σ_s (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 precipitation hardened	18.5	–	–	–	–	–	–	–	3	–	3	3	5	3	3	3	3
AlMg1SiCu as foamed	12.2	–	–	–	–	–	4	5	–	4	4	5	3	3	–	–	–
AlSi7 as foamed	8.2	5	3	2	2	3	–	–	–	–	–	–	–	–	–	–	–

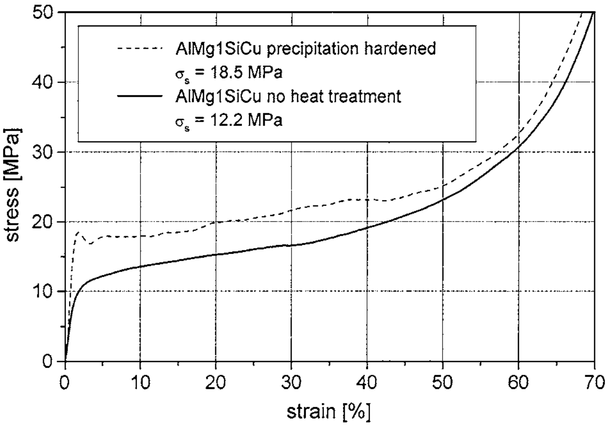

Figure 3 Stress-strain curves for precipitation hardened and as foamed AlMg1SiCu foams, density 0.6 ± 0.03 g/cm^3 (average of 4 measurements given for each state).

Fig. 5 the stresses are related to the static strength σ_s. In both figures a comparison between precipitation hardened and "as foamed" AlMg1SiCu foams is given. Furthermore, values for the casting alloy AlSi7 have been added.

Fig. 4 clearly indicates higher absolute strength levels for the precipitation hardened foams. The observed enhancement of static strength by heat treatment can therefore also be found under cyclic loading conditions. However, the superiority of age-hardened foams seems to fall off for lower stresses and correspondingly higher cycle numbers. Both curves begin to move closer to each other and meet at about 10 MPa, which is 82 % of the assumed static strength for "as foamed" but only 54 % of static strength for precipitation hardened material. Fig. 5 giving relative stresses even shows that for any stress level the relative performance of the age-hardened alloy is inferior to the alloy in the state "as foamed," i.e., the positive effect of age-hardening is partially lost under cyclic conditions.

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 $N_{max} = 3 \times 10^6$. Assuming that samples which reached this limit might have sustained additional load cycles, all averaged values calculated for stress levels were samples survived have to be seen critically, as in reality they would have been higher than indicated in Figs 4 and 5. This is supported by the observations made when two precipitation hardened samples (stress levels 8 and 9 MPa, relative stress levels 43 and 49 %) and one "as foamed" sample (stress level 7 MPa, relative stress level 57 %) 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 3×10^6 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 stresses, all samples survived. In contrast to this, for the precipitation hardened foam the first sample that withstood 3×10^6 load cycles was not found until the stress level was reduced to 9 MPa or 49 % of the static strength. 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.

A general observation is that the statistical scatter of the experimental data is quite large and that many more samples should be tested than done in this study and comparable studies in the literature. Furthermore, deriving an endurance limit after 3×10^6 cycles should also be considered a rather rough estimate. Even the

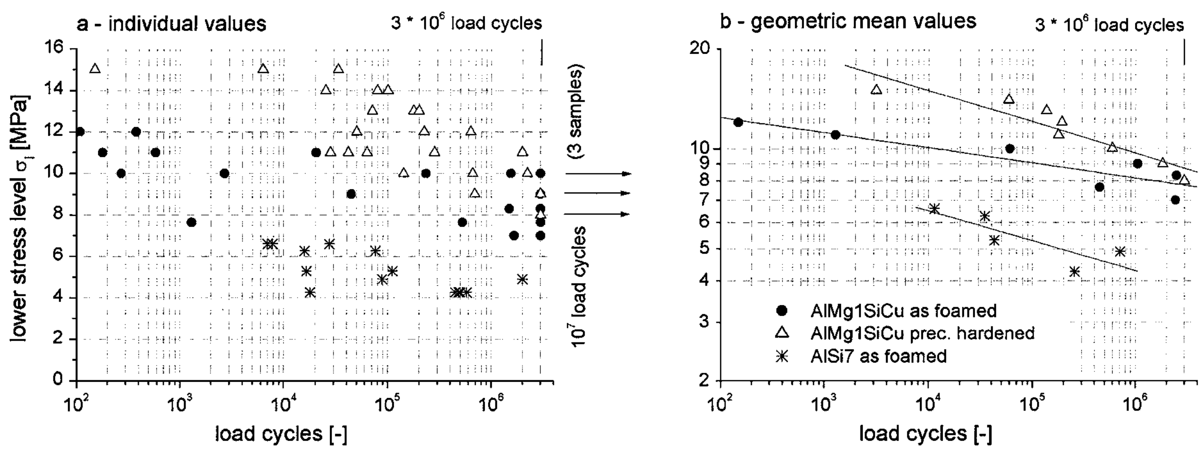

Figure 4 Compression-compression S-N curves for AlMg1SiCu alloys in two different heat treatment states. Individual measurements are given in the diagram to the left, in which arrows denote samples that survived further testing to 10^7 cycles. Mean values derived from the individual measurements are given in the diagram to the right. AlSi7 data is also included.

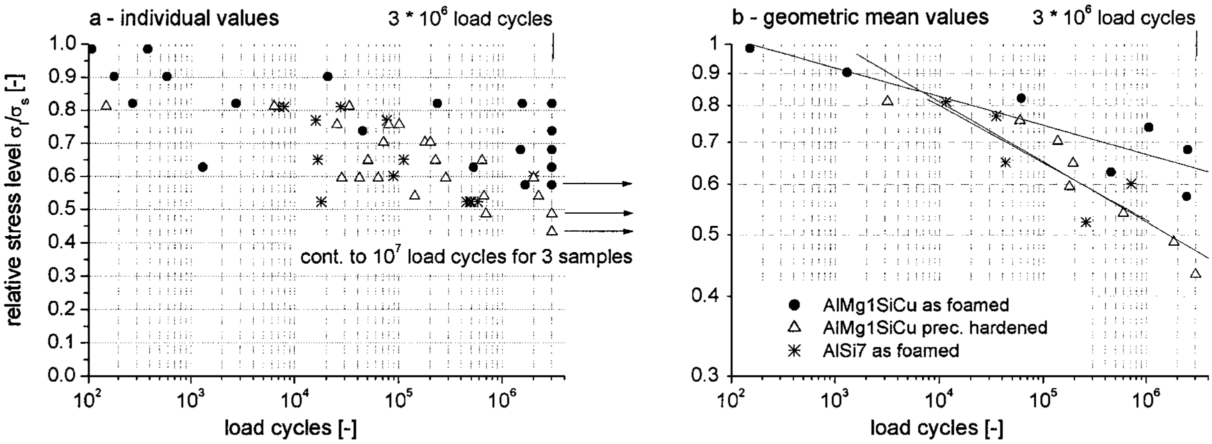

Figure 5 Analogous to Fig. 4. Stresses are given relative to static strength σ_s. Results for AlSi7 alloy foams have also been included.

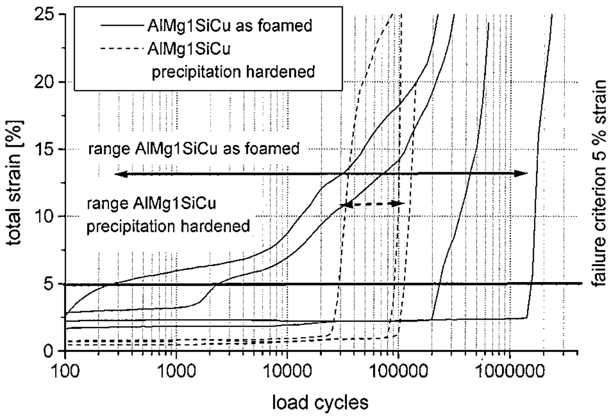

Figure 6 Examples of compressive strain versus load cycle curves for individual specimens of the two different types of alloy AlMg1SiCu tested. Stress levels are 10 MPa or $\sigma_L/\sigma_s = 0.82$ for AlMg1SiCu without heat treatment and 14 MPa or $\sigma_L/\sigma_s = 0.76$ for precipitation hardened AlMg1SiCu.

10^7 cycles suggested as criterion by other authors [3] could be insufficient.

Based on these observations we assume that it is primarily the failure mode already known from static tests that determines also the fatigue behaviour of metal foams. Precipitation hardened AlMg1SiCu 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. Under cyclic conditions the two brittle systems both show a stronger reduction of the relative stresses the foam can bear for a given cycle number than their ductile counterparts. Therefore brittleness causes an increased strength knock-down under cyclic load. Furthermore, the scatter between individual measurements of static compression strength is known to be lower for ductile alloys than for brittle ones. This observation cannot be transferred directly to cyclic loading conditions.

Fig. 6 gives some typical examples of compressive strain vs. load cycle curves obtained for individual specimens of precipitation hardened and non-heat treated AlMg1SiCu. Displayed are only specimens with AlMg1SiCu matrix alloy. The relative stress level $\sigma_{c,max}/\sigma_s$ is 82 % for AlMg1SiCu without heat treatment and 76 % for precipitation hardened AlMg1SiCu. Absolute stress values are 10 MPa and 14 MPa. The average number of load cycles derived from these individual curves are 446126 and 68185, not including a fifth sample of the "as foamed" type that reached the threshold of 3×10^6 load cycles at this stress level. The highlighted failure criterion (5 % deformation) serves to illustrate the scatter between the individual endurance values. In contrast to what is generally acknowledged for quasi-static testing, in this case the precipitation hardened samples seem to outperform their ductile counterparts in terms of scatter. As for quasi-static testing, a distinction of failure modes is possible by comparison of these curves, too: Failure in precipitation hardened samples is characterised by a steady increase in strain with no pronounced change in strain rate. In contrast, as foamed samples distinctively show stepwise failure. The accumulated strain at first increases progressively, until a certain maximum strain rate is reached-the character of the curve switches to a degressive increase. In subsequent phases of strain accumulation, this pattern is repeated. It is tempting to identify this behaviour with the built-up of deformation bands known from quasi-static testing. Decreasing strain rates might then be associated with increases in strength in the original deformation band caused by strain hardening or densification. Both effects do not occur in the same way in brittle alloys. Here failure is based on cracking rather than on deformation, which is why a region within a sample becoming the place of failure will not reach a higher strength state in which it may still contribute to the samples overall performance in the course of the process. This explanation is supported by the observation that in brittle alloys, it is not necessarily the "weakest link," i.e., the cross section with the lowest average density, at which deformation is initiated.

Thus it is near at hand to ascribe the apparent knock-down of fatigue strength for age-hardened alloys to the difference in fracture behaviour of the cell walls. Although foams produced by means of the powder compact foaming process are usually described as having a closed porosity, many cell walls contain cracks which either occur during foaming in the liquid state or during cooling and solidification of the material [17]. There is also an empirical notion that heat treatment of foam samples leads to an increase of crack density. Cracks may be caused either during solution heat treatment where residual hydrogen which is still contained in the remnants of the former blowing agent or in the matrix alloy could form cracks in the solid state or during quenching of the samples in water which could generate high stresses in the cell walls either through local temperature differences or intrusion of water. In addition, the structure of metal foams serves to increase the probability of plastic deformation to occur locally even if loads are kept below the yield stress globally. The phenomenon makes determination of Young's modulus from stress-strain curves a difficult task. In this respect metal foams resemble some grades of lamellar graphite cast iron, for which only tangent modulus can be determined. Repeated loading and unloading in a stress range associated with this effect is almost certain to render the material more prone to crack initiation. Detailed investigations of fracture toughness, crack initiation and propagation in Al foams of different compositions have been published by McCullough *et al.* [18]. Ductile AlMglSi0.6 and brittle AlMglSi10 alloy were compared and *J*-curves measured for both of them based on specimens with a relative density of 0.17. Initiation toughness J_{IC} of AlMglSi0.6 was found to be more than twice as high as that of AlMglSi10, although the cell wall strength of the latter alloy was estimated to be 350 MPa as opposed to 250 MPa for AlMglSi0.6 using Vickers hardness measurements. Similar differences between Vickers hardness values, as well as the opposing failure modes in static compression, have been shown to exist between as foamed AlMg1SiCu and precipitation hardened foams of the same matrix [14]. Thus these measurements, too, hint at the observed lower relative fatigue strength of the brittle alloy.

4. Summary

Heat treatments of the precipitation hardening type lead to a significant increase in static compressive strength of aluminium foams compared to the state of the material directly after foaming. This positive effect, however, is only partially retained when cyclic loading conditions are applied. One observes a stronger drop of strength for heat treated alloys than for untreated alloys. The advantages of heat treatment are therefore partially lost. The reason for this effect is believed to be twofold: Firstly, precipitation hardening treatment of AlMgSiCu and AlMgSi wrought alloys coincides with a change of failure modes from ductile to brittle ones. Associated with this change is a lower fracture toughness and thus facilitated crack initiation and propagation. Both effects favour earlier yielding under cyclic loading. Secondly, the temperature cycle an aluminium foam is subjected to during heat treatment can be identified as a source for an increased crack density. Future developments aiming at exceptional fatigue properties should therefore generally concentrate on foaming processes and heat treatments which lead to a less brittle matrix and a lower crack density, while at the same time attempting to shed more light on the relative importance of these two effects in fatigue. Meanwhile, testing of metallic foams under cyclic load needs to be continued until sufficient amounts of data are collected to derive endurance limits or even Woehler charts from them which stand on a statistically sound basis. To achieve this aim the sooner, a standardisation of test procedures might be worth considering.

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