Fatigue of Aluminium Foams at Ultrasonic Frequencies

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Abstract

Lifetime measurements of cylindrical shaped Alulight-foam specimens have been made using the ultrasonic-resonance-testing-technique. Specimens are subjected to a resonance vibration at a frequency of about 20 kHz and load ratio of R=-1. Fatigue measurements in the range between 10^4 and 10^9 cycles result in SN-curves. All kinds of Alulight-foam show an endurance limit at about 10^7 cycles to failure and a load amplitude between 0.95 ~ 1.30 MPa. The influence of heat treatment to fatigue strength has been measured by testing one material in two different conditions: without heat treatment and artificially aged at 160°C/14h. The obtained SN-curves show improvements of the fatigue strength of 15%.
The correlation of crack initiation sites and structure-geometry can be done, if the specimens are scanned by CT (computed tomography) after testing. Four different effects influencing crack initiation have been identified: three structural features and the effect of mass density on crack initiation. A system of classification of these material defects is introduced and the results show that lifetime prediction can be improved. Possibilities to improve fatigue strength and reduce lifetime-scatter-range of the Alulight-foam by improving the foaming process are discussed.

1. Introduction

Aluminium foams produced from powder metallurgical prepared precursor material have a high potential for use in weight sensitive construction parts. Components in the transportation industry, for example, are often subjected to a high number of varying stress amplitudes. Load sequences of typical automotive components may consist of 10^8 cycles or more, and therefore the fatigue properties in the high cycle range are of special interest. The ultrasonic-resonance testing method offers the possibility to apply load sequences up to 10^9 load-cycles within a short period of time. Correlation of material features with number of cycles to failure increases the precision of lifetime prediction if information on the material structure is available. The possibility to increase fatigue strength or to reduce the lifetime scatter-range may be estimated if the relation between structural effects and fatigue behaviour is known.

2. Material and experimental procedure

Three types of Alulight-foams have been investigated: foamed AlMg0.6Si0.3 and AlMg1Si0.6 as two different types of material conventionally used as wrought alloys and AlSi12 conventionally used as cast alloy. Foams were produced by powder metallurgical processes [1] as rods with surface skin and 160 mm by length and 17 mm by diameter. Specimens with a length of 50 mm have been cut out of the rods. To investigate the influence of heat-treatment on the fatigue behaviour the foamed AlMg1Si0.6-material has been tested in two conditions: without treatment (T1) and artificially aged (T5) during 14h at 160°C.
The basic principle of the ultrasonic-resonance testing procedure can be explained as follows: A sine generator produces an electric vibration of 20 kHz frequency which is amplified and transformed into mechanical oscillations by a piezoelectric transducer. The specimen is attached

to this transformer via a magnifying piece (amplification transducer) and is stimulated to mechanical vibrations. The resulting longitudinal wave leads to tension-compression loading of the specimen with the mean stress equal to zero (R = -1). If the system consisting of ultrasonic generator, transformer, horn and specimen is in resonance, vibration and thus load amplitudes become large enough to cause fracturing of the specimen. The load amplitude which is effective in the specimen is controlled with an electromagnetic gauge, which detects the displacement amplitude at the end of the specimen. Details of the experimental procedure are published elsewhere [2].

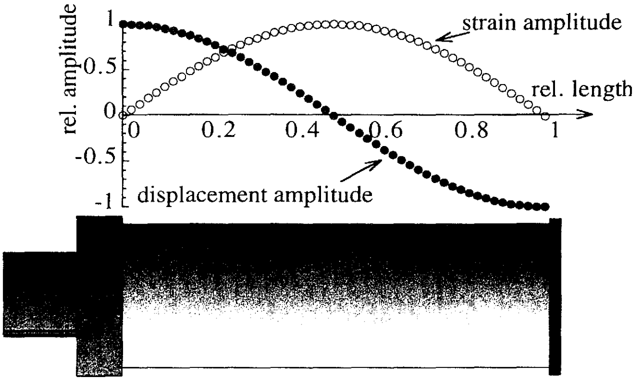

Fig. 1: Shape of specimens and introduction of load via resonance wave

Besides the possibility of saving time, the use of the ultrasonic resonance method makes a very advantageous way of energy transmission into the specimen possible. The material in the coupling area remains almost free of stress. Loading is free of bending, as the specimens are fixed on one end only. The principle of load-introduction is illustrated in Fig.1. The displacement amplitude shows a maximum at the free end of the specimen where it is reflected. If it is designed for resonance frequency, minimum of displacement amplitude is located in the middle and the maximum at the other end of the specimen. The strain can be calculated as the derivative of the amplitude of the displacement wave and is maximal in the middle where the displacement amplitudes are minimum. Strain gages are applied there for monitoring strain during the lifetime test.

3. Results of lifetime measurements

Results of lifetime measurements for all three materials and the two conditions of heat treatment are shown in Fig.2 . All materials show an endurance limit. Either the specimens fail before 10^7 cycles or they also withstand 10^9 cycles . The values of strain amplitudes at the endurance limit are between $\varepsilon_E = 0.24 \sim 0.33 \cdot 10^{-3}$ depending on the kind of material. The stress amplitude values are between $\sigma_E = 0.95 \sim 1.3$ MPa. They have been calculated using a Modulus of Elasticity of E=3.9 GPa. The heat treatment of the foamed material does not only increase the plateau stress [1] but also influences the fatigue behaviour. Artificial ageing of the material at 160°C for 14 hours increased the fatigue strength at all load levels by 15%.

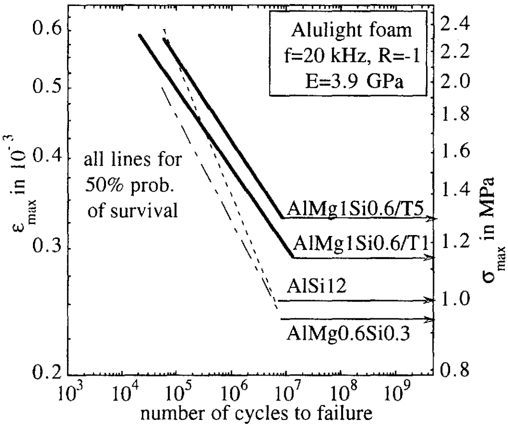

Fig. 2: Results of lifetime measurements for the three tested materials and two conditions of heat treatment (T1 and T5)

4. Damage analysis

During fatigue measurement a slow decrease of resonance frequency of the specimens take place. The decrease becomes faster towards the end of the lifetime. This effect can be correlated with structural damage of the foamed material: during early stages of lifetime, damages at the microscopic level of the structure may occur. These microcracks do not lead to final failure of the specimen but weaken the material and reduce materials stiffness. Towards the end of the lifetime one becomes dominant and propagates at higher rates than microcracks do. Cracks nucleate inside the specimen and, in general, appear during the period of fast decrease of frequency at the skin surface.

Investigations of the fracture surface by SEM-studies show features of fatigue damage (fatigue facets and sometimes striations). But due to the complex structure of the fracture surface the exact place of crack nucleation and direction of propagation cannot be detected. The crack initiation site is estimated using the site of appearance at the skin surface.

For correlation of lifetime data to structural features of the foam at the crack nucleation area, investigations using a medical CT have been performed. The results are images with approximately 0.5 mm resolution of the inside structure of the specimen. These images are used to obtain cell geometry near the crack nucleation site.

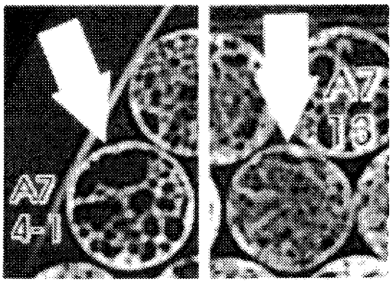

Fig. 3: CT images of specimens' cross-sections near point of crack nucleation can show a large cell (left) or long narrow cell-geometries (right)

4.1 Material features effecting fatigue behaviour

Some of the specimens, especially those failed at relatively early lifetimes, show large cell cross-sections near the place of crack formation (see Fig. 3-left image for example). Cell walls neighbouring large cells may be loaded at higher values if the existence of a similar mechanism as stress concentration around pores in conventional alloys is assumed. Some specimens show cell geometries with long narrow cell formations beneath the skin (Fig. 3-right). These long narrow cells are surrounded by relatively large cell walls and at least some of them are oriented in load direction (illustrated in Fig. 4, left cell wall of large central cell is oriented in load direction). Deflection and bending of this cell wall is inhibited by joined walls and load of this cell wall occurs in tension and compression. The stress response of this cell wall to a certain strain amplitude is much higher due to a higher modulus of elasticity than the respond of walls which can deform by bending. This situation may be present around such long narrow cell geometries and may encourage crack initiation in large cell walls.

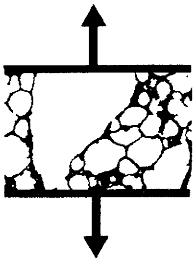

Fig. 4: Large cell wall (left side of large cell) oriented in load direction

Some of the specimens not show any structural influence of large cell cross-sections or cell walls but show cell structures which at a whole seem to be rather inhomogeneous. The left image in Fig. 5 shows an examples of foam structure with constant cell size designated as homogenous structure while the cell size in the right image is quit irregular and is designated as inhomogeneous. This effect may result from different conditions during the foaming process.

These three structural features single large cells, load oriented cell walls, and inhomogeneous cell size have been identified as being responsible for early crack initiation. Most specimens show at least one of the features mentioned above. The influence of more than one of these features may accumulate and make possible early fatigue crack initiation and faster propagation.

The fourth effect taken into account for the present analysis is the influence of mass density. Since most mechanical properties of foamed material scale with mass density [4] it is assumed that the relative density also effects the fatigue strength. Higher values of density should result in longer lifetimes of specimens.

4.2 Classification system

A system of classification is used for estimating and counting the influence of the four types of material features. Since the influence of the four features, if considered each on its own, show quite low correlation with lifetime, this classification system takes into account accumulation effects if several defects appear simultaneously at the site of crack initiation. Lifetime prediction can be improved if the relative lifetime of the specimens is correlated with a number representing the influence of the harmful effects. One can get this number for a certain specimen by counting the number of simultaneously apparent effects at the place of crack nucleation. If there is a cell with a large cross-section the number is increased by one. If there is a cell surrounded by a large cell wall oriented in load direction- the number is again increased. Also if specimens show inhomogeneous structure. The effect of mass density is counted by the inverse of the local relative density multiplied by a certain number to balance structural- and density influence. In this study the number has been obtained by searching best correlation between measured lifetime and the resulting number representing structural features.

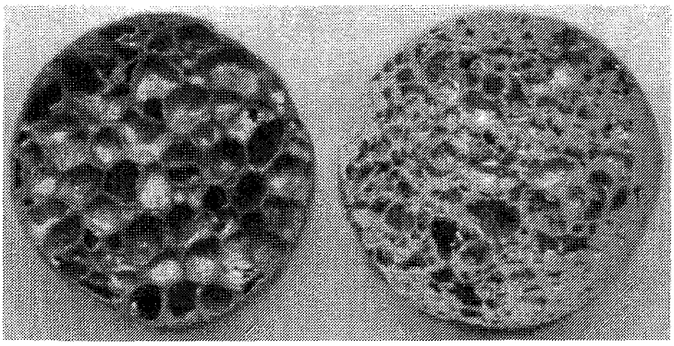

Fig. 5: Specimens showing homogenous (left) and inhomogeneous foam-structure (right)

If structural influences are present at the site of crack nucleation they have been identified by examining CT images. If cells directly beneath the point of crack appearance at the skin show more than double average cell cross-section area (Fig.3 for example), they are recognised as damaging effect and one reason for crack initiation. If the expansion of a cell wall in direction of load is larger than double average cell diameter (> 5mm) then the cell wall has been recognised as a structural defect contributing to early failure of a specimen. After CT imaging the effective tested fraction of volume (middle part of specimen) has been cut out to obtain local mass density and to decide whether inhomogeneous structure is apparent or not.

In order to compare the data of different load levels, the pairs of numbers representing load and lifetime (σ_i/N_i) are shifted to a certain load level (σ_0/N_j). This requires to assume that the fatigue damaging process is independent of the load level. As long as no time dependent processes are involved or processes with another than a logarithmical dependence of number of load cycles (like fatigue damage), the assumption of load independent damage is fulfilled.

4.3 Application to lifetime results

The first material analysed in this study by the above described damage evaluation procedure is AlMg0.6Si0.3 foam. The S-N data are shown in Fig. 6. 21 specimen were used for the present analysis. 17 of them show the structural feature designated as inhomogeneous, 8 of them show large cell cross-section, 7 of them show large, load oriented cell walls. Relative mass density varies between $\rho/\rho_s = 0.11 \sim \underline{0.20} \sim 0.35$ (mean value underlined). The effect of density has been quantified by a number defined as $c^*(\rho/\rho_s)^{-1}$. The constant c is a weight factor and balances the influence of density and the structural influences. A value of c=0.25 has been chosen to be the best value for this material. The results of the analysis-procedure are shown in Fig. 7. The left figure points out that there is an obvious trend that specimens with shorter lifetimes (lower numbers) show higher values of total counts representing harmful effects than specimens with

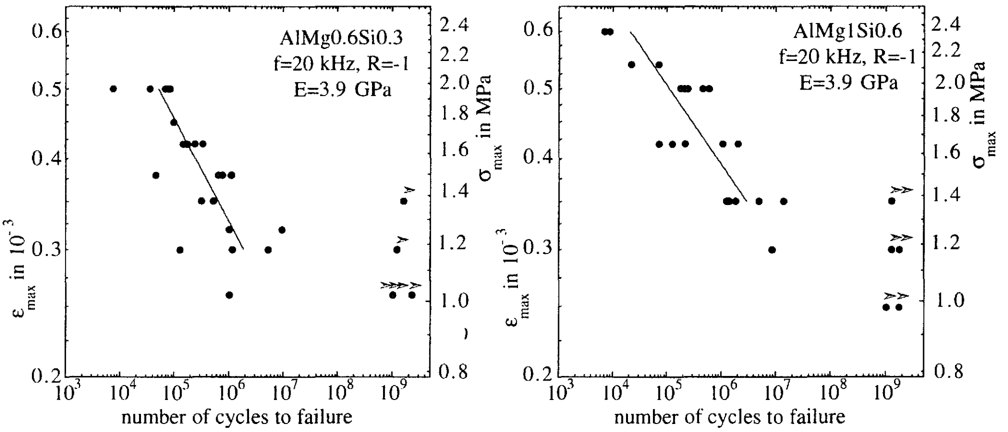

Fig. 6: Lifetime data of the two material AlMg0.6 Si0. 3 and AlMg1 Si0.6

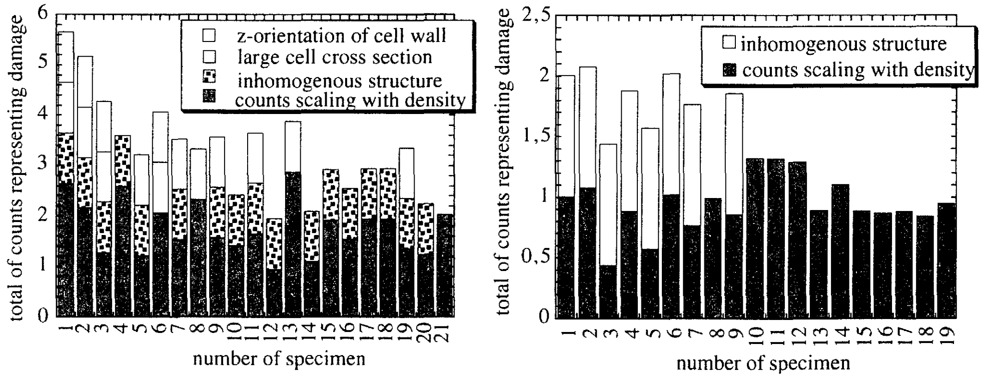

Fig. 7: Counts representing harmful structural features in AlMg0.6Si0.3 (left) and AlMg1Si0.6 (right) foamed material evident at crack nucleation site plotted against number of specimen sequenced in ascending order of lifetime.

longer lifetimes. The different sections of the bars represent the different effects. Almost all specimens of the left part (number 1 to 9), for example, show the influence of large cells. The scatter-range of the fatigue measurements is approximately 2 decades. If the structural features are taken into account lifetime prediction can be done more accurately and the prediction fits the measurements within one decade.

The second material analysed by the damage evaluation procedure is AlMg1Si0.6/T1. 19 specimens were used for analysis of this material. 8 of them show inhomogeneous structure. CT images do not show large cells or cell walls effecting sites of crack nucleation. The relative mass density is again $\rho/\rho_s = 0.20$. The value of the weight factor is smaller than before, c=0.14. The results of the analysation procedure are shown in Fig. 6. The right figure points the same trend: The shorter the lifetime, the higher the number of counts representing damage. Due to the fact that only one structural feature is evident for this material, the relative contribution of mass density to total counts is higher.

5. Summary

Lifetime measurements show an endurance limit for all kinds of Alulight-foam tested. Either the specimens fail before 10^7 cycle or they also withstand 10^9 load cycles. The values of strain-amplitude at the endurance limit are between $\varepsilon_E = 0.24 \sim 0.33 \cdot 10^{-3}$ depending on the kind of material. Values of stress-amplitude are $\sigma_E = 0.95 \sim 1.3$ MPa, using a modulus E= 3.9 GPa for calculation.

Heat treatment of foamed wrought-alloy material influences its fatigue strength. Artificial ageing at 160°C for 14 hours has increased the fatigue strength by 15%.

Analysis of structural influences on fatigue damage shows that large cell cross-sections as well as large cell walls if oriented in load direction contribute to material damage. By eliminating large cells and cell walls the lifetime may be increased on average by a factor of 1.6 for AlMg0.6Si0.3 foamed material.

The effect of structural homogeneity (variation of average cell size) has also been detected as a reason for early failures during lifetime tests. Avoiding this structural damaging effect would increase the lifetime on average by a factor of 1.7 for AlMg0.6Si0.3 and by a factor of 2.2 for AlMg1Si0.6/T1 foamed material.

The fatigue strength is also related to the relative density. Higher density of foam can lead to longer lifetimes. Since fatigue crack initiation and growth is a process related to very local effects at the nucleation site and crack tip, the influence of an average density of foam is less explicit than the influence of local structure geometry. Early failures during lifetime testing are always related to the influence of one or more of the above mentioned structural features.

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