Fatigue behaviour, strength and failure of aluminium foam

O. Schultz, A. des Ligneris, O. Haider, P. Starke
Eurocopter Deutschland GmbH, 81663 Munich, Germany

Abstract

Aluminium foam produced from metal powder (AA6061) and aluminium melt ($AlSi7Mg+15\%SiC_p$) were fatigue tested using Wöhler's method. The stress ratio was kept constant during testing (R=-1) and fatigue tests were thus performed under completely reversed stresses (uniaxial: tensile/compressive). The stress amplitude was then varied from one specimen to the next and the test procedure was able to establish the greatest loading at infinite life ($N \geq 10^7$) without fracture. The number of cycles endured by the test specimens until fracture was recorded. These data were used to determine the fatigue strength of both types of aluminium foam and S-N curves were calculated using Weibull's method. Hysteresis was also measured for different loadings to provide information on the specific fatigue bahaviour of the two types of aluminium foam. Fracture surfaces of representative fatigue-tested specimens were recorded and compared to complete the analysis.

1. Introduction

The foaming process and the quality of foamed material has improved considerably during recent years. This makes it important to evaluate the application of aluminium foam for helicopter components with a view to reducing manufacturing costs and weight. Once material properties and quality are of a suitable standard, manufacturing costs and weight are the most significant factors when it comes to selecting materials and processes for helicopter components.

The conditions under which helicopters operate mean that components and materials are subject to repeated or fluctuating strains. The apparent maximum values of nominal stresses are less than - and often much less than - the static yield strength of the material. It is necessary to have a basic knowledge of fatigue bahaviour, strength and failure of aluminium foam and an understanding of the principles involved, in order to be in a position to evaluate future applications of aluminium foam in vibrating environments (e.g. helicopter components). Aluminium foam produced from metal powder and aluminium melt is of interest for a variety of applications.

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1) Fraunhofer Institut für angewandte Materialforschung (IFAM), Bremen, Germany
2) Hydro Aluminium s.a., Sunndalsora, Norway

J. Banhart, M.F. Ashby, N.A. Fleck: *Metal Foams and Porous Metal Structures.* © MIT Verlag (1999)

2. Preparation of specimens

Specimens (length: 80mm, cross-section: 50x50mm^2) were produced from the aluminium foam material AA6061, manufactured and delivered by IFAM$^{1)}$ and from AlSi7Mg+15%SiC$_p$, manufactured and delivered by HAL$^{2)}$. The specimens were not subjected to additional heat treatment. Skins and density gradient zones near the surface were removed and the specimen only consisted of the pure foam core. Specimens with cracks, damage to cell walls or foaming defects were rejected.

Since the specimens were subjected to fatigue testing under completely reversed stresses (uniaxial: tensile/compressive), it was necessary to bond the specimen to the testing fixtures. A specially adapted bonding device and intermediate fixing plates were therefore used. The bonding surface was also increased by outer bonding elbows. Finally, the effectiv fatigue loaded specimen volume was 50x50x50mm^3. The intermediate fixing plates and test fixtures were centered during testing and bonding to ensure correct alignment of the test adapters. This procedure was carried out to avoid misalignment due to twisting (rotation of clamps/test fixtures) or displacement of their axes of symmetry.

3. Fatigue testing conditions

The fatigue strength was determined using Wöhler's method. 18 nominally identical specimens of each type of aluminium foam were tested by applying 6 different load levels. The loading was constant for each test, with a stress ratio R=-1. The specimens were fatigue tested under completely reversed uniaxial stress. This is a special type of fatigue test in which the mean stress is zero and the stress alternates between equal plus and minus values. The stress amplitude is then varied from one specimen to the next, so that the test procedure is able to establish the greatest loading at infinite life (in practical terms 10^7 cycles) without fracture.

Test loads were monitored continuously in the early stages of the test and then at regular intervals. The strain was also measured simultaneously using an external extensiometer. The fatigue test was continued until the specimen failed. Failure was defined as complete separation. Finally, the number of cycles until failure was determined under conditions of controlled sinusoidal stress amplitudes while observing the strain response.

4. Fatigue strength

The specimens were first subjected to compressive and tensile loads in order to obtain reference information on the static strength of the material determine the appropriate fatigue loads. Specimens were then fatigue tested under the test conditions described above.

Weibull mean curves were calculated using Weibull's method [2] and the least squares method based on results from tensile and fatigue tests. The fatigue strength was then calculated for the aluminium foams tested.

The scatter of the densitiesled to fatigue scatter. Value pairs for fatigue stress and number of cycles to fracture are therefore given as stress/density so that the two materials and extraction directions can be compared.

4.1 AlSi7Mg+15%SiC$_p$ foam produced from aluminium melt

The experimental results and the calculated fatigue curves are shown in fig. 1 for the two extraction directions, perpendicular and parallel to the direction of foam growth in AlSi7Mg+15%SiC$_p$ aluminium foam. The fatigue strength can be determined to 1 MPa perpendicular to the direction of foam growth and 0.6 MPa in the parallel direction. The average aluminium foam density was 0,291±0,027g/cm^3. The fatigue curve for specimens loaded parallel to the direction of foam growth is inferior to the curve for those specimens loaded perpendicular to the direction of foam growth. The difference in fatigue strength for the tested direction might be explained by the density gradient in the direction of foam growth and the anisotropic cell form, both due to the effect of gravity during manufactureing.

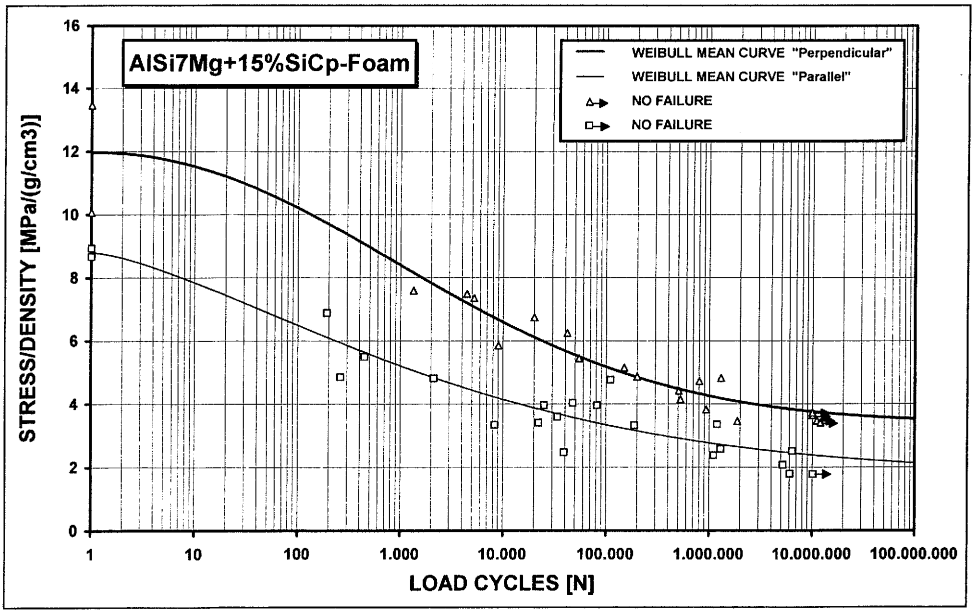

Fig. 1: S-N diagram for AlSi7Mg+15%SiC$_p$ foam loaded parallel (squares) and perpendicular (triangles) to the direction of foam growth

4.2 AA6061 foam produced from metal powder

Value pairs of fatigue stress and number of cycles to fracture and the corresponding Weibull mean curve are plotted in fig. 2 for the AA6061 aluminium foam. The fatigue strength can be determined to 0.8MPa. The tested specimen had an average density of 0.402±0.039g/cm^3.

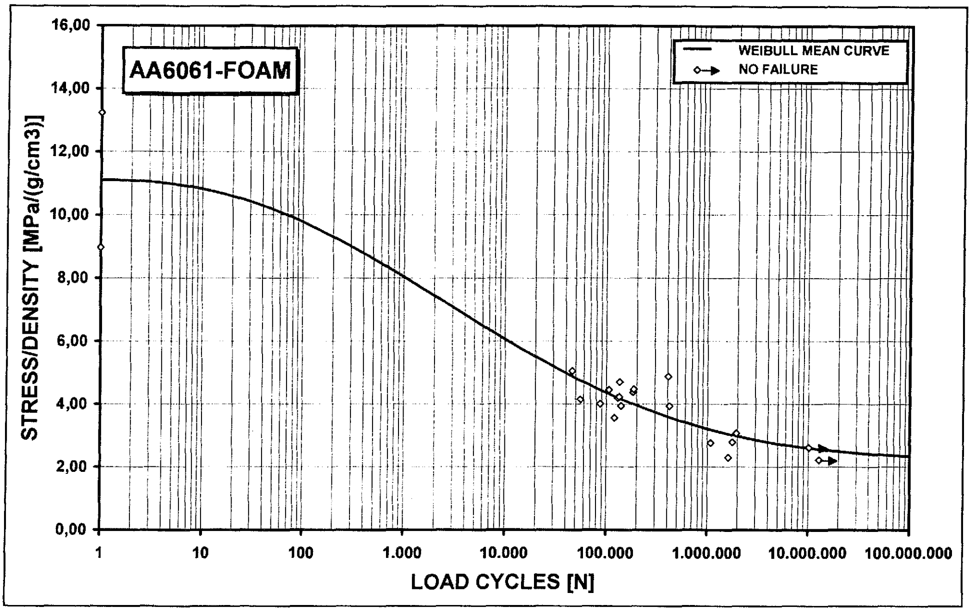

Fig. 2: S-N diagram for AA6061 foam

5. Fatigue bahaviour

A stress-strain hysteresis loop provides basic information on the cyclic stress-strain bahaviour of the tested foams. The measured strain is the total strain comprising the plastic strain and elastic strain. Stress-strain hysteresis represents the total of processes during fatigue such as dislocations, their interaction among themselves, with second phase particles,..., their bahaviour under cyclic strain localization, and crack initiation and propagation.

The progress of hysteresis was measured for different cyclic loads to gain an insight into the specific fatigue bahaviour of the tested aluminium foams.

5.1 AlSi7Mg+15%SiC$_p$ foam produced from aluminium melt

Fig. 3 shows hysteresis for a specimen tested perpendicular to the foaming direction that failed after 1,299,693 cycles. The residual strain increases considerably under tensile loads and decreases under compressive loads. The same phenomenon was observed for the specimen shown in Fig 4 tested parallel to the direction of foam growth. All specimens failed after accumulating a residual strain of 0.7 to 1.2%. These values appear quite high compared to those of the tensile test (0.2 to 0.5%). It appears that tensile loads are more damaging then compressive loads and that the shape of the cells is being increasingly stretched in the direction of loading as fatigue progresses.

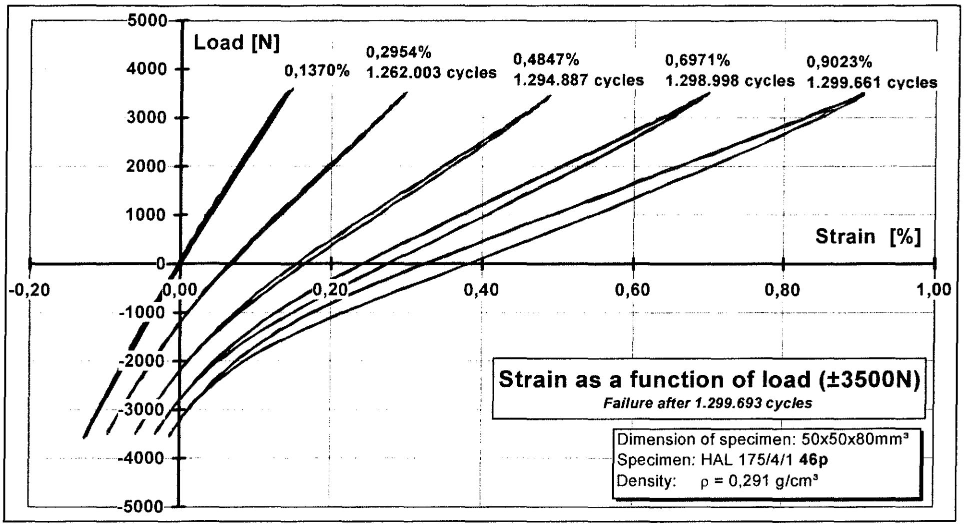

Fig. 3: Load-strain hysteresis as a function of load cycles for a specimen loaded perpendicular to the direction of foam growth (Al-foam: $AlSi7Mg+15\%SiC_p$)

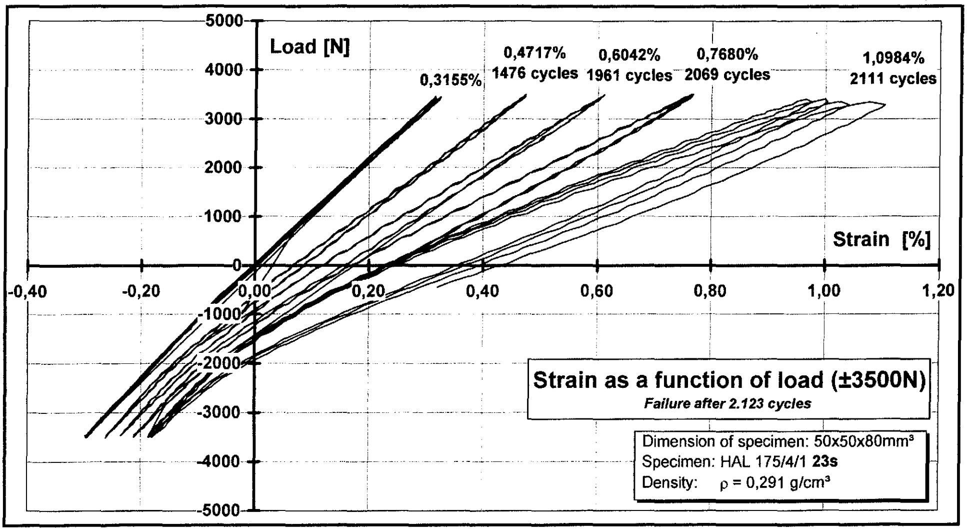

Fig. 4: Load-strain hysteresis as a function of load cycles for a specimen loaded parallel to the direction of foam growth (Aluminium foam: $AlSi7Mg+15\%SiC_p$)

5.2 AA6061 foam produced from metal powder

Fig. 5 shows that residual strain increases even more under tensile loads than shown for the previous aluminium foam material. Even under compressive loads the residual strain increases from cycle to cycle. All specimens of this material failed after accumulating a residual strain of 2.0% to 4.0%. Tensile test results indicate a strain to failure of about 0.9% to 1.0%. Although residual strain increases under tensile and compressive loads and it might be assumed that softening of the aluminium foam occurs during fatigue testing, damage is caused by tensile loads.

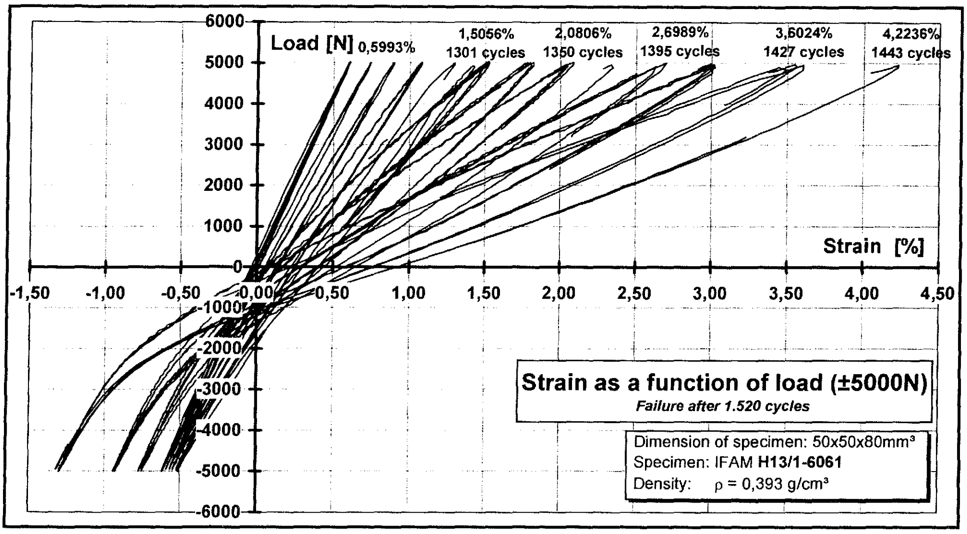

Fig. 5: Load-strain hysteresis as a function of load cycles (Aluminium foam: AA6061)

A significant drop in the elastic modulus may be observed in figures 3, 4 and 5 for both types of aluminium foam. This drop in modulus may be attributed to geometric changes in the cell shape due to strain and cracking of cell walls.

6. Fatigue fractures

As shown in figures 3 to 5, the aluminium foams being tested undergo lengthening due to plastic strain when specimens are subjected to cyclic mechanical loads alternating in equal tensile and compressive magnitudes. After exceeding a certain plastic strain, it may be assumed that the fatigue fracture usually originates at the surface of the specimen in areas with weakest cell walls and unfavorable orientations of the cell wall relative to the applied cyclic loads. The fatigue fracture is then propagated across the weakest section into the specimen until the remaining load-bearing cross-section fails.

6.1 AlSi7Mg+15%SiC$_p$ foam produced from aluminium melt

Figs. 6 and 7 show fracture surfaces of specimens that were subjected to fatigue loads parallel to the direction of foam growth. The specific stress (stress/density) applied to the specimen in fig. 7 is about 30% greater than that applied to specimens from fig. 6. Nevertheless, the specimen shown in fig. 7 endured approximately 40 times more cycles to fracture. The homogeneity of the foam structure in the specimen from fig 7 is clearly the main reason for its superior fatigue resistance.

The specimen in fig. 8 shows a relatively homogeneous foam pore structure within the fracture surface. This specimen was subject to fatigue loading perpendicular to the direction of foam growth. The specific stress and number of cycles to fracture are also about the same as the specimen in fig. 7 which was subject to sinusoidal testing parallel to the direction of foam growth.

6.2 AA6061 foam produced from metal powder

The specimen shown in fig. 9 showed a relatively homogeneous pore structure in the fracture cross-section. The specific fatigue stress applied is about the same as for the specimen in fig. 6 but the specimen of the AA6061 foam endured 25 times more cycles to fracture.

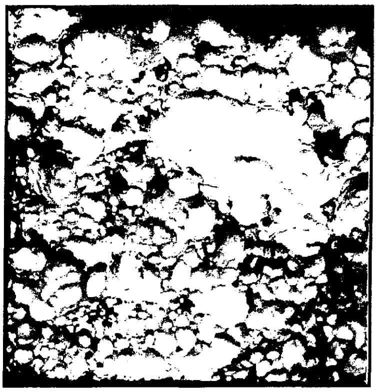

Fig. 6: Fracture surface

Specimen:	HAL 16s
Number of cycles:	39.144
Stress/density:	2,45 MPa/(g/cm^3)
Density:	0,326 g/cm^3

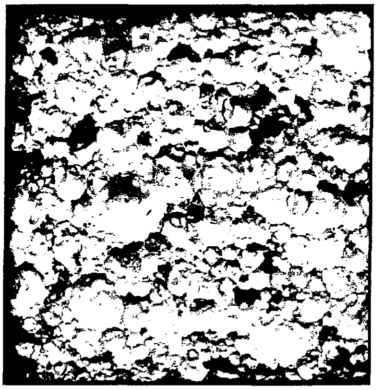

Fig. 7: Fracture surface

Specimen:	HAL 22s
Number of cycles:	1.195.475
Stress/density:	3,34 MPa/(g/cm^3)
Density:	0,299 g/cm^3

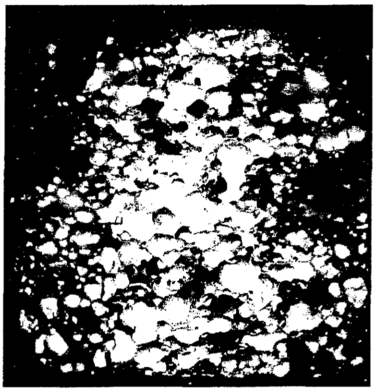

Fig. 8: Fracture surface

Specimen:	HAL 38p
Number of cycles:	1.882.495
Stress/density:	3,46 MPa/(g/cm^3)
Density:	0,289 g/cm^3

Fig. 9: Fracture surface

Specimen:	IFAM J19/2
Number of cycles:	1.082.505
Stress/density:	3,23 MPa/(g/cm^3)
Density:	0,433 g/cm^3

However, the homogeneity of the pore structure is the most important parameter influencing the increase in fatigue strength of aluminium foamed specimens and components.

7. Conclusions

Despite the relatively small number of tested specimens for each fatigue curve, the fatigue test is sensitive enough to confirm anisotropy in aluminium foam produced from an aluminium melt.

The fatigue strength perpendicular to the direction of foam growth is superior to the fatigue strength parallel to the direction of foam growth for aluminium foam produced from an aluminium melt.

The specific fatigue strengths (fatigue strength/density) for both types of foaming processes (using metal powder and aluminium melt) are in the same range.

The advantage of the selected test method is that when specimens fail the fracture surfaces are not destroyed by the test and can therefore be used for subsequent examination of the pore structure.

Testing a much higher number of specimens would improve the statistical significance of the fatigue curves. It would also be interesting to observe crack initiation and crack propagation, and then correlate these results with the fracture surface and hysteresis progress after failure of the specimen. This was not possible within the scope of the experiments carried out during this study because of the automated test procedure.

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References

[1] ASM Handbook, Vol. 19, Fatigue and Fracture, ASM International (1996)
[2] W. Weibull, Fatigue Testing and Analysis of Results, Pergamon Press (1961)
[3] M.F. Ashby, A.G. Evans, J.W. Hutchinson, N.A. Fleck, Metal Foam: a Design Guide, to be published in 1999
[4] J. Banhart, W. Brinkers, Fatigue behaviour of aluminium foams, J. Mat. Sci. Lett. **18**, 617 (1999)