ON THE PARIS EXPONENT AND CRACK CLOSURE EFFECTS OF ALPORAS ALUMINUM FOAM

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ABSTRACT

Fatigue Crack Growth experiments are performed on M(T)-samples made of Alporas aluminum foam. This foam is a commercially available closed cell aluminum foam, which is made from a technically pure aluminum.

The Alporas foam has a rather high Paris exponent of about 15. The Paris crack growth region is from $\Delta K = 0.095$ MPa√m up to 0.13 MPa√m. An existing model, the so-called *Beam Bending* model, for Fatigue Crack Growth in metal foams is verified. A good agreement between predicted values and experimental values was found.

A novel form of crack closure occurs in the Alporas aluminum foam during Fatigue Crack Growth. The behavior deviates from solid metals, due to the larger influence of the compressive part of the fatigue loading on the crack growth. It is hypothesized that the structure of the foam transforms macroscopic compression loads into surface tension loads on a microscopic scale.

INTRODUCTION

Metal foams are a new class of materials with novel properties. Nowadays there is a number of commercially available metal foams. In recent years considerable effort has gone into research and development of metal foams. The use of metal foam may well expand into more and new applications, where they are exposed to dynamic loads. At present the research performed on fatigue of metal foam has been mainly on SN-curves [1] and very few studies have been performed on Fatigue Crack Growth. The understanding of Fatigue Crack Growth is crucial in the design, especially in the aircraft and automotive industries. Therefore it is important to have a better understanding of their fatigue properties and fatigue behavior.

Metal foam consists of a three-dimensional structure of cell edges that connect in cell nodes. In closed cells a membrane-like face seals off a cell from its neighbors [1-2]. The material behavior is influenced by the structure, the inhomogeneity and anisotropy. The in-homogeneity influences the material properties by deviations in local density. Anisotropy in the material behavior is due to anisotropic cell shapes.

In metal foam linear deformation is facilitated by the formation of a plastic hinge at the cell nodes. Compressive and tensile stresses both deform the foam structure of cell edges and cell nodes. For this reason it is expected that compression will influence the Fatigue Crack Growth (FCG). In cyclic loading with alternating compressive and tensile loads, the tensile load behavior is dominant, due to the lower yield strain in tension. Based on literature of foams [2-6], the Paris exponent of metal foam is expected to be much higher than the common value of 2 to 4 for solid metals. For some polymer foams the Paris exponent is typically in the range of 7-17 [2-4]. For aluminum foams values of 20 and 25 have been reported [5], while in powder metal steel a Paris exponent range of 10-18 was correlated with plastic deformations [6]. Crack closure effects have not been reported for metal foams. However, since crack closure occurs in aluminum alloys it may well occur in aluminum based metal foams.

This work is aimed at the investigation of the crack growth in the Paris region [7-8]. The Paris exponent and the occurrence of crack closure are of special interest. The Paris exponent and the crack closure effects are determined from FCG curves and the influence of the load ratio R on the position of the FCG curves.

EXPERIMENTAL

The Alporas foam used in this work is a commercially available closed cell aluminum foam. The foam has a relative density that is 9% of solid aluminum, an average cell diameter of 3.8 mm, a tensile yield stress of 1.4 MPa, a hardening exponent of 0.47 and the Vickers hardness of the material in a cell edge cross section is 32 HV. The material is produced by stabilizing bubbles in a melt of a commercially pure aluminum [9]. The composition of the material in the foam is mainly aluminum with additions of Ca and Ti that are added in the production process of the foam as CaO and TiH_2. The first substance increases the viscosity of the melt and the second substance is added as a blowing agent. The material also contains small amounts of Si and Fe as pollutants. The cell structure contains defects in the form of large cells, which were formed during the production process by coalescence of cells.

To investigate the Paris exponent and crack closure, Fatigue Crack Growth (FCG) experiments are performed on a center-cracked specimen or M(T) sample. The FCG experiments are performed in accordance with ASTM E 647-00 [10] and use an increasing stress intensity (ΔK) regime, either with a constant load amplitude or with a gradually increasing load. Prior to the measurements the sample is pre-cracked. A Schenck Hydropuls PSB with load cells of 100 kN and 10 kN is used, in combination with a sinus load wave frequency of 5 Hz. A pulsed DC-potential drop method is used to measure the crack length in metal foam. The empirical correlation between the measured and actual crack size is determined in a calibration test and is used to determine the crack length during the experiments. The Feddersen formula [10] is used to calculate ΔK for the M(T) sample.

From literature [11] it is known that the apparent strength of foam test samples depends on the ratio of the sample size to the cell size. For this reason a sample thickness T of 40 mm was chosen. This way the sample dimensions are at least ten times the cell size. The M(T) samples were mechanically machined in a configuration of 400*100*40 mm^3 ($H*W*T$) and were mounted using friction plates. The center-crack saw cut is approximately 0.8 mm wide. Due to internal defects in the material it is necessary to use an initial crack length of $a_n \geq 13$ mm.

The fracture surfaces of some M(T)-samples were investigated with a Jeol JSM-6500F Field Emission Scanning Electron Microscope (SEM). A Schottky type field emission (T- Fe) gun with a Zr/O tungsten narrow beam emitter was used with an acceleration voltage of 15 keV. The local composition of the fracture surface was measured using the Energy Dispersive Spectroscopy (EDS) facility of the SEM.

RESULTS

The experimental FCG curves for samples with a thickness of 40 mm are shown in the Fig. 1 on a log(ΔK) scale. These experiments were performed with load ratios (R) ranging from -1 to 0.7. The spread in ΔK in these experimental FCG curves is $\Delta(\Delta K) =$ 0.052 MPa√m, at a crack growth rate of $da/dN = 10^{-2}$ µm/cycle. At a load ratio of $R = 0.1$, the crack initiation has

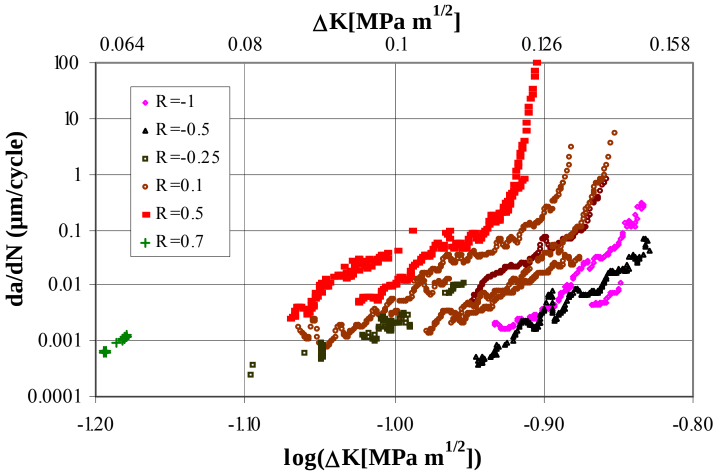

FIGURE 1. Measured FCG curves for Alporas aluminium foam, R values of -1, -0.5, -0.25, 0.1, 0.5 and 0.7

a threshold value of $\Delta K_{TH} < 0.095$ MPa√m. The critical stress intensity K_c is approximated by the values at crack growth rate of $da/dN = 10^2$ µm/cycle. At a load ratio of $R = 0.1$, the approximated K_c varies from 0.14 to 0.25 MPa√m.

The Paris crack growth region is from $\Delta K = 0.095$ MPa√m up to 0.13 MPa√m. The Paris exponent m is determined from the linear part of the ten FCG curves shown in Fig. 1. This part is assumed to be the stable crack growth stage. The average of these exponents is 15.7 with a standard deviation of 1.5. No significant dependence on R is found in relation to the Paris exponent m. Experiments with thinner samples show that the Paris exponent is influenced by the free surface at sample thicknesses below 35 mm. The FCG curves in Fig. 1 show a load ratio dependent shift, indicating a crack closure phenomenon, which will be discussed later.

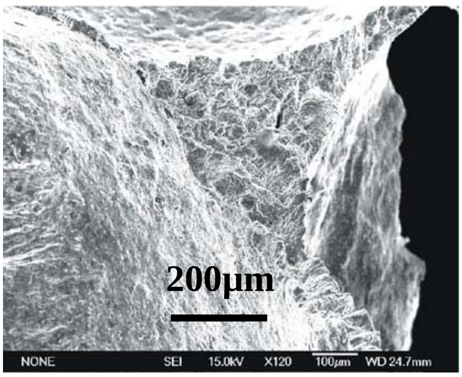

FIGURE 2. SEM picture of a failed cell edge, R = -1

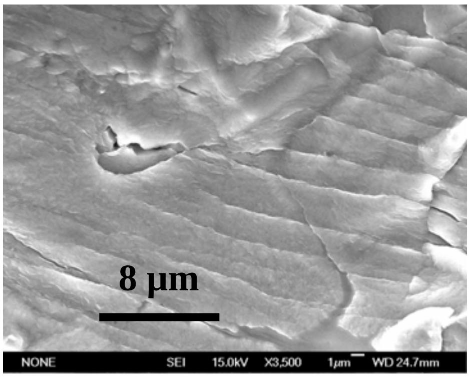

FIGURE 3. SEM picture of striations in Ca- and O-rich area, spacing 2 to 3 µm,

The fracture surfaces are rough and contain particles, cracks and defects. Defects are also found in the surfaces of the cell edges and cell faces. The composition of the material is mainly aluminum with areas where Ti, Ca, Fe and O is present. In the material there are also inclusions of Ti- and Ca-rich particles. In the places with the best-defined striations the element O is found together with Ti+Ca or Ca or Fe, see Figs. 2-3. In places with oxygen and aluminum, the striations are less well defined and clearly influenced by plasticity. When only aluminum is present the fracture surface has a predominantly plastic nature.

DISCUSSION

The experimental FCG curves, shown in Fig. 1, differ from typical FCG curves in the region of crack initiation and in the bumpiness of the curves. The FCG experiments with positive load-ratio (*R*) values do not meet the predominantly elastic requirement [10] of the ASTM E 647-00. This is not considered to be a problem. The Paris exponents determined at these curves do not significantly deviate from the Paris exponents of the other curves. Both elastic and plastic parts of the FCG curves can be used for the determination of the crack closure effect.

The difference between the experimentally found Paris exponents and values reported in literature [5], can be explained by the use of different sample thickness, type of sample and foam density.

The Beam Bending model of J.S. Haung and S.Y. Liu [4] is a fatigue model that is applicable to closed cell foam. In this model the weakest unbroken cell edge in front of the crack tip is subjected to a cyclic bending load. Crack growth will start at the existing defects in the first unbroken cell edge in front of the crack tip and will follow the Paris equation. The stress intensity factor in the bending cell edge is approximated by the stress intensity factor of a supported strut in three-point bending, where the cell thickness is much smaller than its length. On cell edge failure the length of the macro-crack will be increased by the cell cross section. The plastic nature of the fracture surfaces suggests that equation (1) is applicable. This equation is based on cyclic stress strain behaviour using the Coffin-Manson relation [7]:

$$\frac{\mathrm{d}a^*}{\mathrm{d}N^*} = g_6 l \left[\frac{1}{C_2 K' \sqrt{\pi l}} \left(\frac{\rho^*}{\rho} \right)^{-3/2} \right]^{m^*} \left(\Delta K_I^* \right)^{m^*} \tag{1}$$

The macro-scale Paris exponent m^* is equal to $(n'\beta)^{-1}$. The parameters of this equation are explained in table 1. In this formula C_2 is a constant derived from Coffin-Manson law, in which N_f is the fatigue life of a cell wall and $\Delta\varepsilon^{pf}$ is the cyclic plastic strain range:

$$C_2 = \Delta\varepsilon^{\mathrm{pf}} \left(N_{\mathrm{f}} \right)^{\beta} \tag{2}$$

The Paris exponent m^* resulting from the Beam Bending model is in the range of 15-18, when the values from table 1 are used for the parameters for n' and β. These m^*-values are in good agreement with the experimentally found Paris exponent.

The bumpiness of the experimental FCG curves, can be imitated by the Sequential Cell Edge Failure (SCEF) model, which is based on the Beam Bending model. In the SCEF model the fatigue crack will grow in discrete steps as a result of sequential fatigue processes, in which the cell edges fail. In this model the fatigue life of a cell edge is assumed to be proportional to ΔK^{-m}. The resulting FCG curves have been demonstrated for an assumed distribution of cell edge cross-sections [12]. Further work is in progress to link the experimental FCG curves to the actual cell edge cross-sections of the foam.

Table 1. Parameters for the *Beam Bending* model, eq. (1).

Parameter		Remarks
l	2.2 mm	Cell wall length $l = d / \sqrt{3}$, d = 3.8 mm (*d* is cell diameter)
ρ^*/ρ	0.09	relative density of the foam
ε_Y	0.38 (AA1050) [13]	yield strain
K'	200 MPa (AA1050) [14]	Cyclic strength coefficient
β	0.61 (Al) [15] 0.69 (AA1100 annealed) [16]	Coffin-Manson exponent
n'	0.09 (AA2024) [16] 0.093 (Al) [15]	Cyclic strain hardening exponent
g_6	0.0001433 [12]	Fitted microstructural constant

For the influence of the foam structure on the fatigue behavior the following mechanism is proposed. During the fatigue process a cell edge will bend at both ends near the cell nodes. This will happen in opposite directions during tensile loading and during compression loading. A tensile surface stress results in the cell edge surface due to both an external tensile

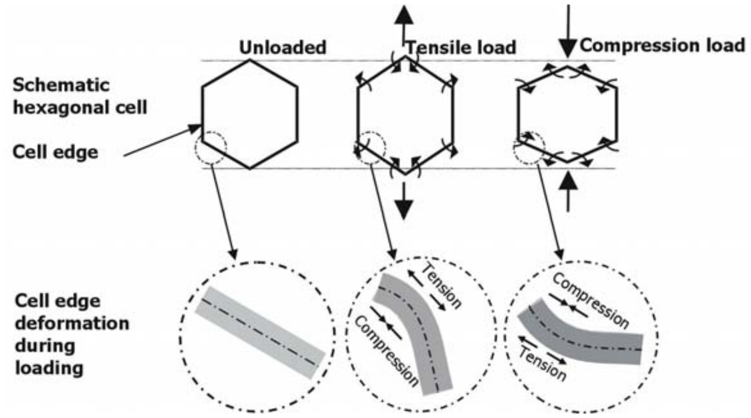

FIGURE 4. Deformation of cell edges during alternating fatigue loading

load and an external compression load, as is shown in Fig. 4. These induced surface tension stresses will manifest themselves at different locations on the cell edge. This means that near the cell node fatigue cracks can develop on two sides of the cell edge and that both tensile load and compression load contribute to the crack growth. This results in a higher amount of stress intensity available for crack growth and more sites where the cracks can grow.

Crack Closure fits are used to compare the FCG behavior to that of solid material. In foam both tension load and compression load are expected to influence the FCG and therefore have an influence on crack closure. This is different from the behavior in solid metals where the literature and the ASTM assume that there is no influence of the compression part of the cyclic load on the FCG.

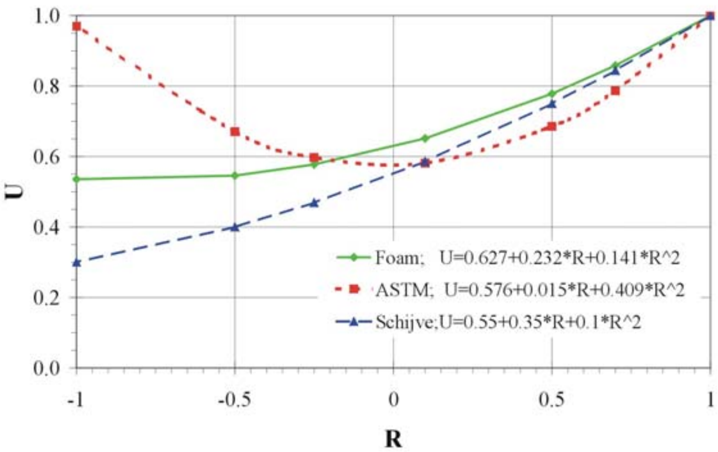

FIGURE 5. Fitted curves U=f(R).

To determine which situation is applicable to metal foam, a comparison is made between crack closure fits for both approaches. In each crack closure fit the position in ΔK of the experimental FCG curves is fitted with respect to the load ratio. The Foam approach fit is using the total available ΔK. The second crack closure fit is made using only the positive part of the available ΔK, thus excluding the compression part of the load. This fit is designated as ASTM approach in Fig. 5. These crack closure fits enable the crack growth rate to be correlated by ΔK_{eff} in the range of $R = 1$ to $R = -1$, assuming an equal ΔK_{eff} leads to an equal crack growth rate [17]. The relation between ΔK_{eff} and ΔK is defined by the crack closure function U in the following equation:

$$\Delta K_{efff} = U * \Delta K \tag{3}$$

The optimized crack closure fits are given in table 2 and are shown together with the Schijve function for solid aluminum alloy 2024-T3 [8] in Fig. 5. The resulting reduction in ΔK spread due to both fits is very similar, see table 2. In table 2, P is the force of the load cycle.

Table 2. Crack closure fits

Approach		Optimized Crack Closure fit $U = a+b*R+c*R^2$, **restriction $U(R = 1) = 1$.**	Spread in ΔK after fit, at $da/dN = 10^{-2}$ μm/cycle
Foam	$\Delta P = P_{max} - P_{min}$, for $-1 \leq R \leq 1$	$U = 0.627+0.232R+0.141R^2$	0.0153 MPa√m
ASTM	$R<0$ $\Delta P = P_{max}$, and $0 \leq R$ $\Delta P = P_{max} - P_{min}$	$U = 0.576+0.015R+0.409R^2$	0.0176 MPa√m
Schijve	$\Delta P = P_{max} - P_{min}$, for $-1 \leq R \leq 1$	$U = 0.55+0.35R+0.1R^2$	0.0357 MPa√m

In the Crack Closure fit for the ASTM approach the efficiency of the process seems to increase for negative load ratios, see Fig. 5. When the maximum load is assumed to be constant, the applied stress intensity will be constant for negative load ratios while the fit changes. This disproves the ASTM approach in the case of foams.

It is clear that the Foam approach fit has a higher efficiency than the Schijve fit for solid metals, especially in the negative load ratio range. This implies that there is a larger ΔK available for crack growth in the metal foam used. This is possible when another process is active in the range of the negative ΔK, which is the case in the proposed cell edge deformation mechanism (Fig. 4).

CONCLUSION

The Alporas closed cell aluminum foam has a rather high Paris exponent, which is about five times the Paris exponent of a solid aluminum alloy. The stable crack growth region or Paris region is low in crack growth rate and narrow in stress intensity compared to the normal range for solid metals. The entire Paris region is close to the unstable crack growth region where plastic failure mode can be expected. This makes the material less suitable for applications where reliable failure predictions are necessary.

The results of the Beam Bending model are in good agreement with the experimental data. Which makes a reasonable accurate predict of the Paris exponent possible, based on properties of the solid base material.

A novel form of crack closure occurs in the Alporas aluminum foam during Fatigue Crack Growth. It is hypothesized that the structure of the foam transforms macro-loads of both compression and tension into surface tension loads on a micro-scale, thus enlarging the effective load cycle available for Fatigue Crack Growth. This hypothesis needs further verification.

Proof of the fatigue process is found in the form of striations, which are clear in places where the composition deviates and contains oxides. Based on the plastic nature of the fracture surfaces, it is most likely that the crack closure effect is caused by surface roughness.

REFERENCES

1. Ashby, M.F., et al., Metal foams; A design guide. Butterworth-Heinemann, Boston, 2000.
2. Gibson, L.J., Ashby, M.F., Cellular solids: structures and properties, Cambridge University Press, Cambridge, 1997.
3. Shipsha, A., Burman, M., Zenkert, D., J. Sandw. Struct. Mater., vol **2,** 103-116, 2000.
4. Huang, J.S., Lin, J.Y., Acta Mater, vol **44**, 289-296, 1996.
5. Olurin, O.B., et al., Int. J. Fatigue, vol **23**, 375-382, 2001.
6. Phillips, R.A., et al., Powder Metal, vol **43**, no 2 149-156, 2000.
7. Dieter, G.E., Mechanical Metallurgy, McGraw-Hill, SI Metric Ed., London, 1988.
8. Schijve, J., Fatigue of Structures and Materials, Kluwer Academic Publishers, Dordrecht, 2001.
9. Miyoshi, T., et al., Adv. Eng. Mat., vol **2**, No 4, 179-183, 2000.
10. ASTM E 647-00 Standard Test Method for Measurement of Fatigue Crack Growth Rates, 2000.
11. Andrews, E.W., et al., Int. J. Mech. Sci., vol **43**, 701-713, 2001.
12. Geerlofs, N., On the Paris coefficient and crack closure effects of Alporas aluminium foam, M.Sc. Thesis, Delft UT, 2003.
13. www.matweb.com
14. Boller, CHR., Seeger T., Materials data for cyclic loading; Part D: Aluminium and Titanium alloys, Elsevier, Amsterdam, 1987.
15. Matěj, Bílý, Material Science Monographs 78; Cyclic Deformation and Fatigue of Metals, Elsevier, Amsterdam, 1993.
16. Suresh, S., Fatigue of materials, Cambridge University Press, Cambridge, 1998.
17. Janssen, M., Zuidema, J., Wanhill, R.J.H., Fracture Mechanics, Delft University Press, 2nd edition 2002.