Compression-Compression Fatigue Behavior of Al-Si-Ca alloy Foams

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Al-Si-Ca 합금 폼의 압축 피로 거동

이창훈, 하 산, 김엄기, 정길도

Key Words : Metal foam(금속폼), Plateau stress(플라투 응력), Fatigue properties(피로특성), Endurance strength(피로강도)

Abstract

The compression-compression fatigue properties of the closed cell Al-Si-Ca alloy foams have been studied. The monotonic and cyclic compressive properties were compared with each other and the fatigue stress-life (S-N) curves were presented. In compression-compression fatigue, the crushing was found to initiate in a single band which broadens gradually with additional fatigue cycles. Progressive shortening of the specimen took place due to a combination of low cycle fatigue failure and cyclic ratcheting which is in accordance with the findings of previous researchers [1-3]. Young's modulus of the foam was found to decrease with the increasing strain in case of fatigue test however in case of monotonic compression test the value of Young's modulus increased with the strain (number of cycles). The endurance limit on the basis of 10^7 cycles obtained by extrapolating the experimental results were 0.98 MPa and 1.70 MPa for load ratios 0.1 and 0.5 respectively which are 34 % and 59 % of the plateau stress.

1. Introduction

Al-alloy foams produced using the melt-based production method show high potential for applications in sandwich structure for panels, in tubes and shells, in packaging and crash protection devices and in the weight sensitive construction parts in transportation and aerospace industries. Construction parts in vehicles and components in airplanes or helicopters are frequently subjected to vibrations and repeated strains, more commonly the cyclic compressions. The apparent maximum values of nominal stresses in such vibrations and/or cyclic compressions are often much less than the static yield stress of the material. Even though these cyclic loadings do not cause any instant failure, in long run they may lead to fatigue damage of the material which may cause catastrophic consequences. Therefore, information about the fatigue behavior, fatigue strength and fatigue failure of aluminium-alloy foams are of great importance. While the monotonic compressive mechanical properties of foams have been extensively studied [4-9] during the last few decades, the cyclic stress-strain response of metallic foams has become at the center of attention for many of the metal foam researchers recently.

A-M. Harte, N.A. Fleck and M.F. Ashby [1] studied the tension-tension and compression-compression fatigue failure of the open cell "DUOCEL" and closed cell "ALPORAS" foams while Y. Sugimura et al.[2] studied the compression fatigue of "ALPORAS" foams. O. B. Olurin et al. [3] explored the fatigue properties of Alcan aluminium alloy foams. B. Zettl et al. [10] investigated the fatigue properties of Al-Mg-Si and Al-Si foams under fully reversed loading condition using the ultrasonic fatigue testing method while O. Schultz et al. [11] studied the fatigue behavior of AlSi7Mg+15%SiCa and AA6061 aluminium alloy foams. A-M Harte, N.A. Fleck and M.F. Ashby [12] also studied the fatigue strength of sandwich beams with ALPORAS aluminium foam core.

Most of the above work showed that the foam structures when subjected to repeated loading, rapidly lose their strength after a certain number of cycles

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depending on the stress amplitude and the mean stress. It was reported that fatigue damage is associated with the formation bands (in case of compression) or macroscopic cracks (in case of tension) [1, 2, 13]. The progressive shortening of the specimen in compression-compression fatigue, and progressive lengthening in tension-tension fatigue were reported and were associated to a combination of low cycle fatigue failure and cyclic ratcheting.

In this paper, we have studied the monotonic compressive properties and the compression-compression fatigue properties of Al-Si-Ca alloy foams. The monotonic compressive mechanical properties and the fatigue properties of the foams were measured using static compression test and compression-compression fatigue test respectively. The experimental S-N curves were obtained up to 10^5 number of cycles and then the extrapolation technique was used to obtain the endurance fatigue strength at 10^7 number of cycle. The endurance strengths obtained in this way were 0.98 MPa and 1.70 MPa for load ratios 0.1 and 0.5 respectively. The variation of the Young's modulus of the foam with increasing strain was investigated. It was found that in case of fatigue test the value of Young's modulus of Al-Si-Ca alloy foam decreases with increasing strain, however, in case of monotonic compression test the value of Young's modulus of Al-Si-Ca alloy foam increased with the increase of strain unlike many other Al-foams.

2. Experimental

2.1 Materials and specimens

The material used in this study was closed cell Al-Si-Ca alloy foam obtained from commercial manufacturer (FOAMTECH Korea). The material was produced using the melt-based process and was obtained in the form of panel of size 600x1200x35 mm. The processing route of the foam is proprietary; hence it is not disclosed here in details.

The FOAMTECH foam has a relatively uniform microstructure and is available in a large range of cell size depending upon the relative density. The foam used in this study had the cell diameter of about 1-2 mm and the relative density 11-13 %. Specimens of size 40x40x35 mm^3 were cut off from the foam panel for both the monotonic and fatigue tests.

2.2 Testing

All the monotonic and cyclic tests were performed using an MTS 810, servo-hydraulic test machine. While used as core material in sandwich panels, foams are more likely to experience stress fluctuation in through thickness direction. Therefore in this study we performed all of the tests in through thickness direction.

Fatigue test was performed at two different load ratios, R= 0.1 and 0.5 and four different endurance ratios in the range 0.65 to 0.90, the test frequency being 5 Hz. The specifications of the fatigue test specimens are shown in Table 1.

3. Results and Discussion

3.1 Monotonic compression

The monotonic (static) stress-strain curve of Al-Si-Ca alloy foam having relative density 12 % is shown in Fig. 1. The curve shows an initial linear elastic region

Table 1 Specifications of the fatigue test specimens

Load Ratio (R)	Endurance ratio (%) (σ_{max}/σ_{pl})	Relative density (ρ^*/ρ_s)	Load (N)	Cross section area (mm)	σ_{max} (MPa)	σ_{pl} (MPa)
0.1	0.65	0.11	3,000	1,600	1.875	2.88
	0.7	0.13	3,300	1,600	2.063	2.95
	0.8	0.12	3,700	1,600	2.313	2.89
	0.9	0.12	4,200	1,600	2.625	2.92
0.5	0.7	0.12	3,300	1,600	2.063	2.95
	0.80	0.11	3,700	1,600	2.313	2.89
	0.85	0.13	4,000	1600	2.500	2.94
	0.90	0.12	4,200	1,600	2.625	2.92

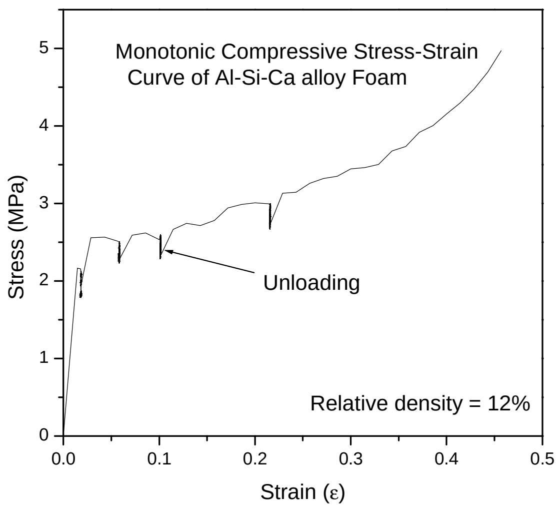


Fig. 1 The monotonic compressive stress-strain curve of Al-Si-Ca alloy foam (relative density = 12 %).

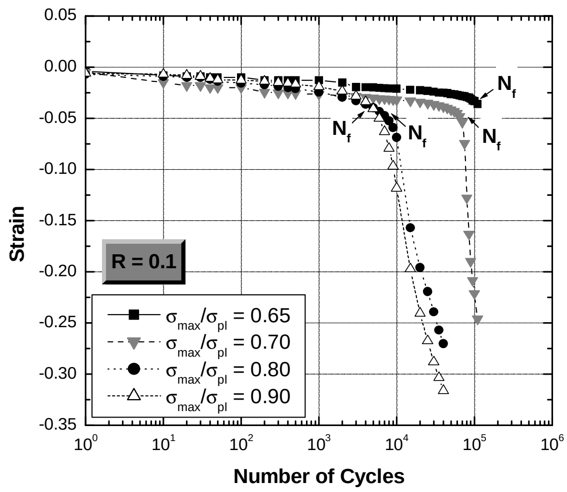
where partially reversible cell wall bending occurs, followed by a plastic plateau stress at which successive bands of cells collapse, buckle and yield, and finally a densification region where the stress rises sharply as complete compaction commences.

At 1.5 % strain, the unloading stress-strain curve showed an elastic modulus of 795 MPa while the average plastic plateau stress (σ_{pl}) of the foam obtained from the monotonic compression test was 2.89 MPa.

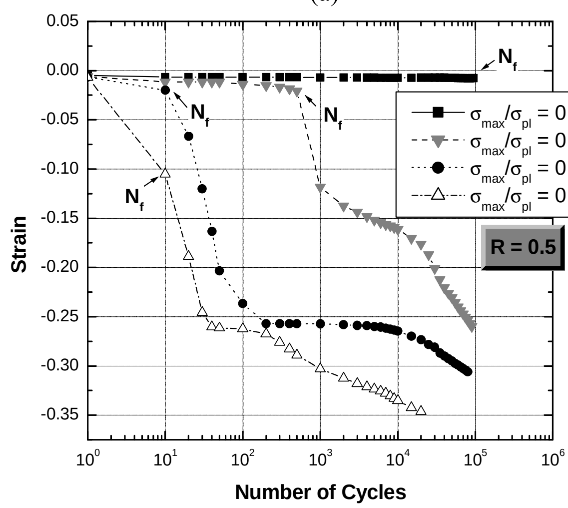
3.2 Compression-Compression Fatigue

The strain versus number of cycle graphs of Al-Si-Ca alloy foams in case of load ratio, R= 0.1 and R= 0.5 are shown in Figs. 2 (a) and (b) respectively. Four specimens of similar relative density (11-13 %) were taken in each of the cases and for each of the specimens a different endurance ratio (σ_{max} / σ_{pl} ≈ 0.6 to 0.9) was utilized by applying different magnitude of maximum stress (σ_{max}).

Both of the figures show that the strain increases with the number of cycle which means that shortening of the specimen takes place with the increasing number of cycle. However, an incubation period is evident, for all values of endurance ratio, at the end of which the rate of shortening is accelerated abruptly. This sudden rise of the rate of progressive shortening takes place at a strain level approximately 4% which is about equal to the monotonic yield strain of the foam. The number of cycle after which the abrupt increase of progressive shortening takes place is taken as the fatigue life at that stress. The fatigue life of the foams at different maximum stresses (i.e. different values of σ_{max} / σ_{pl} ratio) are shown in Figs. 3 (a) and (b) for R = 0.1 and R = 0.5 respectively. In other words, Figs. 3 represent the



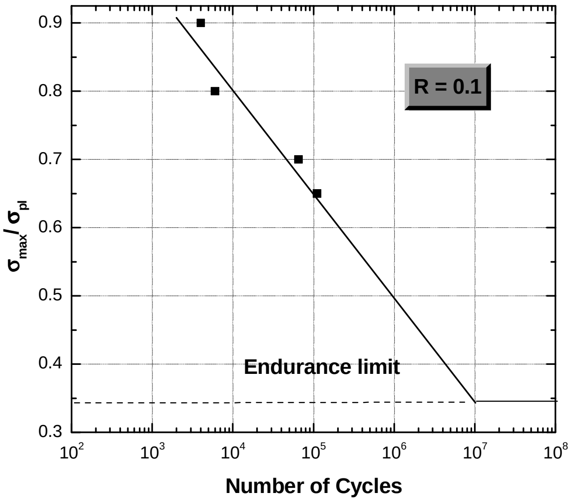
(a)



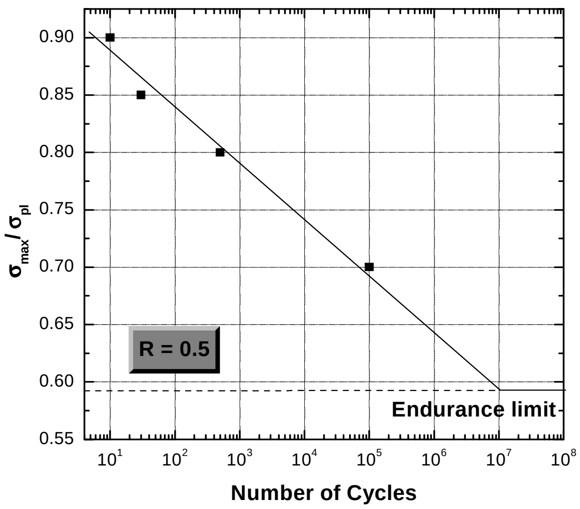
(b)

Fig. 2 The strain versus number of cycle graphs of Al-Si-Ca alloy foams showing the progressive shortening of specimens: (a) R = 0.1 (b) R = 0.5.

S-N curve of Al-Si-Ca alloy foam. It is evident that the fatigue life decreases with increasing stress level. The experimental data in Fig. 3 were fitted with straight line on a semi logarithmic plot. The tests were performed at a frequency 5 Hz, up to 10^5 number of cycle. Further increasing the exponent value of the number of cycle by just one, would increase the testing time by ten times, therefore we didn't perform the experiment beyond 10^5 number of cycle. However, it is known that Al-alloy foams generally show the endurance strength at 10^7 cycles [1, 2, 14]. Hence, we extrapolated the experimental S-N curve up to 10^7 number of cycles to obtain the endurance strength. In case of R = 0.1 and R = 0.5, the endurance ratios were found to be 0.34 and 0.59 resulting endurance strength 0.98 MPa and 1.7 MPa respectively. Thus it is evident that the endurance

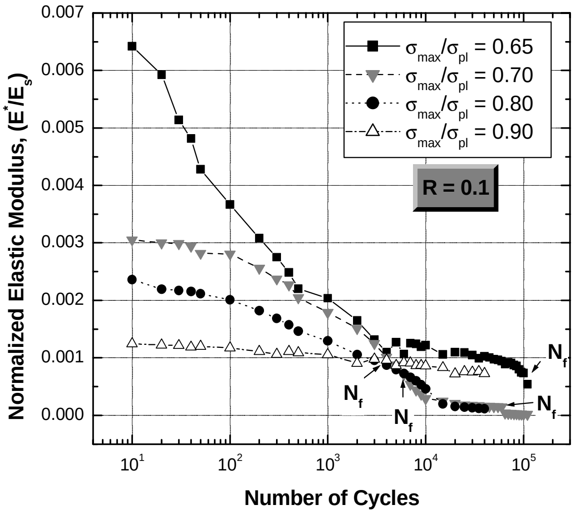


(a)

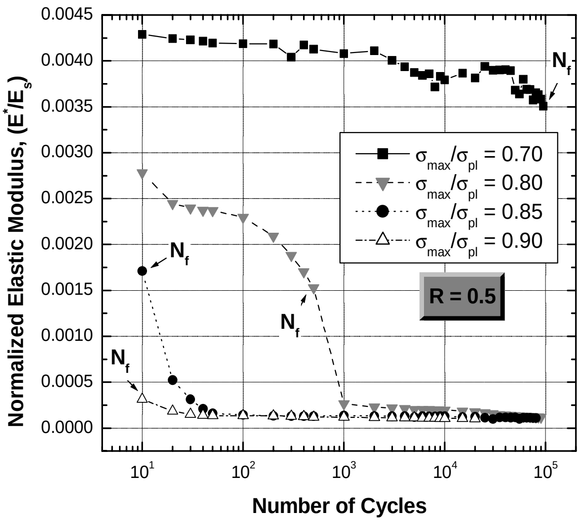


(b)

Fig. 3 The S-N curves of Al-Si-Ca alloy foams in case of compression-compression fatigue test: (a) R = 0.1 (b) R = 0.5.



(a)



(b)

Fig. 4 The normalized elastic modulus versus number of cycle graphs of Al-Si-Ca alloy foams in case of compression-compression fatigue test: (a) R = 0.1 (b) R = 0.5.

fatigue strength of the foam decreases as the amplitude of stress is increased in compression-compression fatigue.

3.3 Evolution of Young's Modulus

In order to determine whether or not the micro mechanism in monotonic test and compression-compression fatigue test are same, the unloading modulus of the foam measured at various strain level in case of the monotonic and the fatigue tests were compared with each other. The unloading modulus in fatigue was measured by measuring the cyclic strain during each fatigue cycle, while in case of monotonic compression it was measured by periodically interrupting the test at 1.5 %, 3 %, 5 %, 10 % and 21 % strain respectively where the specimens were unloaded approximately up to 10 % and the unloading data were recorded. The unloading curves of the foam showed much stiffer slopes than the loading curve.

Figs. 4(a) and (b) shows the variation of Young's modulus in compression-compression fatigue test with respect to the number of fatigue cycle for R= 0.1 and R= 0.5 respectively. It is evident that the modulus value decreases gradually with increasing number of fatigue cycle. Typical plots of unloading modulus E, in case of

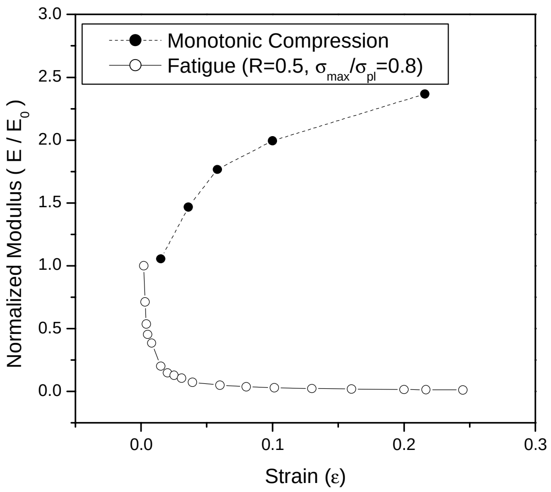


Fig. 5 Comparison of the normalized elastic modulus versus strain of Al-Si-Ca alloy foams in case of monotonic and compression-compression fatigue test: (a) R = 0.1 (b) R = 0.5.

the monotonic and fatigue tests, normalized by the initial value E_0 (= 758 MPa) are compared in Fig. 5. It is seen that the value of Young's modulus of Al-Si-Ca alloy foam decreases with increasing strain in case of fatigue test, but in case of monotonic compression test the value of Young's modulus rather increases with the strain unlike DUOCEL and ALPORAS foam studied by Harte et al. [1]. Therefore it is concluded that the failure mechanism of Al-Si-Ca alloy foam in case of monotonic and fatigue test are probably different from each other. The drop of Young's modulus in case of fatigue test is assumed to be a result of geometric changes in the cell-geometry and cracking of cell walls [14] which causes damage in the material, reducing the Young's modulus. Visual observation of the specimens during deformation also revealed that in case of fatigue test a single crush band formed after an incubation number of cycles, which then broadened with additional fatigue cycles and extensive low cycle failure occurred in the crush band. It was noticed that in the crush band the foam walls became disintegrated and rattled forming debris.

On the other hand, the increase of Young's modulus in case of monotonic compression test may be associated with the densification of the material. The precise details of the mechanism responsible for decrease or increase of Young's modulus remain to be quantified and are expected to be addressed in further detail in subsequent studies.

4. Conclusions

The monotonic and fatigue properties of closed cell Al-Si-Ca alloy foam of relative density 11-13 % produced from melt-based method, have been investigated. Experiments were performed at different load ratios and different endurance ratios. The results can be summarized as follows:

1. Fatigue failure in Al-foams occur at the monotonic yield strain of the foams. In case of Al-Si-Ca alloy foams this value is 4% nominal strain.

2. The endurance fatigue strength of Al-foams decreases as the amplitude of stress increases in compression-compression fatigue load. In case of Al-Si-Ca alloy foams the endurance strength on the basis of 10^7 cycles were 0.98 MPa and 1.70 MPa for load ratios 0.1 and 0.5 respectively.

3. The Young's modulus of the Al-Si-Ca alloy foams were found to decrease with increasing strain like DUOCEL and ALPORAS foams but in case of monotonic compression test the Young's modulus value rather increases unlike other Al-foams including DUOCEL and ALPORAS.

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