Fatigue tests of zinc aluminium matrix syntactic foams filled with expanded perlite

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Abstract. Metal matrix syntactic foams (MMSFs) are cellular materials which have high specific energy-absorbing properties accompanied by lower density compared to the bulk material. A special type of closed-cell metal matrix foams (MMFs) is the metal matrix syntactic foam. In this research, fatigue tests were carried out of ZA27 zinc aluminium matrix syntactic foams filled with expanded perlite. The stress levels were defined from the plateau stress of the quasi-static upsetting tests (90; 70; 50 and 30%) with R=0.1 stress ratio and f=10 Hz frequency. The results were evaluated statistically.

1. Introduction

Nowadays, the mass reduction of components has a primary role in industrial applications. These components have to be lightweight with enhanced specific mechanical properties which means the improvement of the used materials and structures. Increasing the specific energy-absorbing properties of the structure to compressive loads can be achieved by using lower density and higher strength materials. One of the best solutions for this demand is the group of closed-cell metal foams.

Metal matrix syntactic foams (MMSFs) are closed-cell foams in which the second phase (or filler) consists of hollow or expanded particles. Various matrix and filler materials are used by researchers to create MMSFs. The most common matrix materials are lightweight metals such as aluminium alloys [1,2], magnesium- [3,4] or titanium alloys [5]. There are also some researches where iron- [6] or zinc alloys [7] are used as a matrix. The first filler materials in MMSFs were fly-ash microspheres [8]. However, these days the most common second phase is ceramic hollow spheres, which can be made from high purity alumina [9], silicon carbide [10] or mixed oxide ceramics [1]. There are some researches based on iron hollow spheres [11] as the filler and also some cost-efficient alternatives such as lightweight expanded clay particles [12] or expanded perlite [13].

The main load for MMSFs as energy-absorbing structures is compression. Quasi-static compressive behaviour of these materials has been widely investigated [14–22], which is a standardised test method (ISO 13314:2011 – Mechanical testing of metals – Ductility testing – Compression test for porous and cellular metals). There are also researches on dynamic properties, wear and thermal properties of these materials [23–27].

Being familiar with the fatigue properties of foam structures is crucial for the constructability and future projection of the failure method at known stress levels. There are some publications on cyclic loading of MMFs, but most of them are focused on open and closed cell foams [28–37].
2. Cyclic testing of MMFs in the literature

Yang et al. investigated the compression fatigue properties of open-cell aluminium (99.0% purity) foams that were fabricated by space-holder method with three different porosities (50, 60 and 70%). The fatigue tests were carried out with R=0.1 stress ratio and f=10 Hz frequency. The stress levels were defined from the yield strength of the foams measured with quasi-static compression tests. The fatigue strengths showed a linear decrease with the increment of the porosity. Local deformation regions were observed at strain rates $\varepsilon=2\%$ and 4% [38].

Zhou et al. also investigated the compressive fatigue properties of commercially available open-cell aluminium (6101 alloy) foams with R=0.1 stress ratio. The cyclic frequency was $f=20$ Hz, and the stress levels were calculated from an equation. The S-N curves were characterised by an abrupt strain jump following an incubation stage in which the forms are progressively shortened at relatively slow rates depending on the stress level [39].

Zhao et al. evaluated the tension fatigue properties of closed-cell aluminium alloy foam, specifically the damage evaluation and damage mechanism. The loading frequency was $f=20$ Hz with $R=0.1$ stress ratio. The stress levels were defined as discreet values lower than the tensile strength measured with quasi-static compression tests. They observed a large scatter in the fatigue damage of the foams due to the variability of the specimens and developed a statistical damage model [40].

Schultz et al. observed the fatigue properties of closed-cell 6061 aluminium foams produced with powder metallurgy, with an average density of 0.4 g/cm$^3$ and AlSi7Mg+15%SiC$_p$ foam produced from aluminium melt, with an average density of 0.3 g/cm$^3$. Six stress levels were tested with $R=-1$ stress ratio. The specific fatigue strengths were in the same range for both type foams [41].

Kim and Kim investigated the specimen aspect ratio on compressive fatigue properties of closed-cell Al-Si-Ca alloy foam. The loading frequency was $f=50$ Hz with $R=0.1$ stress ratio. The four stress levels were defined from the plateau strength obtained from quasi-static compressions. It turned out that the onset of cyclic shortening of foams with a lower aspect ratio took place earlier than the specimen with a higher ratio. Also, their fatigue strength was lower compared to the specimen with a higher aspect ratio, while the quasi-static stress-strain curves had almost the same Young’s modulus, yield stress and plateau stress [42].

Katona et al. investigated the compressive fatigue properties of ceramic hollow sphere filled aluminium matrix syntactic foams with $R=0.1$ stress ratio. Al99.5 and AlSi12 alloys were applied as matrix material and Globocer as filler. The cyclic frequency was $f=10$ Hz, and the stress levels were defined from the compressive strength ($\sigma_c$) of the MMSFs measured with quasi-static compression tests. Regarding the matrix material, the softer matrix ensured higher load levels for the fatigue strength than the more rigid matrix [43].

Szlanckik et al. published on MMSFs filled with expanded perlite investigating the relation between the density (0.7 – 1.1 g/cm$^3$) and the compressive fatigue properties. The fatigue tests were carried out with $R=0.1$ stress ratio and $f=10$ Hz frequency. The stress levels were defined from the 1% compressive stress ($\sigma_c$) of the MMSFs measured with quasi-static compression tests. The fatigue criteria were at $\varepsilon=2\%$ strain rate. Both the fatigue limit and the slope of the Wöhler curve increased with the density. They also observed that the fatigue properties of MMSFs with same density but different filler materials differ [44].

Taherishargh et al. observed the fatigue properties of A356 aluminium matrix syntactic foams filled with expanded perlite focusing on the microstructure characterisation. The compressive fatigue tests were done with R=0.1 stress ratio and $f=10$ Hz frequency. The load levels were defined from the quasi-static compressive plateau stress of the MMSFs. Two different failure mechanisms were identified depending on the applied load level, that resulted in characteristic deformation – loading cycle curves. Traces of fatigue beachmarks and extensive plastic deformation were found on the microstructural scale [13].

There are only a few publications on the fatigue properties of metal matrix syntactic foams; therefore, it is important to produce new results in the field. Most of the research groups investigate the compressive fatigue properties with $R=0.1$ stress ratio factor and $f=10-50$ Hz frequency.
3. Materials and methods

3.1. Materials
ZA27 zinc aluminium alloy was used as matrix material, and expanded perlite (EP) particles were applied as filler obtained from Australian Perlite Pty. with a size range of 3–4 mm. The chemical composition of the used expanded perlite is 75 wt.% SiO$_2$, 14 wt.% Al$_2$O$_3$, 4 wt.% K$_2$O, 3 wt.% Na$_2$O, 1.3 wt.% CaO, 1 wt.% Fe$_2$O$_3$, 0.3 wt.% MgO and 0.2 wt.% TiO$_2$ with traces of heavy metals. ZA27 contains 25.0–28.0 wt.% Al, 2.0–2.5 wt.% Cu, 0.01–0.02 wt.% Mg, max. 0.075 wt.% Fe, max. 0.006 wt.% Pb, max. 0.006 wt.% Cd, max. 0.003 wt.% Sn and Zn as the balance.

The samples were produced with counter gravity infiltration. In this process a disk of ZA27 alloy was placed above the packed EP particles in a graphite crucible and the assembly was heated in an electric furnace to 535 °C for 30 min to melt the alloy. The EP particles were kept in place by a steel mesh. The infiltration was initiated by a 1 kg weight forcing the molten alloy between the EP particles. The solified samples were removed and machined. The samples were heat-treated at 365°C for 1 hour and cooled in water-ice mixture. A subsequent aging was at 140°C for 24 hours. The density range of the produced MMSFs was between 1.71 – 2.02 g/cm$^3$ calculated from their mass divided by their volume.

3.2. Fatigue test
Samples from the produced MMSFs were tested with quasi-static compression tests to specify the density-dependent plateau stress ($\sigma_{pl}$) values. The ISO 13314:2011 standard defines the plateau stress, which is calculated between 20 and 40% strain of the measured samples in this research. The load levels of the fatigue tests were calculated as the k=30; 50; 70 and 90% of this stress value for each fatigue sample. Figure 1. shows one cycle of the fatigue tests and the most important parameters. Three samples were tested on every load level up to ~5-10-15% engineering strain.

![Figure 1. Parameters of the compressive fatigue test (one cycle)](image)

The tests were carried out with f=10 Hz frequency, while the stress ratio was set to R=0.1. The fatigue limit was 2·10$^6$ cycles, and the failure criterion was 2% engineering strain according to other previous researches [13]. Ø20×30 mm samples were tested (the aspect ratio was H/D=1.5). For lubrication beeswax was used on the contact surfaces. The tests were performed on an Instron 8872 machine with 25 kN load cell. The displacement was measured with the crosshead displacement. The instantaneous failure of the examined MMSF with fatigue test is shown in Figure 2.
4. Results
First, the density-dependent plateau stress values were defined with quasi-static compression tests. The results are plotted in Figure 3. The equation of the fitted curve is:

$$\sigma_{pl} = 175.07\rho^2 - 582.75\rho + 525.92$$  \hspace{1cm} (1)

![Figure 3. Plateau stress in the function of the density](image)

| Sample | Density, $\rho$ (g/cm$^3$) | Calculated plateau stress, $\sigma_{pl}$ (MPa) | Load ratio, $k$ (-) | Minimum stress, $\sigma_{\text{min}}$ (MPa) | Maximum stress, $\sigma_{\text{max}}$ (MPa) |
|--------|-----------------|-----------------|-----------------|-----------------|-----------------|
| EP-1   | 1.98            | 58.17           | 0.9             | 5.23            | 52.35           |
| EP-2   | 1.71            | 41.34           | 0.9             | 3.72            | 37.20           |
| EP-3   | 1.88            | 49.12           | 0.9             | 4.42            | 44.20           |
| EP-4   | 1.80            | 44.22           | 0.7             | 3.09            | 30.95           |
| EP-5   | 1.82            | 46.04           | 0.7             | 3.22            | 32.22           |
| EP-6   | 1.86            | 47.81           | 0.7             | 3.34            | 33.46           |
| EP-7   | 1.83            | 45.91           | 0.5             | 2.29            | 22.95           |
| EP-8   | 1.88            | 49.36           | 0.5             | 2.46            | 24.68           |
| EP-9   | 1.78            | 43.16           | 0.5             | 2.15            | 21.58           |
| EP-10  | 1.87            | 48.49           | 0.3             | 1.45            | 14.54           |
| EP-11  | 1.86            | 47.74           | 0.3             | 1.43            | 14.32           |
All samples’ geometry and mass were measured before the fatigue tests. Table 1 summarises each specimen’s density and the fatigue test properties.

On each load level, three specimens were examined (Figure 4) for the appropriate statistical evaluation. In the case of each specimen, the cycle numbers at 2% engineering strain were determined. If the fatigue limit was reached before the failure criterion, the testing stopped (e.g. k=30% specimens). Based on these data, the number of cycles to failure (Nf) at a specified load level was calculated as the average of the three cycles numbers. In order to create the Wöhler-like curve of the investigated metal foam, a line was fitted on the evaluated numbers of cycles to failure – load level points by the least square method. The created Wöhler-like curve, which is only valid in the finite lifetime region, was plotted in a load ratio – number of cycles to failure graph in Figure 5.

![Figure 4. Engineering strain in the function of the number of cycles](image)

![Figure 5. Wöhler-like curve](image)

5. Conclusions
From this research, the following conclusions can be drawn:
- The relationship between the quasi-static compression plateau stress and the density of the investigated MMSFs can be described with a quadratic equation.
- The failure of the EP MMSFs is instantaneous and occurs in the upper region of the samples; however, further evaluation is needed.
- The fatigue properties of the investigated density-range EP zinc aluminium matrix foams can be determined for various load levels from the created Wöhler-like curve in the finite lifetime region.

In comparison to the results available in the literature, this research dealt with MMSFs filled with expanded perlite particles which broaden the data on the fatigue properties of different MMFs. It is important to be aware of the stress values behind the load levels and the density of the specimens, therefore, the different MMFs can be compared properly. Another important parameter for the proper comparison is the definition of the failure criterion. With all in sight the produced ZA27-EP MMSFs have higher density and cyclic compressive stress bearing than most of the previously investigated materials, but a lot of parameters are missing for distinct conclusions to be drawn.

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