Materials Science & Engineering A 679 (2017) 350–357

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Fatigue properties of ceramic hollow sphere filled aluminium matrix syntactic foams

Bálint Katona[a], Gábor Szebényi[b,c], Imre Norbert Orbulov[a,c,*]

[a] Department of Materials Science and Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Bertalan Lajos utca 7., Budapest 1111, Hungary
[b] Department of Polymer Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Műegyetem rakpart 3., Budapest 1111, Hungary
[c] MTA–BME Research Group for Composite Science and Technology, Műegyetem rakpart 3., Budapest 1111, Hungary

ARTICLE INFO

Keywords:
Mechanical characterization
Composites
Porous materials
Fatigue

ABSTRACT

Metal matrix syntactic foams, consisting of two grades of aluminium alloys and a set of oxide ceramic hollow spheres, were investigated in the aspect of cyclic loading. The results of the compressive – compressive cyclic loading with the load asymmetry factor of R=0.1 ensured full reliability design data for the investigated material in the lifetime region, while the fatigue limits were determined by staircase method. Based on the measurements the Wöhler curves of the foams were constructed, including the median curves, their confidence boundaries and the fatigue strength. Regarding the matrix material, the softer matrix ensured higher load levels for the fatigue strength than the more rigid matrix. Considering the size of the reinforcing ceramic hollow spheres, larger spheres performed better than the more vulnerable smaller ones. One common failure mode was isolated for the investigated foams: the samples were broken along a shear band, similar to the case of quasi-static loading.

1. Introduction

Metal matrix syntactic foams (MMSFs) consist of a set of hollow spheres (ceramic, metallic or mixed) in metal matrix. The hollow spheres are commercially available in various grades from different suppliers [1–3]. As matrix, usually some kind of lightweight metal is used. MMSFs can be sorted into two subgroups of materials. On one hand they can be mentioned as particle reinforced metal matrix composites (composite metal foams – CMFs), because they contain particle like hollow spheres within the diameter range Ø0.1…10 mm. On the other hand, they can be sorted as cellular materials (foams), due to the hollow nature of the reinforcement.

The basic mechanical properties of MMSFs have been widely studied. The publications focus mainly on the compressive behaviour of the foams (as most common loading mode). Due to its utmost importance the quasi-static compressive test of the metallic foams has been standardized [4,5]. There are certain research groups, dealing with syntactic foams: for example Fiedler et al. [6–10] have been developed low cost syntactic foams filled by perlite particles. Gupta et al. [11–19] have been investigated various MMSFs, including extremely light, SiC hollow sphere reinforced systems. Lehmhus et al. [17,20–25] developed high performance MMSFs, based on steels. Skolianos et al. [26] have been interested in powder metallurgy processed MMSFs. Rohatgi et al. [27–33] have been conducted extremely wide range experiments on MMSFs, aiming to characterise their properties in details and to highlight the MMSFs as potential solutions for many industrial applications. Moreover, the wear properties have been investigated and described in [34–41].

The behaviour of MMSFs in cyclic loading is also important, because many applications involve repeated loading. However, only a few publications are available in this field and most of them are focused on 'conventional' open and closed cell foams. In their comprehensive work Ashby et al. addressed the tension, compression and shearing mode fatigue tests of different aluminium foams and gave remarkable suggestions for the test samples geometry and conditions [42], later Degischer and Kriszt summarized some basic aspects based on the available literature [43]. Soubielle et al. investigated ~400 µm pore size replicated aluminium foams in tension-tension loading (R=0.1). The foams displayed cyclic creep coupled with a strong influence of relative density [44]. Amsterdam et al. performed monotonic and cyclic tension tests on closed cell foams produced by powder metallurgy. Tension–tension fatigue tests started with the constant ratchetting of the foam samples followed by an accelerated elongation that lead to failure. [45]. Harte et al. compared the fatigue failure of commercially available open

---

* Corresponding author at: Department of Materials Science and Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Bertalan Lajos utca 7., Budapest 1111, Hungary.
E-mail addresses: orbulov@eik.bme.hu, orbulov@gmail.com (I.N. Orbulov).

http://dx.doi.org/10.1016/j.msea.2016.10.061
Received 5 August 2016; Received in revised form 10 October 2016; Accepted 12 October 2016

and closed cell aluminium alloy foams in tension-tension and in compression-compression loading. The open cell foam had a relatively uniform microstructure, and underwent homogeneous straining. In contrast, the closed cell foam was more irregular in microstructure, and exhibited a single crush band formed and broadened with additional fatigue cycles [46]. McCullough and Fleck performed cyclic tension and compression tests on closed cell AlMgSi alloy based foams in the relative density range of 0.1–0.4. The fatigue strength of the foams increased with the relative density and the dominant cyclic deformation mode appeared to be material ratchetting [47]. Banhart and Brinkers investigated aluminium-silicon alloy Al+7 wt% Si) closed cell foams produced by powder metallurgy (0.5 wt% TiH_2), with different relative densities. The cylindrical specimens were loaded in compression-compression mode. The authors highlighted that the compression strength and the failure criterion were not unambiguous in the case of metallic foams [48]. Pure Al foams with similar structure were tested in cyclic compression by Sugimura et al. A significant novelty in their work was the application of image analysis to record strain maps and to follow the formation and thickening of the deformation bands. The closed cell Al alloys had a relatively well defined fatigue life in cyclic compression, associated with the plastically buckled membranes of the cell walls resulted in a single cyclic deformation band [49]. Zhou and Soboyejo investigated AlMgSi based open cell foams under cyclic compression loading, that resulted in crack nucleation on the surface of the struts. The cracks grew until final failure occurred in the individual struts. In the vicinity of the cracked struts the loads were transferred to the adjacent struts. This led to the acceleration of fatigue damage by formation of macroscopic deformation band(s), resulted in the onset of abrupt strain jumps [50,51]. Lehmhus et al. investigated powder metallurgy produced Al6061 alloy foams in as foamed and in precipitation hardened condition under cyclic compression-compression loading. The positive effect of precipitation hardening (e. g. the increment in strength values under monotonic loading) was only partially experienced in cyclic loading [52]. The work of Lin et al. emphasized the application of porous TiNb alloys as bone replacements [50,51]. The cracks that caused fatigue failure appeared on the surface of the struts in the vicinity of the largest pores [53]. Hakamada et al. focused their work on the cyclic compression tests of closed cell Al foams produced by spacer method using NaCl space holders and a spark plasma sintering equipment. Under cyclic compression the strain increased gradually with cycles and no distinct strain jump was observed for the specimen [54]. Zettl et al. investigated AlMgSi and AlSi alloy based, powder metallurgy produced closed cell foams by ultrasound fatigue testing method under fully reversed tension-compression loading. Preferential areas for crack initiation were initial defects like precracks or holes in the interior sections of cell walls. No strain localization or formation of deformation bands were found and the effect of frequency magnitude found to be negligible within three decades [55,56]. The effect of sample dimensions, especially of the aspect ratio was investigated by Kim and Kim on closed cell Al-Si-Ca foams. The cyclic compression-compression tests revealed that, the onset of cyclic shortening of foams with lower aspect ratio took place earlier and the fatigue strength was lower compared to the specimens with higher aspect ratio [57]. Kolluri et al. performed cyclic compression-compression tests at constant stress amplitude levels on closed-cell Al foam in laterally constrained and unconstrained condition. The results showed that while the early stages of strain accumulation due to fatigue loading were independent of constraint, the rapid strain accumulation stages behaviour were sensitive to the constraint [58]. One step further, sandwich beams (with Al alloy foam core) were also tested in cyclic four-point-bending by Harte et al. The combined experimental and theoretical study showed that a reduction in the strength of sandwich beams existed for cyclic loading compared to monotonic loading [59]. Moreover, Schultz et al. investigated foams in the aspect of potential helicopter components [60].

As it is presented above, the different research groups published results about versatile foam systems and different cyclic loadings. Most of the investigations apply R=0.1 stress asymmetry factor, but the test frequencies can differ significantly. On the other hand, MMSFs have been not mentioned yet. The only similar work on CMFs that contain steel hollow spheres in aluminium matrix (made by gravity casting) or in steel matrix (made by powder metallurgy method) was published by Vendra et al. Under cyclic compression loading, the CMFs showed high cyclic stability and the deformation of the composite foam samples could be divided into three stages – linear increase in strain with fatigue cycles (stage I), minimal strain accumulation in large number of cycles (stage II) and rapid strain accumulation within few cycles up to complete failure (stage III). The deformation of the MMSFs occurred to be uniform compared to regular metal foams, which deform by forming collapse bands at weaker sections [61].

The aim of this paper is to widen the fatigue properties datasets available for the compression-compression loading of MMSFs by the investigation of Al99.5 and AlSi12 matrix MMSFs with different filler materials.

2. Materials and methods

Al99.5 and AlSi12 alloys were applied as matrix materials, their chemical compositions are listed in Table 1. As filler, Globocer (GC) grade ceramic hollow spheres were applied, provided by Hollomet GmbH. [1]. The material of the hollow spheres consists of 38 wt% Al_2O_3, 43 wt% SiO_2 and 19 wt% $3Al_2O_3{\cdot}2SiO_2$. The hollow spheres follow a normal distribution regarding their diameter (1425 ± 42 μm) and wall thickness (60 ± 1.7 μm), while their density is 0.816 g cm^{-3}. The amount of the filler material was maintained at ~65 vol%, ensured by gentle tapping and knocking during the filling process [62,63]. The MMSFs were produced by pressure infiltration. During the infiltration 400 kPa infiltration pressure was applied for the infiltration time of 30 s. The infiltration temperature was always set to 50 °C above the melting temperature of the matrix materials (660 °C for Al99.5 and 575 °C for AlSi12). The infiltration pressure was significantly larger than the threshold pressure of the hollow spheres, therefore the amount of un-infiltrated voids could be neglected (please refer to the micrographs in Sections 3.1 and 3.2). However, due to the nature of the pressure infiltration and because of the uneven wall thickness of the hollow spheres, the infiltration pressure may have exceeded the crush strength of a few hollow spheres. In these cases, the spheres were infiltrated (less than 3 vol% of the spheres). The infiltration process is described in details elsewhere [64–66]. The produced foams were designated after their constituents, for example Al99.5-GC stands for an MMSF sample with Al99.5 matrix and ~65 vol% of Globocer filler material. Cylindrical samples with diameter of Ø8.5 mm and height of 12.75 mm (1.5 aspect ratio) were machined from the produced blocks.

For classic fatigue tests, load levels (k) should be determined, that describe the maximum load (σ_{max}) during each fatigue cycle in a relation to a limit strength. In the case of conventional metals, the load levels are usually related to the proof strength ($R_{p0.2}$) that is measured by simple tensile tests. In the case of MMSFs the proof strength can be substituted by the compressive strength (σ_c, the first local maximum in the engineering compressive stress – strain diagram, that causes irreversible failure, see Fig. 1).

The compressive strength (σ_c) of the foams, was measured for each material type on six samples (Table 2). On this basis, the load levels can be defined as the ratio of the maximal load and the compressive

Table 1
Chemical composition of the matrix materials (in wt%).

Matrix	Si	Fe	Mn	Mg	Cu	Zn	Al
Al99.5	0.250	0.400	0.050	0.050	0.050	0.050	rem.
AlSi12	12.830	0.127	0.005	0.010	0.002	0.007	rem.