

Creep of aluminum syntactic foams

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Abstract

Aluminum syntactic foams with densities of 1.2–1.5 g/cm³ were deformed at 500 °C under constant uniaxial compressive stresses ranging from 5 to 14 MPa. The foam creep behavior is characterized by a short primary stage and a long secondary stage where the strain rate is constant and minimum, followed by a tertiary stage at high stresses. The minimum strain rate varies with stress according to an apparent stress exponent n with a low value ($n \approx 1$) for stresses below 8 MPa, and a high value ($n \approx 14$) above 8 MPa. Finite-element modeling provides predictions for the foam strain rates that are in qualitative agreement with experimental results. Modeling also shows that the matrix transfers load to the ceramic elastic spheres, explaining the exceptionally high creep resistance of these syntactic foams as compared to aluminum foams without ceramic spheres. Modeling finally reveals that stresses vary with position in the matrix and time during creep, and that the onset of tertiary stage is associated with the appearance of sharp stress concentrations in the matrix.

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1. Introduction

Syntactic metallic foams consist of hollow spheres surrounded by a metallic matrix [1] and are usually produced by metal infiltration of a packed preform of ceramic (or metallic) hollow spheres with sub-millimeter size [2–13]. The hollow nature of the spheres provides two functions. First, the empty space within the spheres produce closed pores, which encompass up to ~60 vol.% of the total foam volume, depending on sphere packing efficiency and wall thickness. Second, the ceramic shells create a percolating, continuous skeleton within the foam, resulting in enhanced strength and stiffness as compared to unreinforced foams with the same average density.

In previous studies, Balch et al. [10,11] studied the ambient-temperature compressive properties of syntactic aluminum foams containing hollow silica-mullite spheres and discussed their compressive stiffness, strength, damage properties and energy absorption in terms of load transfer between the matrix and the spheres. The same aluminum syntactic foams previ-

ously examined by these authors at ambient temperature are investigated in the present study at elevated temperature. The compressive creep rate is measured for various constant uniaxial stresses (ranging from 5 to 14 MPa) at temperatures as high as 500 °C (corresponding to a homologous temperature of 0.83). Finite-element modeling (FEM) is carried out on simplified periodic and quasi-periodic models and compared with the experimental creep results.

2. Experimental procedures

We use aluminum syntactic foams cut from the same billet produced for a previous investigation; experimental procedures for foam fabrication are described in details in the original references [10,11] and are summarized here briefly. Hollow silica-mullite spheres with 15–75 µm diameter and 2–5 µm wall thickness (provided by EnviroSpheres PTY Ltd.) were tap-packed into a preform which was pressure infiltrated with molten aluminum of commercial purity at 710 °C. The solidified billet was then cut into parallelepiped specimens with 7 mm × 3 mm × 3 mm dimensions whose densities were measured by helium pycnometry.

Constant-load compressive creep tests were conducted on these specimens in air at temperature between 250 and 500 °C and for engineering stresses ranging from 1 to 14 MPa. Creep

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deformation was significant only at temperature above 325 °C and for stresses above 5 MPa. Thus, creep results are presented here only for the highest temperature of 500 °C and for stresses above 5 MPa. For all samples, a total cumulative engineering strain of 5% was not exceeded unless, in a few cases, fracture of the specimen was the goal. A direct-loading compression creep machine was used under constant-load condition. The engineering strain was calculated from cross-head displacement data measured continuously by a linear voltage displacement transducer.

3. Experimental results

The foam specimens displayed a density in the range 1.23–1.48 g/cm³, corresponding to relative densities of 0.46–0.55 (as compared to pure aluminum) and a sphere volume fraction $f = 59$ –71% (using a density of 0.62 g/cm³ for the spheres, as measured by Ref. [11]). Foams showed a uniform spatial distribution of spheres, good aluminum infiltration of the volume between spheres and few fragmented or infiltrated spheres, as illustrated in Fig. 1. As reported previously [11], the sphere walls are porous and of varying thickness.

Fig. 2(a and b) shows creep curves measured for foams tested at 500 °C for stresses between 5 and 13 MPa. All curves exhibit a primary creep stage with continuously decreasing strain rate, followed by a secondary stage where the average strain rate is constant (strain fluctuations on the creep curves of Fig. 2(a and b) were due to small thermal fluctuations in the creep furnace). Finally, for stresses above 9 MPa (Fig. 2(b)), a tertiary stage characterized by increasing strain rates appears after relatively short times and this stage is usually associated with severe damage in the foams visible as crush bands and wrinkled specimen sides. By contrast, for stresses below 9 MPa, no tertiary stage is observed, even after very long testing times of about 1 week (6×10^5 s, not represented in Fig. 2(a) extending to 1×10^5 s).

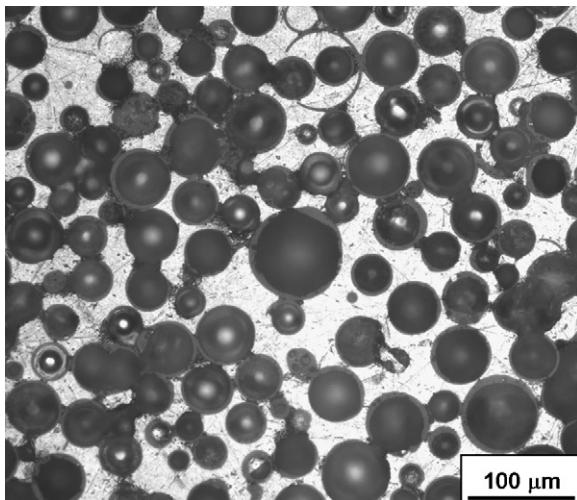


Fig. 1. Micrograph of metallographic cross-section for syntactic foam, showing ceramic hollow microspheres and pure aluminum matrix.

4. Modeling

The structure of syntactic foams is too complex to permit simple analytical models of the type developed for creep of reticulated single-phase foams, which is based on strut bending and compression [14,15]. Thus, FEM was carried out using the commercial ABAQUS package [16]. Such a numerical approach has also the advantage, as compared to analytical modeling, to provide spatially and time-resolved information on the stress distribution within the foam.

Unit cells consisting of aluminum matrix containing fully bonded hollow spheres were used. Periodic boundary conditions, where the faces of the unit cell are kept flat and parallel

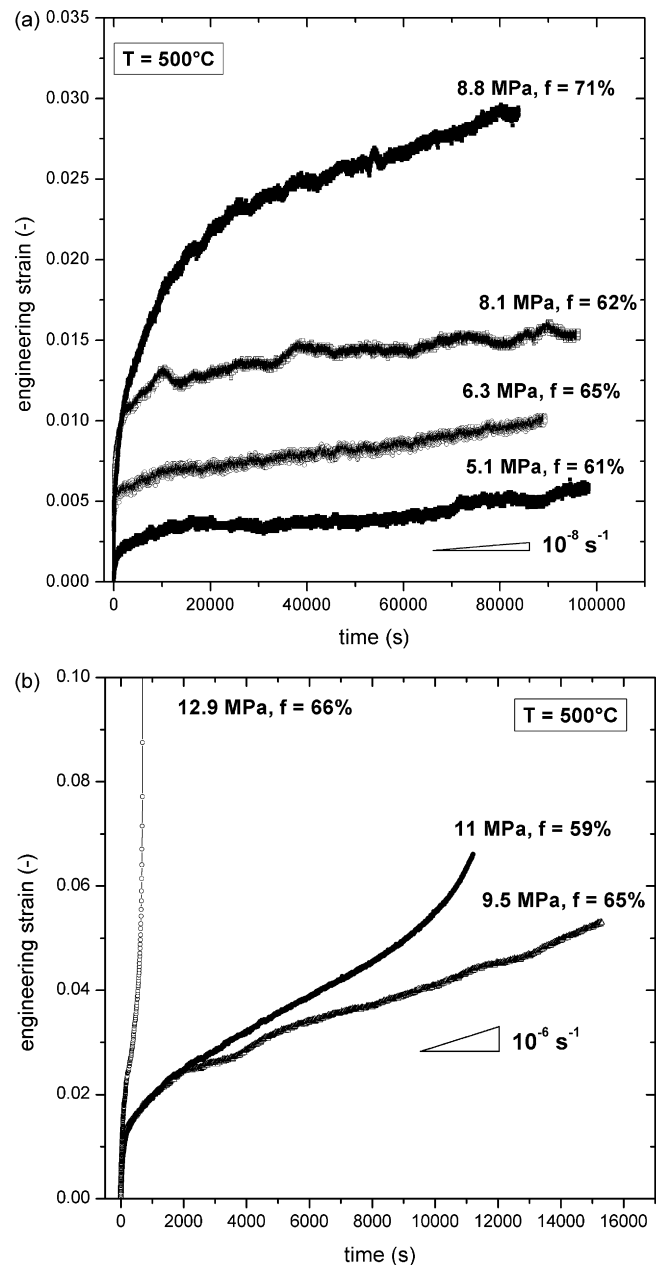


Fig. 2. Creep strain as a function of time measured for foams (with volume fractions $f = 59$ –71%, indicated next to each curve) deformed at 500 °C for compressive stresses: (a) below 9 MPa and (b) above 9 MPa.

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