Materials & Design 83 (2015) 230–237

Contents lists available at ScienceDirect

Materials & Design

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

Compressive behaviour of aluminium matrix syntactic foams reinforced by iron hollow spheres

Attila Szlancsik [a], Bálint Katona [a], Kristóf Bobor [a], Kornél Májlinger [a], Imre Norbert Orbulov [a,b,*]

[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] MTA–BME Research Group for Composite Science and Technology, Műegyetem rakpart 3., Budapest 1111, Hungary

ARTICLE INFO

Article history:
Received 18 December 2014
Revised 2 June 2015
Accepted 4 June 2015
Available online 19 June 2015

Keywords:
Metallic foam
Compressive strength
Metal matrix composite
Hollow sphere
Absorbed energy

ABSTRACT

Aluminium alloy syntactic foams reinforced with iron hollow spheres were produced by low pressure, liquid phase inert gas infiltration technique. Four Al alloys (Al99.5, AlSi12, AlMgSi1 and AlCu5) and Globomet grade iron hollow spheres were used as matrix and reinforcing material, respectively. The produced composite blocks were characterised according to the ruling standard for compression of cellular materials in order to ensure full comparability. The compressive test results showed plastic yielding and a long, slowly ascending plateau region that ensures large energy absorption capability. The proper selection of the matrix material and the applied heat treatment allows for a wide range of tailoring of the mechanical properties. For design purposes, the full-scale finite element method (FEM) model of the investigated foams was created and tested on Al99.5 matrix foams. The FEM results showed very good agreement with the measured values (typically within 5% in the characteristic properties and within 10% for the whole compression curve).

1. Introduction

Metal matrix syntactic foams (MMSFs) consist of a metallic matrix material and a set of hollow spheres. MMSFs were developed for lightweight structures, requiring high strength and energy absorbing capacity [1]. The matrix material is usually an aluminium alloy (light and low cost), but nowadays high strength iron based matrices are also investigated [2–11]. As filler material, commercially available mixed-oxide ceramic [12–15], metallic [12] or SiC [16,17] hollow spheres are frequently applied, however Taherishargh et al. have been made efforts for the application of low cost perlite filler as well [18–20].

The professional literature mainly focuses on the production and mechanical properties of MMSFs. For example, Lehmhus and Weise et al. investigated the mechanical behaviour of hollow glass microspheres-iron matrix syntactic foams. In particular, the strain-rate sensitivity response at three different strain rate levels was studied by taking into account the influence of type and volume fraction of glass spheres. The materials' behaviour was found to be very similar to that of the metal matrix [2,6–8]. Castro and Nutt produced steel based MMSFs, filled with ceramic hollow spheres by gravity fed and mechanical pressure infiltration. In the case of gravity fed infiltration the simple compression behaviour of the MMSFs was studied, and a TRIP steel syntactic foam exhibited the highest compression strength and energy absorption capacity [4]. In the case of mechanical pressure infiltration the basic mechanical properties of a ferritic and a pearlitic steel MMSF were studied under compression loading. The pearlitic foam had greater compression strength and energy absorption capacity than the ferritic [5]. The research group of Rabiei studied composite metal foams (CMFs) produced by gravity casting technique. The foam was comprised of steel hollow spheres packed into a random dense arrangement, with the interstitial space infiltrated with a casting aluminium alloy. The composite displayed superior compressive strength (~65 MPa within 10–50% strain range) and energy absorption capacity (~30 MJ m^{-3} at 50% strain) [21–24]. Rabiei et al also published CMFs produced by powder metallurgy. The CMFs were built up from the combination of carbon steel or a 316L grade stainless steel matrix and hollow spheres respectively. The energy absorption at densification for carbon steel samples ranged from 18.9 to 41.7 MJ m^{-3} and for the stainless steel sample it was 67.8 MJ m^{-3} [3,22]. Later the effect of loading rate and spheres size were also taken into account: the smaller hollow spheres performed better at each loading rate level up to 8 ms^{-1}

---

* 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.matdes.2015.06.011
0264-1275/© 2015 Elsevier Ltd. All rights reserved.

[25]. The fatigue properties of Al–steel and steel–steel CMFs under cyclic compression were also described in details [11].

Besides iron based matrices and/or hollow spheres numerous other investigations on the compressive properties of Al based, ceramic hollow sphere filled MMSFs have been published. Balch et al investigated the load partitioning in MMSFs by diffraction techniques and found that the best performance can be achieved if the matrix yield strength and hollow spheres crush strength are equal [26,27]. Dou and Wu et al investigated the quasi-static and high strain rate response of cenosphere-pure aluminium MMSFs. The foams exhibited distinct strain rate sensitivity, with peak strengths increased from ~45–75 to ~65–120 MPa, and energy absorption capacity increased by ~50–70% [28–30]. Goel et al. studied the same material pair of varying densities and cenosphere sizes at different strain rates (0.01–10 s^{-1}). The plateau stress, densification strain, energy absorption and strain rate sensitivity parameter as a function of relative density, strain rate and cenosphere size have been reported [31–33]. Luong et al. investigated the quasi-static and high strain rate compressive properties of Al4032/cenosphere composites. While the matrix did not show any strain rate sensitivity, the composite showed higher strength and energy absorption capability at higher strain rates [34]. Mondal et al. performed wide range of materials testing such as classical quasi-static [35], high strain rate [32] or elevated temperature compression [36] tests, wear tests [37,38] and finite element analyses [39]. Palmer et al. studied the mechanical properties of MMSFs incorporating 45 and 270 µm ceramic microspheres in Al1350, Al5083 and Al6061 alloy matrices. The produced foams remained intact at strains up to 50% despite significant fracturing, resulting in high and repeatable strain energies [40]. Kiser et al. investigated the mechanical response of a family of ceramic microballoons reinforced Al matrix MMSFs under both uniaxial and constrained die compression loadings. The energy absorption capacity (160 ± 70 MJ m^{-3}) found to be extremely high in comparison with values that are typical of metal foams [41]. Beside classical MMSFs (as a base for comparison) [42] Tao et al. produced Al particle toughened MMSFs by pressure infiltration. With the introduction of Al particles, the ductility and the compressive strength increased by ~30%. As a result, the specific energy absorption capacity was also increased by ~80% [43]. Subsequently, MMSFs with bimodal ceramic hollow spheres were produced and studied. The MMSFs had ~10% higher porosity, which led to 8% higher densification strain [44]. Zhang and Zhao investigated the mechanical response of four types of Al based MMSF with different sphere sizes and densities under static and dynamic conditions. The plateau strength and the energy absorption of the MMSFs were largely determined by the volume fraction of Al and to a lesser extent by the properties of the ceramic spheres [45]. Although the most common matrix materials are Al and steel, other perspective matrices, such as Mg [46–50], Zn [51,52] and Ti [53,54] alloys were also studied.

The modelling of the structure of MMSFs has been also discussed in professional literature. The reconstruction of the structure is often supported by X-ray tomography [55–60] and relies on analytical approaches (for example by Zsoldos et al. [61]). Bardella and Genna published papers on the determination of the elastic properties of syntactic foams [62–64]. These articles are based on three phase unit cell models considering the matrix – wall – porosity structure of syntactic foams. Marur has published a very similar approach [65]. A three phase concentric sphere model was used to estimate the effective elastic constants, and the results were compared to other theories and experimental data. In a subsequent paper Marur took into account the influence of weak interfaces between the inclusion (hollow spheres) and the matrix [66]. Later the applicability of the formulae and the conclusions were also confirmed by numeric methods [67]. Porfiri and Gupta focused on the development of a model to estimate the elastic constants for syntactic foams as function of particle wall thickness, size, and volume fraction. The model can be used to predict the Young's modulus of MMSFs containing microballoons of a wide range of wall thickness and volume fraction [68]. Based on their experimental work [69,70], Rohatgi and his research group presented a model that can predict peak stress, plateau stress, densification strain, and composite density of hollow ceramic sphere-reinforced MMSFs subjected to unconstrained compression. The results showed good agreement with the experimental data available in literature [71]. Kiser et al. gave a prediction for the crush strength of MMSFs in constrained upsetting condition, with an effective strength that depends on the relative wall thickness [41].

According to the above mentioned research contributions the aims of this paper are (i) to give details about the mechanical properties of Al alloy based, Fe hollow sphere reinforced MMSFs; (ii) to describe a full-scale finite element method (FEM) model able to follow the compressive properties of the produced MMSFs.

2. Materials and experimental methods

Four types of MMSF were produced by low pressure inert gas assisted infiltration technique. The applied matrices were Al alloys, their measured chemical compositions are listed in Table 1. For this investigation a PhillipsXL-30 type electron microscope (SEM) equipped with an EDAX Genesis energy dispersive X-ray spectroscopy (EDS) analyser was applied.

Globomet (GM) grade hollow pure Fe spheres were applied as filler material (supplied by Hollomet GmbH, Dresden, Germany [12]). The nominal diameter of the hollow spheres was 1.92 ± 0.07 mm (obtained by measuring 1000 hollow spheres on an Olympus SZX 16 type stereo microscope). Their average wall thickness was 23 ± 0.6 µm, while their density was 0.093 g cm^{-3}. The actual diameter distribution of the spheres followed Gaussian distribution as it is plotted in Fig. 1a. The volume fraction of the reinforcement was maintained at ~65 vol%, by continuous tapping of the mold [73,74]. A typical macro photograph and a SEM image about the surface of the hollow spheres are presented in Fig. 1b and c respectively.

For the infiltration process, a special mold was developed and fabricated (Fig. 2). The mold (#7) was coated by a thin graphite layer (FormKote T-50; Everlube Products, Peachtree City, GA) and filled halfway by the hollow spheres (#6) during continuous tapping in order to achieve ~65% volume fraction [73,74]. Subsequently, the hollow spheres were fixed in position by a 316L stainless steel net (#5) and placed in a furnace (Lindberg/Blue M) for pre-heating (300 °C for 0.5 h). Meanwhile, the matrix material was melted and heated above its melting point by 50 °C in a Power-Trak 15–96 induction furnace. In the next step, the molten matrix material (#4) was poured into the mold, on the hollow spheres. Subsequently, the inert gas (Ar) was injected into the system through a pressure reducer and the upper pipe system (#1 and #2) at 400 kPa infiltration pressure. A steel plate (#3)

Table 1
Chemical composition of the applied matrix materials (only the significant elements are tabulated, measured by EDS).

Matrix	Main components (wt%)						Closest standard equivalent [72]
	Al	Si	Fe	Mg	Cu	Other	
Al99.5	99.5	0.1	0.1	–	–	0.3	Al1050
AlSi12	86.0	12.8	0.1	0.1	–	1.0	A413
AlMgSi1	97.0	1.1	0.5	1.1	–	0.3	Al6082[a]
AlCu5	95.0	–	–	–	4.5	0.5	Al2011

[a] Closest alloy, except the Mn content (should be 0.4–1.0 wt%).