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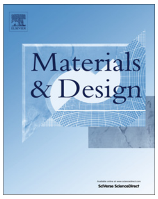

Description of the compressive response of metal matrix syntactic foams

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ABSTRACT

The mathematical description of the compressive behaviour of metal matrix syntactic foams (MMSFs) was investigated and analysed in order to provide continuous functions as input data for finite element and other numerical methods. MMSFs are advanced composite materials having promising application fields in aviation, transport and automotive industry as well as in civil engineering. As foam materials, their typical loading is compression; therefore the compressive properties of MMSFs have been studied. The continuous mathematical description of their response to compressive loading is still missing, but would be important in order to support the design (for example the finite element method) of MMSFs. The aim of this paper is to provide a comprehensive, but relatively simple method to handle the mathematical description of the compressive response of MMSFs. The resulted continuous functions were validated by numerous measurements and good agreement was found for each MMSF types and cases. Due to this the provided functions can be used in the computational design of MMSFs.

1. Introduction

Metal matrix syntactic foams (MMSFs) are metal matrix composites (MMCs) built up from a metallic matrix and thousands of ceramic hollow spheres. Due to the particle-like hollow spheres they can be also considered as porous materials or metallic foams as well as particle reinforced MMCs. The most common matrix materials are aluminium alloys (however iron matrix syntactic foams were also reported in [1,2]) while the ceramic hollow spheres are composed of various oxide ceramics. MMSFs have many beneficial properties such as low weight, outstanding specific properties, high mechanical energy absorption capability and good creep resistance. It is worth mentioning that the specific mechanical properties of MMSFs can be 50–100% higher than those of conventional foams' [3,4]. MMSFs are used as energy and sound absorbers, collision dampers or as material of hulls and shells in deep-sea applications, aeronautics or automotive industry.

The porous materials such as MMSFs receive increasing interest and therefore mainly their mechanical properties have been widely studied. Balch et al. [5,6], Dou et al. [7], Kiser et al. [8], Mondal et al. [9], Palmer et al. [10], Rabiei and O'Neill [11], Rohatgi et al. [12], Tao and Zhao [13] Wu et al. [14], Zhang and Zhao [15] and the authors themselves are all interested in the compressive testing of MMSFs. In the works mentioned above the results of quasi-static, dynamic, free and constrained compression test were published in details with parameters like microballon's type and size, porosity, type of matrix material etc. taken into account. Besides, papers of MMSF production were also published [16–19]. Moreover Couteau and Dunand published results about the long term creep characteristics of MMSFs [20], while Ramachandra and Radhakrishna [21], Rohatgi and Guo [22] and Mondal et al. [23] investigated the wear and corrosive properties of MMSFs. According to the hardness of MMSFs Ramachandra and Radhakrishna [24] and Orbulov and Németh [25] reported the results of various global, depth sensing, dynamic and local hardness tests. The wear mechanism of MMSFs is also a popular research field, because the ceramic hollow spheres can act as lubricant reservoirs and thus improve performance.

A few papers are dealing with the modelling of MMSFs. For example Bardella and Genna published two papers on the determination of the elastic properties of syntactic foams and sandwich structures containing syntactic foams [26,27]. These articles are based on a three phase unit cell model considering the matrix–wall–porosity structure of the syntactic foams. Both works show that (i) the actual distribution of wall thickness of the ceramic hollow spheres seems to have little influence on the overall properties of the syntactic foams; (ii) the presence of unwanted voids in the matrix has a significant effect on the elastic moduli of the composite; and finally (iii) the applied three phase model yields results in good agreement with both experimental and numerical (finite

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element method) results. However according to the authors' best knowledge only polymer based syntactic foams were investigated experimentally in detail.

Marur has done something very similar [28]. In the first corresponding paper the author dealt with the calculation of the effective elastic moduli of syntactic foams. 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. The computed effective elastic moduli were within the theoretically possible lower and upper bounds, and somewhat overestimated the experimental (polymer based) data because the assumed perfect bonding between the matrix and the ceramic hollow spheres. In the second paper Marur take into account the influence of weak interfaces between the inclusion (hollow spheres) and the matrix material [29]. The imperfect interface resulted in displacement discontinuity (modelled by a compliant layer with imperceptible thickness). The displacement jump at the interface was linked to the corresponding tension using a linear spring model. Finally, explicit analytical expressions were derived for the homogenised bulk modulus of syntactic foams with imperfect interface. The computed effective elastic moduli were compared with experimental data available in the literature and very good agreement between the theory and test data was found.

The last four papers mentioned above deal with the elastic properties of the syntactic foams, however most of these cases also involve plastic deformation and even crack initialization and propagation. The authors found only one publication on this field [30]. This is a parametric study covering the crushability behaviour of conventional structural foams. Results from one-step and multi-step procedures were utilised to generate the functional forms for each of the five parameters that represent various features of the stress–strain response. These functions were utilised to develop stress–strain responses of the foams at densities that were not initially available for experimental characterisation. In addition, it was also shown that the parametric forms are useful for development of "crushability maps" that can be employed for selection of suitable density foam for a specific application based on a certain design criterion (i.e., maximum strain-energy density or final porosity level). However the applied function would not be suitable for the modelling of MMSFs, because they fail to represent the sudden stress drops after the first peak in the compressive stress–strain diagram as described in detail in our previous papers [31].

In the work of Avalle et al. metallic foam samples of matrix alloy AlSi7 have been produced and mechanically tested under quasi-static and dynamic load [32]. Model parameters for 'crushable foam' material model were determined covering a density of 0.3–0.8 g cm^{-3}. Strain hardening was described on the basis of uniaxial compression by fitting a Rusch model to the experimental data, deriving its parameters as function of density. The predictive capabilities of the parameterised models were evaluated using experimental data gathered for load cases characterised by superimposed uniaxial and hydrostatic compression.

According to the above mentioned references our aim is to provide a continuous mathematical description of the stress–strain curves of MMSFs in order to give useful data for the computational design (for example finite element analysis) of MMSFs.

2. Materials and experimental methods

The investigated materials were self-made MMSFs, produced by pressure infiltration technique. For the process details please refer to our previous papers [25,31,33]. In order to get general conclusions five matrix alloys (Al99.5, AlSi12, AlMgSi1, AlCu5, and AlZn5 see Table 1 for chemical composition) and two kind of ceramic microballoons (SL150, SL300 see Table 2 for chemical composition and morphological properties [34]) were combined, resulting in ten different MMSF block types and having density within a narrow range: 1.44 ± 0.07 g cm^{-3}. These materials were solution treated (see Table 3 for the parameters of heat treatments). Cylindrical specimens for compression tests were machined from each block of material with different aspect ratios (height to diameter ratios, H/D). The diameter of the specimens was 14 mm in all cases and specimens with $H/D = 1$, $H/D = 1.5$ and $H/D = 2$ were tested. The specimens were designated according to their constituents and aspect ratio (for example AlMgSi1-SL150-1 stands for an MMSF specimen built from AlMgSi1 matrix and 64 vol.% SL150 type ceramic hollow spheres, this specimen had $H/D = 1$). Two typical optical microscope images are shown in Fig. 1. To get average results six specimens were compressed for each condition. Thus in summary 180 compression tests (5 matrices × 2 ceramic hollow sphere types × 3 aspect ratios × 6 specimens) were performed. The compression tests were performed on a MTS 810 type universal testing machine in a four column tool at room temperature. The surfaces of the tool were grinded and polished. The specimens and the tool were lubricated with anti-seize material. The tests were performed and evaluated according to the ruling standard about the compression tests of cellular materials (DIN50134:2008 [35]). The deformation rate during the compression tests was maintained at 0.01 s^{-1} in order to ensure quasi static conditions. During the tests the engineering stress–engineering strain curves were registered and later processed to find an appropriate mathematical description for the compressive response of MMSFs.

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

Matrix	Main components (wt.%)					Closest ASM equivalent
	Al	Si	Mg	Cu	Zn	
Al99.5	99.5	–	–	–	–	Al1050
AlSi12	86	12	–	–	–	A413
AlMgSi1	97	1	1.2	0.3	–	Al6061
AlCu5	95	–	–	4.5	–	Al2011
AlZn5	90.4	–	3.9	0.5	5.2	Al7022

3. Results and discussion

The registered engineering stress–engineering deformation curves have a typical form, shown by thick black line in Fig. 2. Similar stress–strain diagrams can be divided into three main parts containing altogether five sections as explained and published in previous papers [33,36]. The curves have four main characterising parameters. The slope of the initial part is defined as structural stiffness (S (MPa), see [35] about the standardised compression tests of cellular materials). At the end of the initial part – at point C – a local maximum occurs in the diagram. The stress reaches the compressive strength (σ_c (MPa)) at the fracture strain (ε_c (%)) [35]. At this point the first crack appears in the specimen and a large and sudden drop in the stress value can be observed due to the reduced load bearing capacity caused by the fracture of the microballoons and the movement of the recently formed specimen halves. In the case of continuous functions it is hard to follow this sudden stress drop [30]. From point D to E the fracture band expanded and the crack became thicker and the neighbouring microballoons broke. This deformation phenomenon consumed significant strain and mechanical energy due to the fracture of the ceramic microballoons and due to the plastic deformation of the matrix. The area under this, so-called plateau region is the absorbed mechanical energy (W (J/m^3)). This is the fourth main characterising parameter of the MMSFs, as it indicates the damping and protecting capability of