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On the mechanical anisotropy of the compressive properties of aluminium perlite syntactic foam

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ABSTRACT

A novel metallic syntactic foam is produced using a counter-gravity infiltration casting method. To this end, expanded perlite particles are combined with an aluminium alloy matrix. This enables close control of geometry at a relatively low production cost. The mechanical properties of the material are studied using finite element analysis. Numerical calculation models are generated directly from micro-computed tomography in order to capture their complex internal geometry. For verification purposes, numerical results are compared with experimental measurements of similar samples where available. But in contrast to experimental testing the numerical analysis is non-destructive and hence allows the repeated testing of samples in multiple loading directions. Thus, material anisotropy can be investigated for the first time. To this end, the quasi-elastic gradient, the 1% offset yield stress and the plateau stresses are obtained from virtual compression tests in three perpendicular directions (one coincides with the casting direction). Results indicate a weak anisotropy of the mechanical properties.

1. Introduction

Metallic syntactic foams (MSF) are made by combining lightweight filler particles with a metallic matrix [1]. Due to the relatively low strength of commonly used filler materials, metallic syntactic foams often exhibit mechanical properties similar to cellular metals. Their most important characteristic is an excellent energy absorption at a constant and controlled stress level [2,3]. Furthermore, cellular metals and MSF exhibit a high strength-to-weight ratio [4], damp vibrations [5] and have versatile thermal properties [6]. The density of MSF is higher compared to cellular metals at the same level of porosity [1] due to the additional mass introduced by the filler particles. However, MSF exhibit both superior elastic stiffness and strength [7,8]. In MSF the embedded filler particles can be hollow or porous [8]. The bulk material porosity and mechanical properties of these structures strongly depend on the filler material. The most common metal matrix material studied is aluminium and its alloys with various filler materials such as silicon carbide (SiC) spheres [1], fly ash cenosphere [9,10] and alumina (Al_2O_3) particles [11].

Al/Ceramic spheres MSF have been tested using both static and dynamic compression tests. Results were acquired for two types of ceramic spheres obtained from different suppliers (Envirospheres Pty Ltd., Australia and Omega Minerals Ltd., Germany). Experimental tests include Al/Ceramic sphere foams with four different aluminium volume fractions. Higher matrix volume fraction (aluminium volume fraction, $V_{Al} = 0.6$) sample has shown higher plateau strength and energy absorption under static compression loading when compared to a lower matrix volume fraction sample ($V_{Al} = 0.32$). Al/Ceramic spheres MSF reveal that their plateau stress and energy absorption capability mostly depend on the volume fraction of the aluminium matrix [12]. The mechanical properties of the ceramic spheres only have a minor impact on the properties of the bulk material. This was attributed to the fact that Al is stronger than the porous ceramic spheres. It was found that higher Al volume fractions in the foam structure leads to improved mechanical response of the structure, such as plateau stress due to denser Al matrix network. Another MSF material is developed by Luong et al. using aluminium alloy A356 filled with silicon carbide hollow spheres (SiC) [1]. They reported that the compressive and plateau strengths were higher compared to aluminium/fly ash cenosphere metallic syntactic foam under uni-axial loading [9,10,13]. The compressive strengths of Al/SiC foams was recorded at 160 MPa, however for the Al/fly ash cenosphere this parameter was found to be only 75 MPa [10].

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Several types of metallic syntactic foams (MSF) are usually manufactured using pressure infiltration casting, see, for example [1,7,8,12,14]. The work by Zhang and Zhao [12] describes the manufacturing of an aluminium matrix foam made by the infiltration of porous ceramic spheres [12]. The ceramic spheres studied were synthetically made using ceramic fine powder (particle size: 1–10 μm) which can be tailored into a variety of sphere sizes [15–18]. Rohatgi et al. [14] reported that a high volume fraction and uniform distribution of particles was achieved using infiltration casting method when fly ash filler materials is used in A356 aluminium alloy matrix. A new type of metallic cellular foam material was introduced recently using low-cost expanded perlite (EP) particles as a filler material making use of the infiltration casting manufacturing route (see Fig. 1). This new type of metallic cellular foam is referred to as perlite-MSF (perlite-metallic syntactic foam) in the following parts of this manuscript. The production cost of perlite-MSF is relatively low compared to other MSF due to its inexpensive filler and matrix material. A thorough review on the production process can be found in the manuscript [19]. Investigations have shown that the mechanical properties of perlite-MSF can be improved by reduction of the EP particle size and T6 treatment [20]. The investigation in [19] further indicates a higher plateau stress and energy absorption of perlite-MSF for decreasing particle size ($d = 1.0 \ldots 1.4$ mm) due to changes in the aluminium micro-structure and a more uniform geometry of cells compared to larger EP particles ($d = 4.0 \ldots 5.6$ mm). This is in contrast with the work done by Castro et al. [7] which involved alumina spheres (as a filler materials) infiltrated with two types of aluminium alloys (i.e.: ductile A1100 and hardened A6061). Static and dynamic impact loading tests showed that the use of smaller size alumina spheres ($d = 1$ mm) does not increase the energy absorbed by the metallic syntactic foam compared to larger alumina spheres ($d = 2.5$ mm) [8]. The investigation in [8] however is using A201 aluminium alloy as a matrix in their sample. In comparison with the mechanical properties of the other MSF the dynamic compression testing of perlite-MSF revealed more efficient energy absorption in high speed compression [21]. An increase in compression resistance in high impact loading was ascribed to the filler particles (i.e.: perlite) which entrapped air. High impact loading caused the pressure of this entrapped air within the perlite particles to increase resulting in a higher macroscopic compressive resistance (see Fig. 2).

Fig. 1. Photograph of A356/perlite metallic syntactic material.

In the present paper, the mechanical characterisation of perlite-MSF under quasi-static compression is performed numerically for the first time. Numerical models were generated using micro-computed tomography (μCT) imaging in order to capture the complex internal morphology of the material. Finite element analysis of these models then allows the computation of stress distribution and the detailed study of deformation mechanisms. Furthermore, unlike in destructive experimental testing the virtual samples can be compressed in multiple directions enabling the characterisation of mechanical anisotropy. Mechanical anisotropy in the present work is defined as the dependence of the mechanical properties on the compressive loading direction.

2. Finite element analysis (FEA)

Micro-computed tomography (μCT) data of perlite-MSF samples has been obtained in order to capture accurate three-dimensional models of their complex meso-structure. Due to their low density, the perlite particles appear transparent and only the aluminium phase is visible. In total, three foam samples from the same production batch with a medium perlite particle size (diameter $d = 2.0$–2.8 mm) were scanned using the μCT imaging approach. A voxel length of 35.32 μm was used that ensures capturing all relevant geometrical detail. The masses m, heights H and diameters D of the scanned samples are listed in Table 1. The numerical models in the present study are cubic sub-volumes with the side length of $l = 21.15$ mm that have been sliced from the scans of the cylindrical samples.

A model of a cellular structure must be sufficiently large to form a representative volumetric element (RVE) that exhibits the same properties as the complete structure [3]. Simulation of larger volumes unnecessarily increases the computational cost and should therefore be avoided. According to previous studies [1,2] the minimum side length over pore diameter ratio (l/d) for RVEs of cellular metals is 6–8. The numerical models of this study have a side length of $l \approx 21.15$ mm (see Table 2) and the pore (particle) size

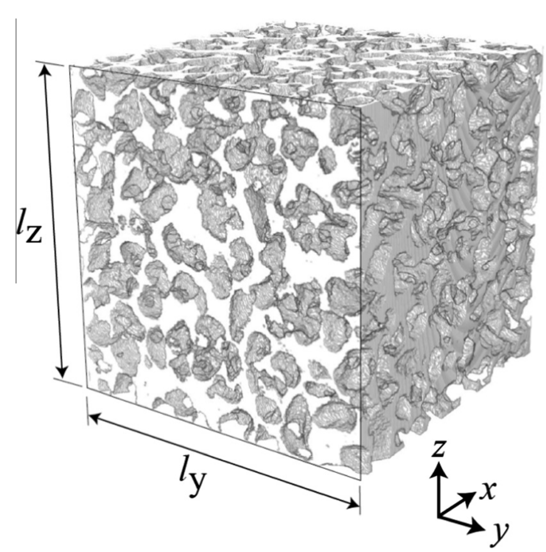

Fig. 2. Optical micrograph of perlite-SMF on the frontal-yz plane of sample A, showing coexisting small and large pores with interconnected morphology.