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Geometrical characterization of perlite-metal syntactic foam

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ABSTRACT

This paper introduces an improved method for the detailed geometrical characterization of perlite-metal syntactic foam. This novel metallic foam is created by infiltrating a packed bed of expanded perlite particles with liquid aluminium alloy. The geometry of the solidified metal is thus defined by the perlite particle shape, size and morphology. The method is based on a segmented micro-computed tomography data and allows for automated determination of the distributions of pore size, sphericity, orientation and location. The pore (i.e. particle) size distribution and pore orientation is determined by a multi-criteria *k*-nearest neighbour algorithm for pore identification. The results indicate a weak density gradient parallel to the casting direction and a slight preference of particle orientation perpendicular to the casting direction.

1. Introduction

Perlite-metal syntactic foam (P-MSF) is a novel cellular metal and is usually classified as a metal-matrix syntactic foam. Cellular metals exhibit an exciting mix of properties including controlled energy absorption [1,2], versatile thermal properties [3,4], structural damping [5,6], and a relatively high specific stiffness and strength [7,8].

The key targets in the development of P-MSF are cost-effectiveness and consistent properties. Cost-effectiveness is ensured by the usage of low cost raw materials in conjunction with simple and scalable manufacturing procedures [9]. The consistency of properties is determined predominantly by the geometry of the metallic phase of cellular metal, i.e. the material meso-structure. The metallic phase is the inverse volume of the porosity and hence its geometry can be controlled by adjusting the shape and distribution of pores. In P-MSF this is accomplished by using expanded perlite particles that define the size, shape and position of pores in the syntactic metal foam.

Due to strong interdependence of pore geometry and the mechanical properties of cellular metals, the geometrical analysis has been the focus of several studies. The majority of studies applied a simplified model of the cell structure which is distinguishably different from the actual foam geometry, e.g. [10,11]. In recent years, the application of micro-computed tomography (μCT) made it possible to recreate an actual 3D digital model of the foam structure which permits the investigation of its exact geometrical properties. A study by Maire et al. [12] was among the first to use the μCT analysis to capture the complex meso-structure of a cellular metal. This approach was subsequently refined for an in-depth analysis of metallic foam materials. A study by Bock and Jacobi [13] focused on the characterization of high porosity foams with interconnected porosity. They investigated strut geometry and derived values for the volumetric strut density, diameter, and orientation. Periodic porous materials produced by additive manufacturing were studied by Vanderesse et al. [14]. They individually estimated the average thickness, length, and orientation of the struts by an automated procedure. Etiemble et al. [15] investigated copper foams used as battery electrodes. They determined the interdependence of pore size, sphericity and tortuosity and the effect of chemical treatment on the foams. Vesenjak et al. [16] used μCT analysis to characterize the structure of advanced pore morphology (APM) foam elements. Both the spatial and the size distribution of the pores were determined by inscribing spheres within their geometry. This study was extended [17] to investigate the relation between pore geometry and aluminium alloy used for the production of APM foam elements and introduced an improved method for pore identification based on a watershed transform. The method allows also for determination of the pore sphericity and orientation. Saadatfar et al. [18] studied metallic foams prepared under various conditions to determine the effect of the manufacturing parameters on the foam geometry. The geometry was analysed using a micro-computed tomography and a watershed algorithm. One important limitation of these studies is the restriction to almost convex and spherical shape of the pores.

The current paper extends this research by addressing a novel P-MSF metal foam with *interconnected* pores. This necessitates a new approach

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for pore identification from μCT data as pores are no longer separated by a solid phase. To this end, an improved watershed algorithm has been implemented in combination with a *k*-nearest neighbour algorithm for the efficient merging of fragmented pores. This innovative approach allows for an in-depth analysis of the P-MSF geometry. The results of this study contribute to a better understanding of relationship between the P-MSF manufacturing and its meso-structure that governs its mechanical properties.

2. Manufacturing

A detailed description of the manufacturing procedure of P-MSF is given in [9]. In brief, the manufacturing is done in two steps, i.e. the particle packing and the infiltration casting. The manufacturing of studied samples is described hereafter.

Expanded perlite particles are received in bulk at low cost and sieved for size separation. For the current study, the selected particles passed through a sieve with 3 mm perforations and were retained by a 2 mm sieve. In the case of perfectly spherical particles this translates to a particle size range of 2–3 mm. Particles were then poured into a mould with diameter of 31 mm to a height of approximately 47 mm. To achieve a dense and uniform particle packing, the mould filling was done in 5 steps, where an equal amount of particles was added and tapped for densification in each step. After filling, a stainless steel mesh was positioned across the upper surface to keep the packed particle bed in position for casting.

The aluminium Alloy A356 was used for the infiltration casting of the packed particle bed. The mould containing the particles was slowly lowered into a reservoir with molten aluminium alloy until excess aluminium escaped through the overflow hole at the top of the mould. The mould was then lifted from the reservoir and left to cool down to an ambient temperature, during which the aluminium solidified. Additional thermal treatment may be applied to change the aluminium microstructure but has no effect on the material meso-structure [19].

Six perlite-metal syntactic foam samples (Fig. 1) were prepared in the same production batch and subsequently analysed for the purpose of this study. They were of cylindrical shape with an outer diameter of 30.70 mm and a height of approximately 44 mm. The sample properties are given in Table 1.

3. Methodology

Micro-computed tomography (μCT) enables scanning of the highly complex internal structure of porous materials [1]. The μCT scanning subdivides a three-dimensional geometry into a set of voxels. The density of the captured sub-volume is represented as a grey level of the voxels, which enables segmentation of materials with different densities. The perlite particles in the P-MSF have a significantly lower density compared to the aluminium matrix and can easily be segmented and removed from the resulting 3D image to obtain only a metallic porous structure.

Fig. 1. Perlite-metal syntactic foam sample.

Table 1
Properties of the analysed P-MSF samples.

Sample name	S13	S18	S23	S24	S29	S32
Diameter [mm]	30.70	30.70	30.70	30.70	30.70	30.70
Height [mm]	43.75	43.60	43.57	43.50	43.90	43.70
Mass [g]	33.80	33.82	32.17	32.74	35.90	34.25
Porosity [/]	0.651	0.652	0.669	0.661	0.628	0.647

The acquisition of μCT data was performed with an accelerating voltage of 100 kV and a current of 100 μA. During the samples scanning around 1325 two-dimensional (2D) layers with a resolution of 1000 × 1000 pixels were acquired with a pixel size of 35.32 μm (Fig. 2a). The distance between layers was also equal to 35.32 μm. Individual layers were combined into a 3D image after the data acquisition.

The first step in the μCT image analysis is the density segmentation which identifies the material domains based on the selected grayscale threshold colour. The threshold was set in such a way that the volume of the computer model matched the volume of the aluminium in the scanned perlite-metal syntactic foam sample. The reference volume was determined by subtracting the mass of contained perlite particles from the total sample mass and dividing the result by the density of Al356 aluminium.

Density segmentation results in a black and white 3D image, where black voxels represent the material and white voxels represent the voids and empty space (Fig. 2b). The volume of the material, i.e. aluminium alloy domain will be denoted as V_m. The white voxel domain must be divided into the pore volume V_p (white in Fig. 2c) in the sample and the outer space volume (grey in Fig. 2c). The border between the sample pores and the outside space was determined for each layer of the 3D image separately using the best fit circle approach (the red circle in Fig. 2c). Best fit circle was determined from the diameter measurements of the material (black pixels) geometry. The diameter was measured in 16 equally spaced angular directions and average values were used for the best fit circle. The porosity of the sample can then be computed as:

$$p = V_p/(V_m + V_p). \tag{1}$$

The axial and radial porosity distributions in each cylindrical sample were computed to determine the porosity changes. *The axial porosity* was determined as a porosity of single layer of voxels in a transversal plane, i.e. plane perpendicular to the vertical sample axis, by using Eq. (1). The porosity for the whole sample height was then determined in one voxel vertical steps. *The radial porosity* was calculated for voxels contained within a cylindrical plane of one voxel thickness and a variable radius. The centre axis of all cylindrical planes corresponded with the sample vertical axis. The radial porosity was then computed by using Eq. (1) for each one voxel radius step up to the outer sample diameter.

A feature segmentation procedure for identification of individual pores was developed to characterize the internal geometry of the P-MFS. First, a distance transform algorithm [20] was applied to the 3D voxel model. The distance to the closest material voxel (black) was determined for each pore voxel (white). The result is shown in Fig. 3a, where black colour represents the aluminium and grey colour represents the value of the distance transform function. The higher the value (distance), the darker is the colour.

Next, the watershed transform algorithm [21] was used for feature segmentation. The algorithm works similar to pouring water in the scalar distance transform field where the pouring starts at each local