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The effects of manufacturing parameters on geometrical and mechanical properties of copper foams produced by space holder technique

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ABSTRACT

We describe a powder metallurgical space holder method to produce open-cell metallic foams. By changing the values of the main manufacturing parameters such as volume percentage and the particle size of the space holder agent, we produce different copper foam samples which cover a wide range of solid fraction, pore size and cell wall thickness. All the specimens were synthesized based on a series of designed experiments. We demonstrate how the foams' density, cell size and specific surface area can be accurately controlled using two easily adjustable manufacturing parameters. The three-dimensional structure of these foams was investigated using X-ray micro tomography. The image quality is sufficient to measure local structure and connectivity of the foamed material, and the field of view large enough to calculate material properties. By combining the finite element method with the tomographic images, we calculate the mechanical response of the foams. We show that the foams' bulk and shear moduli are strongly correlated to their cell size, cell wall thickness and specific surface area. These parameters can be easily controlled during manufacturing.

1. Introduction

Porous metallic materials, generally known as metallic foams, exhibit interesting characteristics such as high strength to density ratio and excellent thermal and sound absorption properties. Open porous metallic foams have been successfully used in heat and mass transfer applications; some examples include bipolar plates in fuel cell stacks [1–3] and filtering media in separating components [4]. In spite of having numerous methods for mass production of closed cell metal foams, there are a limited number of them to produce open cellular structures. The powder metallurgical (PM) process based on using space holder materials is one of promising methods for synthesis of open-cell metallic foams [5]. This process enables control of the foam structure and physical properties by tweaking a small number of processing parameters. The PM process consists of four distinct steps: (1) blending of metallic powder and a space holder; (2) cold welding of metal particles through a compaction process; (3) removing of the space holder agent and finally (4) solid-state sintering. A wide range of materials can serve as pore forming filler such as ceramics, polymers, salts and even metals either as particles or hollow spheres [5]. The space holder agent can be removed from the green bodies, either prior to [6–8], or after [9,10] sintering once the strut structure has evolved. The metal foams produced inherit some of the intrinsic properties of the space holder particles. For instance, the volume fraction, morphology and particle size of the space holder play an important role in altering some cellular architecture features like porosity percentage, pore shapes and cell sizes of the foam products which consequently can define structural and mechanical properties. The nature of this inheritance, however, is quite complex and therefore has been the subject of much research in recent years [8,9,11–14]. Some of these efforts have also led to advances in techniques for metallic foam synthesis. For example Zhao et al. [9] patented the Lost Carbonate Sintering (LCS) method in which potassium carbonate is thermally decomposed or aqueously leached after the sintering process. This could prevent distortion in the cell walls due to premature removal of the space holding agent. Some industrious works were also focused to model and correlate the mechanical properties into the intrinsic characteristics of open cellular metallic foams mainly produced through methods rather than space holder technique [15–18].

An important question that has yet to be answered comprehensively in this context is the following: what are the structural, morphological and mechanical factors of the produced foam using the space holder technique which are directly affected by the properties of the space holder particles? The answer to this question will be sensitive to the controlled experimental conditions/parameters in the lab and it will shed light on the complex relations between the physical and structural properties of the metallic foam and the

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size and concentration of the space holder particles. The aim of this study is to provide some key insights into this. One way to investigate this question is to examine the 3D structure of foams produced, specifically their geometrical and topological features. This requires access to the full 3D structure of the porous metal products. High-resolution X-ray Computed Tomography (XCT) or MRI techniques are now routinely used to probe complex porous structures [19–21]. In the present work, we manufacture 13 partially open-pore copper foam samples based on a series of designed experiments differing in both volume percentage and particle size of the space holder material. We then employ XCT and a series of 3D image analyses techniques to characterize the structure of these foam samples (Section 2.3.1). Later in Section 2.5 we combine the tomographic data with the Finite Element Method (FEM) to simulate the mechanical response of the foam [22–24] and its correlation with the structural features of the foam which is in turn determined through the manufacturing process by means of the space holder material properties. This provides us with an understanding of how the mechanical response of the foam samples change with the adjustment of the size and concentration of the space holder particles.

Table 1
Details of CCD experimental runs.

	Standard order	Run order	Specimen code	f_s	d_s
Fractional	1	12	M6030	−1	−1
	2	7	M6050	−1	+1
	3	4	M8030	+1	−1
	4	8	M8050	+1	+1
Axial	5	1	M7030	0	−1
	6	2	M7050	0	+1
	7	11	M6040	−1	0
	8	5	M8040	+1	0
Central points	9	6	M7040-09	0	0
	10	10	M7040-10	0	0
	11	9	M7040-11	0	0
	12	13	M7040-12	0	0
	13	3	M7040-13	0	0

2. Materials and methods

2.1. Experimental setup

As mentioned in the introduction, we use the LCS technique developed by Zhao et al. [9] to produce open-cell copper foams. In this method, potassium carbonate (K_2CO_3) powder plays the role of the void space holding agent which can be removed either by thermal decomposition or aqueous dissolution. Thus, carbonate volume percentage and its particle size can be used as the control parameters to adjust the porosity percentage and pore diameter of the final foam product. The 99.9% pure copper (Cu) powder with particle sizes below 45 μm and commercial potassium carbonate with different sizes were provided as raw materials. At first step, copper powder was ball milled at 350 rpm in 5 h. and ball per powder (BPP) ratio of 5 in order to guarantee high mechanical behavior of foam products which is described elsewhere [25]. The K_2CO_3 particle size of 300–600 μm was chosen and classified into three distinct ASTM mesh numbers of −20 +30, −30 +40 and −40 +50 represented as 30, 40 and 50 in this paper. After making a powder blend in proper constitutions, green bodies were produced by

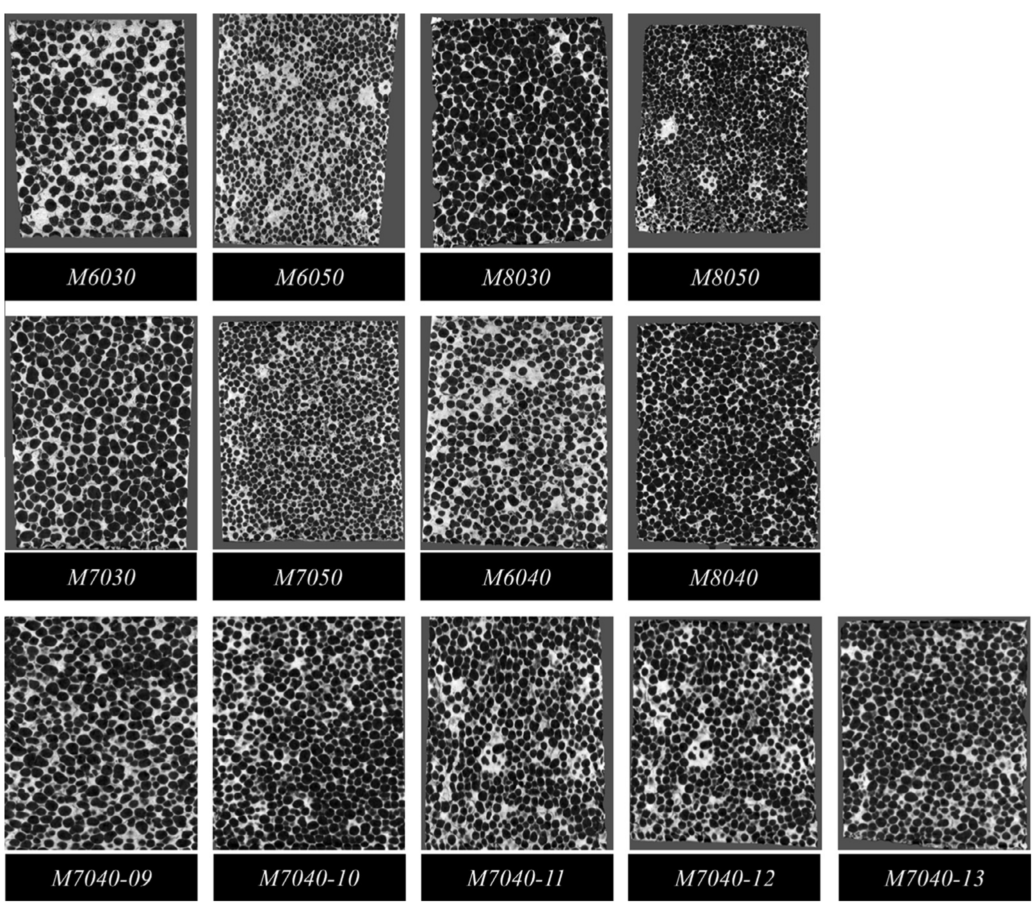

Fig. 1. Micro CT images of 13 copper foam samples.