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The effect of density and feature size on mechanical properties of isostructural metallic foams produced by additive manufacturing

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Abstract—Simple models describing the relationship between basic mechanical properties and the relative density of various types of porous metals (such as foams, sponges and lattice structures) are well established. Carefully evaluating these relationships experimentally is challenging, however, because of the stochastic structure of foams and the fact that it is difficult to systematically isolate density changes from variations in other factors, such as pore size and pore distribution. Here a new method for producing systematic sets of stochastic foams is employed based on electron beam melting (EBM) additive manufacturing (AM). To create idealised structures, structural blueprints were reverse-engineered by inverting X-ray computed tomographs of a randomly packed bed of glass beads. This three-dimensional structure was then modified by computer to create five foams of different relative density ρ_r, but otherwise consistent structure. Yield strength and Young's modulus have been evaluated in compression tests and compared to existing models for foams. A power of 3 rather than a squared dependence of stiffness on relative density is found, which agrees with a recent model derived for replicated foams. A similar power of 3 relation was found for yield strength. Further analysis of the strength of nominally fully dense rods of different diameters built by EBM AM suggest that surface defects mean that the minimum size of features that can be created by EBM with similar strengths to machined samples is ~1 mm.

Keywords: Metal foam; Cellular solids; Reverse engineering; Open-cell foam; X-ray computed tomography

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1. Introduction

Metallic foams have been the subject of many investigations, due to their potential across a wide range of application areas [1] arising from their interesting mechanical [2,3], thermal [4], electrical [5,6] and acoustic [7] properties. Foam properties can be tailored to suit particular applications, for example by varying the relative density, ρ_r, defined as the ratio of foam density to the fully dense solid. Several models exist allowing the mechanical properties to be estimated from such parameters; the most generally applicable and widely used being the equations of Gibson and Ashby [3], which are based on the definition of a simple cubic unit cell and the use of beam theory to predict the response to load. Example relations for predicting elastic modulus (E) and strength (σ) are given below:

$$\frac{E^*}{E_s} = C_1 \rho_r^2 \tag{1}$$

$$\frac{\sigma^*}{\sigma_s} = C_2 \rho_r^{3/2} \tag{2a}$$

$$\frac{\sigma^*}{\sigma_s} C_2 \rho_r^{3/2} \left(1 + (\rho_r)^{1/2}\right) \tag{2b}$$

where the terms with a superscript * relate to the foam and those with a subscript s relate to the constituent metal and C_1 and C_2 are constants of proportionality. The bracketed term in Eq. (2b) is a density correction term for foams having a relative density greater than 0.3 [2].

While such equations offer a simple means of capturing broad trends in foam response, they are not always accurate for specific types of foam. In such cases it can be difficult to determine the cause of the discrepancy, although this is usually interpreted as a departure from the beam-bending mechanisms underlying Eqs. 1, 2a, 2b, 3 [8]. In many cases the exponent relating density to Young's modulus is found to be bigger or smaller than 2. This is despite the fact that an exponent of 2 would be expected even for more complex structures than those considered in the Gibson–Ashby analysis. This response is supported by the results of Rossoll and Mortensen [9], who used finite element simulations of seven strut building blocks representative of certain foam

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structures (gas injection [10], replication [11]) to explore the expected variation in elastic response with density. They found that an exponent of 2 gave a good match for most of the density range considered. A drop in relative modulus was observed for a tapered structure representing replicated foams only below a relative density of 0.03, which in practice is not encountered in these materials.

There are, however, specific cases that produce notable departures from this relation. For example, it is often observed experimentally that the stiffness of foams processed by replication is better described by an exponent close to 3 in Eq. (1). This has been explained by Mortensen et al. [12] as being due to changes in the architecture of the foam with density (i.e. the geometrical structure of the foam is not density independent).This was supported by considering a structure formed of interpenetrating spheres (the pores) where decreases in foam density arise by bringing the pore centres closer together. In this case the foam is more accurately described as consisting of relatively thin struts and somewhat thicker nodes where the struts interconnect [13], rather than the ideal Gibson–Ashby structure. This brings in a number of additional aspects to be considered: (i) if beams deform by bending, then the thinnest regions of the struts will dominate the behaviour [14], (ii) changes in foam density change both the shape of the connecting struts and the number of struts that meet at nodes; (iii) there will be a distribution of strut sizes with the larger struts having a dominant effect; (iv) there is a relative density $\rho_{r,c}$ (taken to be $\rho_{r,c} = 0.05$ in Ref. [12]), where the structure loses integrity and is unable to able to bear load. It is predicted that the elastic response of such a foam will follow the equation below, which is found to produce a consistent slope with density variations with data from replicated foams:

$$\frac{E^*}{E_s} = \frac{\left(1 - 2\left(\frac{1-\rho_r}{1-\rho_{r,c}}\right)^{2/3} + \left(\frac{1-\rho_r}{1-\rho_{r,c}}\right)^{4/3}\right)}{\left(1 - 2\left(\frac{1-\rho_{r,0}}{1-\rho_{r,c}}\right)^{2/3} + \left(\frac{1-\rho_{r,0}}{1-\rho_{r,c}}\right)^{4/3}\right)} \tag{3}$$

where all terms are as defined previously, with $\rho_{r,0}$ the initial packing fraction of a powder, typically 0.36 for random packing.

Direct experimental investigation of such relationships are not easy to perform because most methods for manufacturing porous metals do not allow a systematic variation of density and pore shape, pore location, etc., so as to systematically determine the influence of each of these factors. The topological structure will be strongly influenced by the processing route, the choice of which is often limited by the parent material [15]. To isolate and analyse the effect of relative density on foam properties one needs a highly controllable manufacturing method.

Additive manufacturing (AM) has recently emerged as a fabrication route for complex three-dimensional (3-D) parts. In such methods the object is built up by the addition of thin layers of material on top of one another, as defined by a stereo lithography (STL) file. This file, which is the geometrical blueprint for the manufactured object, can be defined by CAD or input from 3-D measurements so as to create a clone of an original object. Electron beam melting (EBM) is an AM technique that has been shown to be particularly well suited to the manufacturing of complex architectures including regular porous metallic lattice structures [16,17]. Typically, it has been employed for making biomedical porous implants [18] and impact energy

Table 1. Mean properties of the 5 fabricated foam sample sets and corresponding single rod samples after the compression and bending tests.

Foam samples							Dense rod samples			
Sample set	File obtained through	Relative density, (ρ_r)		Young's Modulus (GPa)	0.1% offset yield strength (MPa)	Peak Compressive resistance σ^* (MPa)	Diameter (mm)	Micro Vickers Hardness	Porosity volume fraction	Flexural 0.1% Yield Strenght. (MPa)
		File	Measured							
I	STL	$0.13 \pm 7 \times 10^{-3}$	$0.16 \pm 4 \times 10^{-3}$	0.65 ± 0.05	7.72 ± 0.57	11.7 ± 3.6	0.56	391 ± 12.8	0.028	733 ± 59
II	XCT	$0.20 \pm 6 \times 10^{-3}$	$0.24 \pm 6 \times 10^{-3}$	1.79 ± 0.15	29.7 ± 3.1	35.0 ± 4.6	0.75	366 ± 17.3	0.070	730 ± 64
III	XCT	$0.26 \pm 7 \times 10^{-3}$	$0.28 \pm 6 \times 10^{-3}$	3.19 ± 0.21	48.3 ± 5.3	56.7 ± 9.1	0.97	386 ± 21.3	0.019	904 ± 48
IV	STL	$0.33 \pm 7 \times 10^{-3}$	$0.35 \pm 7 \times 10^{-3}$	5.63 ± 0.36	88.7 ± 7.4	102.7 ± 10.9	1.13	375 ± 15.5	0.029	1028 ± 35
V	STL	$0.40 \pm 7 \times 10^{-3}$	$0.44 \pm 5 \times 10^{-3}$	10.92 ± 0.41	119.4 ± 5.8	156.9 ± 9.4	1.43	377 ± 17.6	0.009	1111 ± 21
							1.71	381 ± 19.4	0.029	–
							1.90	382 ± 19.4	0.037	–