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Size effects in compression in Electron Beam Melted Ti6Al4V diamond structure lattices

S.J.N. Morrish [a,*], M. Pedersen [b], K.F.W. Wong [b], I. Todd [a], R. Goodall [a]

[a] Dept. Materials Science & Engineering, University of Sheffield, Sir Robert Hadfield Building, Portobello St, Sheffield S1 3JD, UK
[b] GKN Aerospace Services Ltd, Filton, Bristol BS34 7QQ, UK

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ABSTRACT

In experimental work on the mechanical properties of stochastic metal foams, the consensus is that a minimum of six pores along each direction are required to give representative mechanical properties. This theory is tested for another porous metal, regular lattices, built using repeating unit cells of the diamond structure (a tetrahedral structure, in a cubic formation) by Electron Beam Melting (EBM) from grade 5 Ti6Al4V. Samples with different numbers of unit cells are made, using 3 different sets of EBM manufacturing conditions, and tested in compression. In all cases, a minimum of four unit cells are needed to ensure that size-independent mechanical properties are measured. Small changes in manufacture lead to large differences in properties.

1. Introduction

On a macroscopic scale, the inherent mechanical properties of materials are typically not size dependent. However, when the size of specimens approaches the scale of structure within a material, this can change. While for most materials this would require small dimensions, porous solids have structure much closer in size to that of typical test pieces. When mechanical properties of stochastic metal foams are investigated, the minimum number of pores required to ensure reliable results is widely accepted to be six pores [1,2]. This derives from work where mechanical tests were performed on metal foam samples of different average numbers of pores across the shortest dimension, and a convergence of properties over increasing numbers of unit cells was observed [3,10]. This led to the conclusion that 6 unit cells is the minimum required to ensure reliable mechanical properties, and has since been used to set minimum sample sizes in many studies.

With the recent, widespread use of additive manufacturing technologies, the manufacture of alternative porous metals has been possible. From knowledge of metal foams, a six unit cell minimum has been widely adopted for experimental investigations of lattice technology [4–7].It is known that the mechanics of lattices and foams can be very different, even when made at the same density using the same material and manufacturing method [8]. In additive manufacturing methods using powder, extracting loose powder can be challenging if lattices with many unit cells are made. This is especially the case where unit cell sizes are smaller, leading to a preference for samples with as few unit cells as possible for experimental testing. This work tests the compressive mechanical response of a series of lattices with different numbers of unit cells, to determine the correct minimum to use.

2. Material and methods

Diamond structure lattices were manufactured, with ~6 mm side length unit cells, containing struts of ~1 mm diameter and ~2.6 mm length. The struts were designed computationally as octagonal prisms of exactly 1 mm in diameter and 6 mm in unit cell size. On this scale, a computational octagonal prism is an acceptable shape choice to produce cylindrical struts [9].

A total of 48 lattices were produced (in three sets containing 32, 8 and 8 lattices) as cubes from 2 to 9 unit cells along each side. The manufacturing method was Electron Beam Melting (EBM) on Arcam AB® S12 and A2 machines (Arcam AB, Gothenburg, Sweden). Each set was produced using grade 5 Ti6Al4V pre-alloyed powder of 45–100 μm average diameter. The exact powder composition varied from build to build due to recycling methods and oxygen pick up over the lifetime of the powder. This combination of differences was to test the reproducibility of the experimental results across inherently different samples.

* Corresponding author.

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The lattices were compression tested on a Zwick Roell machine with a 50kN load cell at a constant starting strain rate of 10^{-3} s^{-1}. Stress-strain curves were obtained, and elastic modulus, 0.02% offset yield strength and first peak compressive strength (the stress achieved before a consistent stress decrease was observed, corresponding to the first collapse of part of the lattice) were determined.

3. Results and discussion

The results were calculated from compressive stress-strain curves. An example of a typical curve and analysis is shown in Fig. 1. The number of unit cells is the number along the side length of the sample, which in this case of a cube, is an identical number in every direction; the behaviour of non-cubic sample shapes would be dictated by the direction containing the smallest number of unit cells

A main set of 32 samples (4 repeats of each size) were manufactured on an Arcam A2 EBM machine using powder with less than 0.2% oxygen content (the standard specification). The settings were the standard Arcam nett theme for lattices, with hatching turned off.

The data for the range of properties determined from the main set of samples are shown (as the average of the 4 repeats, with standard deviation indicated by error bars) in Fig. 2. It is apparent that the first two points (for samples of 2 and 3 unit cell side length) are systematically lower than the rest, while a consistent average value, albeit with some scatter, is obtained for all properties for 4–9 unit cell side length samples (the average of these values is indicated by the horizontal line in the graphs). Such scatter is likely to come from the inherent variability in the materials, engendered by, for example, the inherent surface roughness and defect population of EBM produced parts [9].

The observation that properties tend to be insensitive to sample size of 4 unit cells and beyond is consistent with Andrews et al. criterion of 6 or more pores/unit cells, although this data indicates that samples of 4 unit cells could give reliable mechanical properties. This insensitivity may come from the regular structure of lattices compared to the irregular structure of foams. As long as the size is sufficient to neglect surface effects, there is no need for larger sizes to allow the effect of random pore size, shape or position to be statistically reduced by the inclusion of more pores or unit cells.

To explore the size effect problem further, two additional sample sets of the same lattices were built in different ways. The first of these was made on an Arcam S12 machine, using powder, with less than 0.2% oxygen content (in-specification). The settings used were the standard Arcam 70 μm preheat, followed by the standard nett theme for lattices, with 3 contour passes and a hatch. This set of samples and their data are referred to as *S12*. The second set was made on an Arcam A2 machine, using powder, with 0.325% oxygen content (outside the standard specification). The settings used were an altered 70 μm preheat, followed by the standard nett theme for lattices, with 3 contour passes and a hatch, and no changes made to any other settings. This set of samples and their data are referred to as *A2 High O_2*. Both of these sets contained an example of each lattice, and the results obtained are plotted in Fig. 3. Some of the data for the samples with 9 unit cells along the dimension are not plotted, as these samples did not fail within the load capacity of the test machine. For later discussion, the original set of samples is referred to as *A2*.

In terms of absolute properties, a significant variation is seen in all properties between the values recorded for the main data set, the S12 and A2 High O_2 sets (noting that the latter are based on a single set of samples). Each data set has different average relative densities, with the main data set having the lowest density and lowest mechanical properties. However in the A2 High O2 and S12 data sets, the difference in density is contrary to the difference in mechanical properties seen.

The A2 High O_2 data has higher values, despite a lower density, expected due to the effect of the powder composition and different machine settings. The properties for the S12 set have lower values than the A2 set, indicating a strong influence of the build conditions in general, not just the powder, where both the physical machine design and the build themes are different.

Setting aside the variation in values, the results from Fig. 3 are consistent with the identification, that for regular lattices samples with $\geqslant$4 unit cells across the smallest dimension, results converge for mechanical properties.

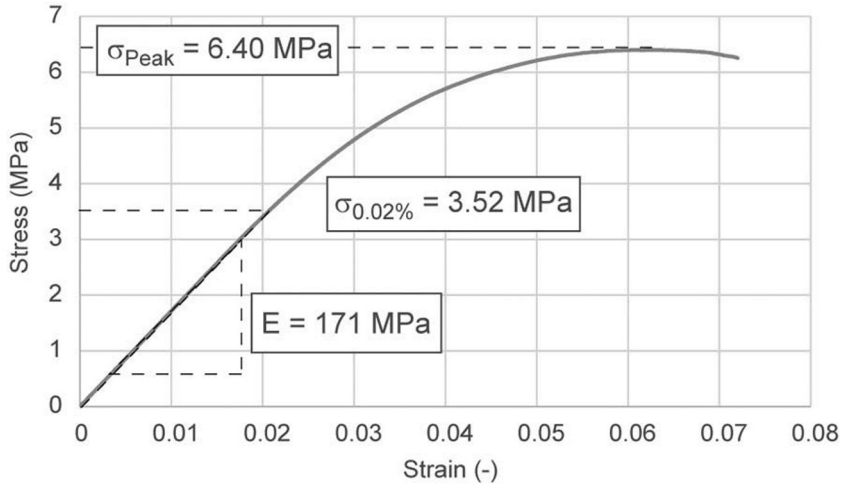

Fig. 1. Example stress-strain curve for one of the 4 unit cell lattices from the main data set, indicating: (a) the determination of elastic modulus, E, (b) 0.02% proof stress, σ0.02% (c) first peak compressive strength.

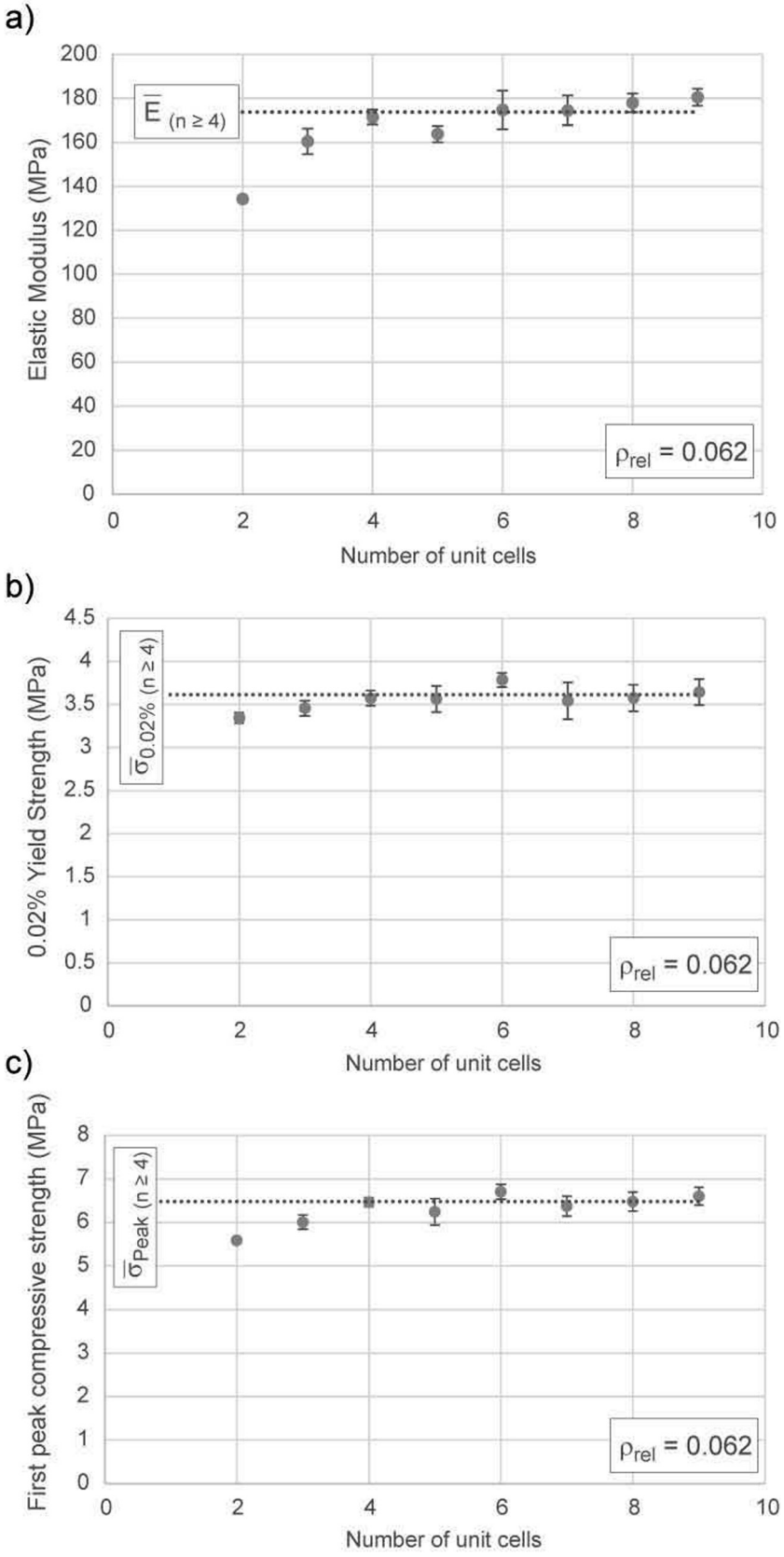

Fig. 2. All results for the main sample set for: (a) elastic modulus, (b) 0.2% yield strength and (c) first peak compressive strength against number of unit cells. The value indicated by the line represents the average of all results for $\geqslant$4 unit cells.

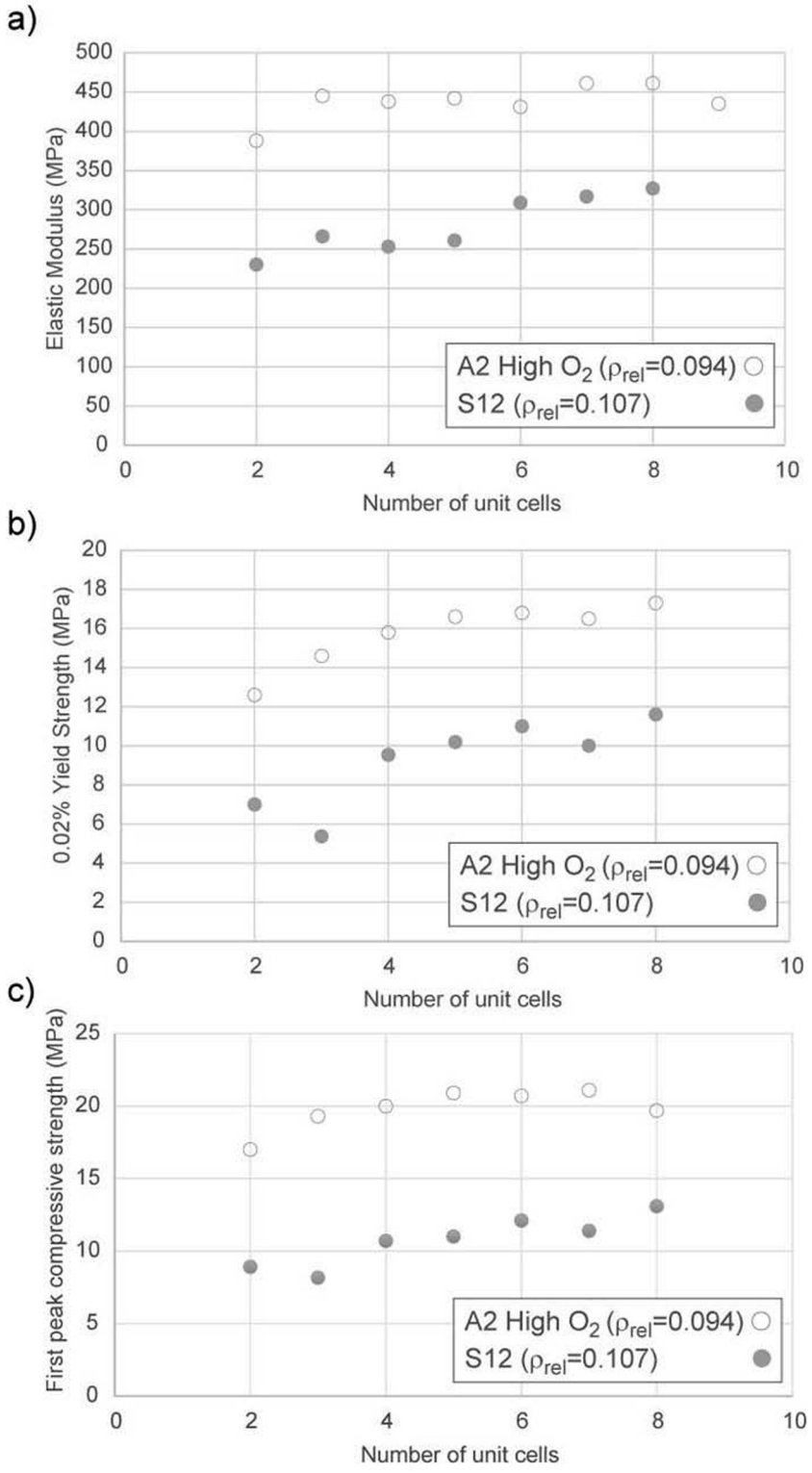

Fig. 3. All results for the S12 data set (filled symbols), and A2 High O_2 data set (open symbols) for: (a) elastic modulus, (b) 0.02% yield strength, and (c) first peak compressive strength against number of unit cells.

4. Conclusions

For the regular lattices tested, uniaxial mechanical test results converged for sample sizes of 4 unit cells or greater. While the widely-used criterion of 6 unit cells or greater is suitable, it is conservative, and smaller sample dimensions where required can lead to representative results. In addition, EBM build conditions and starting material powder have a clear effect on the mechanical properties of lattices, which indicate the importance of consistency across tests.

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