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Fabrication and characterisation of a fully auxetic 3D lattice structure via selective electron beam melting

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Abstract
A three-dimensional fully auxetic cellular structure with negative Poisson’s ratio is presented. Samples are fabricated from Ti6Al4V powder via selective electron beam melting. The influence of the strut thickness and the amplitude of the strut on the mechanical properties and the deformation behaviour of cellular structures is studied.

Keywords: auxetic, negative Poisson’s ratio, selective electron beam melting (SEBM), Ti6Al4V, additive manufacturing, periodic cellular metals

(Some figures may appear in colour only in the online journal)

1. Introduction
Periodic cellular structures were first considered in the field of lightweight construction due to their high specific stiffness, damping and energy absorbing properties [1]. Usually, the mechanical properties and the deformation behaviour can be controlled by appropriate choice of the underlying unit cell [2, 3] and by adjusting the relative density [4].

Due to the high geometric freedom of additive manufacturing processes such as selective electron beam melting (SEBM, [5, 6]), selective laser melting (SLM, [7, 8]) or 3D laser lithography [9] very complex cellular structures can now be built. Periodic structures based on various unit cells were studied experimentally [3, 6, 10–14], including the regular honeycomb [15], the cubic cell [3, 16] and the diamond lattice [17]. Although, from a metal point-of-view, Ti6Al4V powder is used most often, examples fabricated from copper [18, 19] or In718 [20] can also be found.

Another interesting property of specific cellular materials is their possibility to exhibit auxetic behaviour which was first reported by Lakes for auxetic foams. Other than regular materials, auxetic ones become broader when stretched and thinner when compressed [21]. This behaviour is described by a negative Poisson’s ratio. One of the first and most studied auxetic cells is the inverted honeycomb [22]. Studies of three-dimensional auxetic structures dealt amongst others with dilational metamaterials [24], inverted Kelvin cells [25], bucklcrystals [26], re-entrant cells [23, 27–29], the double-arrowhead structure [9] and buckling-induced patterns [30]. Interesting chiral structures were proposed as well [31–35]. It was found that besides the choice of unit cell, the unit cell parameters such as the ratio of thickness and length of the struts have a significant influence on the reason for failure during compression [28, 34]. Furthermore, the re-entrant angle and the relative density were found to determine the mechanical properties [23, 29].
Auxetic cells do not only offer the possibility of strain-stiffening behaviour [36] for curved applications, depending on the cell geometry they can be advantageous for specific load cases as well as the different elements they consist of can bear different sorts of loads [36, 37]. Furthermore, they may undergo a significant volume change when loaded [36]. They are reported to possess higher fracture toughness [38, 39] and higher energy absorption capability [40, 41]. Negative Poisson’s ratio materials were discussed to be used in various applications such as wine bottle corks [21], sensors [42], filters [43] and sandwich panel cores [44]. Biomedical implants [45, 46] are just as imaginable as parts in the aerospace field, for example in wings [47, 48].

In order to find novel auxetic structures, a systematic way of identifying auxetic structures is of great help. A method of employing eigenfrequency analysis was described in [49].

In this paper, one of the previously numerically identified fully auxetic three-dimensional cellular structures was manufactured from Ti6AlV4 powder using SEBM and characterised. The influence of a variation of the unit cell parameters on the mechanical properties is investigated.

2. Methods

2.1. Unit cell

The investigated unit cell is the 13th eigenmode of the regular cubic unit cell [49] (see figure 1). The struts can be described as alternating sines whose turning points meet in the nodal points. Besides the nodal distance l and the strut thickness d, also the amplitude A of the sine can be varied. FEM compression tests predict a negative Poisson’s ration of −0.4 in all cartesian directions for an approximate amplitude of 1.4 mm [49].

2.2. Sample fabrication

The cubic unit cells with chiral nodes were arranged periodically to form 3D lattice samples (figures 2(a)–(c)) with 3 × 3 × 5 unit cells. The samples were additively manufactured using an Arcam Q10 SEBM system, which uses an electron beam to selectively melt a powder bed to build up a part layerwise. The used material was Ti6Al4V powder with a powder particle size ranging from 45 to 105 μm. The parts were sliced to layers of 50 μm. The system uses a constant voltage U of 60 kV to accelerate the electrons. The process operates at a vacuum level 3 × 10⁻³ mbar with regulated helium. Four process steps are repeated until the whole part is completed: (1) raking of a new powder layer, (2) preheating of the powder layer with a defocused electron beam, (3) selective melting of the powder layer according to sliced CAD-data with a focused electron beam, (4) lowering the table by 50 μm. A more detailed description can be found in [50].

The influence of two geometric parameters on the mechanical properties was studied: the amplitude of the sine and the relative density of the samples. For constant nodal distance, an increasing relative density can be realised by an increasing strut thickness. A manufactured sample consisting of 3 × 3 × 5 unit cells with an amplitude of 1.5 mm can be seen in figure 2 in front, bottom and slightly rotated view.

The samples with varying amplitude (0.50–1.75 mm) were molten with an electron beam current I of 3 mA at a speed v of 450 mm s⁻¹. This equals a used line energy \( E_L = U \cdot I / v \) of 0.4 J mm⁻¹. The samples with varying relative density were fabricated using a constant amplitude of 1.5 mm and varying line energies between 0.4 and 0.8 J mm⁻¹. All unit cells had a quadratic cross section with a strut thickness d of 0.3 mm in the CAD file. This value is the resolution limit of the SEBM device and makes sure that the resulting thickness of the struts depends mainly on the used SEBM melting parameters. The nodal distance was 5 mm for all samples. Before testing, all samples were ground slightly on the top and bottom face to ensure flat contact planes between the samples and the compression stamps.

2.3. Characterisation

Relative density. The relative density was determined by measuring the samples’ dimensions (length l, width b, height h) and the weight m. The relative density was calculated using the following equation

\[
\rho_{rel} = \frac{\rho_i}{\rho_{mat}} = \frac{m}{V} \cdot \frac{1}{\rho_{mat}} = \frac{m}{l \cdot b \cdot h} \cdot \frac{1}{\rho_{mat}}
\]

which compares the density of the structure \(\rho_i\) with the density of the used material \(\rho_{mat}\). One has to bear in mind the...
process inherent roughness of struts fabricated by SEBM [3] that is caused by the sticking of totally or partially unmelted powder particles to the lower and lateral surfaces of the liquid melt pool. The actual struts are thicker than their mechanically active diameter [51].

**Strut thickness.** The thickness of the struts was measured with a calliper. Ten measurements were taken at randomly chosen positions and struts. Half of the struts were oriented parallel to the building direction and half of the struts were oriented perpendicular to the building direction.

**Compression test and evaluation.** The mechanical properties of the samples were determined using a Wolpert compression test machine with a 2 kN load cell. A preliminary force of 0.01 kN was applied to account for potential compression settings. The measurements were conducted displacement-controlled with a speed of 1 mm min⁻¹. All compression tests with varied line energy were recorded with an Allied Vision Technologies Pike F-210 camera at a resolution of 1000 × 1000 pixels with one picture per second. The room was darkened and indirect light was used to make sure that the conditions of illumination stayed constant. The compression test with varied amplitude of the strain was recorded with a Baumer LXG-200M camera with a resolution of 5120 × 3840 pixels.

First, one sample each was compressed until densification to determine the elastic region of the stress–strain diagram. Then ten loading–unloading compression tests were conducted in the elastic region for three samples per set of parameters. The elastic modulus was determined as the slope of the secant of the quasi-elastic straight lines in loading and unloading.

The Poisson’s ratio was evaluated during loading of the sample with the help of a commercial Digital Image Correlation (DIC) software Chemnitzer Werkstoffmechanik GmbH Vedac 6.0. The software compares the grey values of an initial image with one or more subsequent images. A searched image region (n × n pixels) around a set evaluation point is tracked in an analysed image region (N × N pixels, N > n). A cross-correlation algorithm calculates a coefficient K for all possible positions of the searched image region in the analysed image region. The cross-correlation coefficient K is a measure for the similarity of the compared regions. The position of the searched image that corresponds to the maximum value of K is interpreted as the position where the searched image region was moved to. The trajectories and derived strains of the evaluation points can be displayed. An evaluation point was placed on each nodal point of the recorded layer of cells of the sample (see figure 2(d)). The high number of evaluation points together with a median filter that considered the behaviour of the nearest neighbours makes sure that the results are not influenced by locally differing data. The Poisson’s ratio \( \nu_{xy} \) is defined as

\[
\nu_{xy} = -\frac{\varepsilon_{xx}}{\varepsilon_{yy}}
\]

where \( \varepsilon_{yy} \) is the strain in the direction of the applied force and \( \varepsilon_{xx} \) is the strain perpendicular to the applied force in the evaluation direction. It can be evaluated as the slope of the strain \( \varepsilon_{xx} \) when plotted in dependency of the strain \( \varepsilon_{yy} \). The Poisson’s ratio was calculated as the mean value of ten measurements of three samples that were built in the same SEBM process with the same parameters.

3. Results and discussion

3.1. Obtained relative densities

The relative densities of the samples obtained by varying line energy \( E_l \) are depicted in figure 3. The higher the used line energy, the more energy is transferred to the powder bed and the more powder is molten. This leads to thicker struts which can also be seen in the samples depicted in figure 3. Values of the strut thickness are indicated as well. The error refers to the standard deviation between the ten measured positions. Strut

![Figure 2](image-url)
thicknesses between 0.79 and 0.90 mm were observed. Of course, the caliper is not suited to take into account the roughness of the struts or to reveal the mechanically effective strut diameter. Still, the values give an idea of the obtained strut thicknesses.

The possible relative densities depend on the realisable strut thickness $d$ and the chosen nodal distance $l$. The nodal distance which was chosen in this study, allowed for an easy removal of the lightly sintered powder around the structures after the building process using a mixture of the same powder and pressurised air. The thicker the struts or the smaller the nodal distance, the smaller the pores in between the struts and the harder the powder removal until the channels are too small for a complete powder removal (see also [20]). The minimum strut thickness on the other hand is determined by the minimum electron beam diameter in the used manufacturing system. Other aspects one has to bear in mind are the process inherent roughness of the struts [3, 51] and their stairs-like build-up [6]. If the angle towards the building direction is too high, the struts will not be mechanically stable. Additionally, when using different unit cells and thus different angles towards the building direction, the resulting thickness and roughness will differ if the same process parameters are used [6]. The choice of compression direction towards build direction has an influence on the mechanical properties, too [6, 17]. Here, the choice of manufacturing and geometric parameters led to samples that were mechanically stable enough for compression behaviour while the struts at the same time were still flexible enough to show the auxetic effect.

### 3.2. Compressive behaviour

The stress–strain curve of a sample with low amplitude ($A = 0.6$ mm) can be seen in figure 4. Significant states of the sample during compression are depicted for better illustration of the compression behaviour.

In the beginning, the stress increases linearly with the applied strain. The cells are compressed elastically (figure 4, (1)) until the first deformation band buckles. Each deformation band can be assigned to a decline in stress which is again followed by an increase in stress until the next deformation band fails (figures 4, (2)–(7)). It can be seen that after the buckling of the top and bottom layer of complete unit cells (figures 4, (2)–(3)), the buckling of the next failing layer of cells leads to a sideways spreading of the sample between the top and bottom layer of struts. In the end, when the struts of the last layer of cells begin to touch each other, densification appears as a steep rise in stress (figures 4, (8)). Small amplitudes of the struts lead to stiff samples with almost no absorption capacity via bending. As soon as the maximal bearable stress for a layer of struts is reached, it fails by buckling. Small instabilities or imperfections may further decrease the maximal bearable stress.

The stress–strain curve of a sample with high amplitude ($A = 2.0$ mm) (see figure 5), depicts significant points of the compression behaviour. Three regions are clearly visible: first the elastic region, followed by a plateau in stress and then densification. Furthermore, the lack of steep peaks indicates a lack of deformation bands. Instead of that, the cells are compressed elastically by bending of the struts figure 5, (1) until the horizontal struts begin to touch each other (figure 5, (2)) which can be seen as the start of the plateau region. Then, layers of cells fail one after the other which is displayed by small descents in stress (figures 5, (3)–(6)). The last step is again densification of the sample (figures 5, (7)–(8)). The higher the amplitude of the unit cell, the more bending dominated is the compression behaviour. Compared to the sample with low amplitude, the elastic region is much wider whereas densification happens approximately at the same value, namely 72% strain for the sample with low and 75% for the sample with high amplitude.

The main possible deformation modes for cellular structures are stretching and bending induced by buckling [4, 53]. Additionally, shearing of the cross-section is possible and a consideration of Timoshenko beam theory might lead to more accurate analytical modelling [29]. The distinct peaks in figure 4 which are caused by deformation bands which are typical for rather stiff and brittle foams [1]. By changing the unit cell amplitude, the compression behaviour can be changed from buckling to bending dominated behaviour. In [28], the intensity of the peaks corresponding to failure bands could also be varied by changing the unit cell dimensions. A distinct plateau could not be observed for all samples. A similar observation regarding the change in deformation behaviour away from failure bands was made in [3, 13] when the compression behaviour for different unit cells was studied.

Figure 6 shows the stress–strain curves for samples with different relative densities and an amplitude of 1.0 mm: an elastic region is followed by a plateau stress with small fluctuations and finally by a densification region. For the samples with a line energy of 0.6, 0.7 and 0.8 J mm$^{-1}$ densification could not be reached as the necessary force exceeded the used load cell of 2 kN. As the amplitude was rather high, the samples could be compressed bending-dominated
without abrupt failure of deformation bands. The higher the relative density, the higher the elastic modulus and the plateau stress, the sooner densification begins. The main characteristics of the stress–strain curve correspond to the sample with high amplitude in figure 5.

A failure due to shearing at 45° as reported in literature [6] could not be observed. The compression behaviour is rather comparable to the perpendicular crush bands that were reported for a cubic cell in [3]. Alike the mechanical properties, the deformation behaviour depends significantly on the studied unit cell.

### 3.3. Elastic modulus

Figure 7(a) shows the elastic modulus for varying relative density: the thicker the struts, the higher the elastic modulus. In a log–log plot, the elastic modulus depends on the relative density according to a power law of the form

$$E \propto \rho_{\text{rel}}^m,$$

where the exponent $m$ reaches different values for different compression behaviour. An exponent of $m = 2$ is assigned to bending dominated compression behaviour. The slightly higher exponent of 2.5 in figure 7(a) can be caused by the roughness of the SEBM manufactured struts [3]. The mechanically active diameter is lower than the actual strut diameter [51]. As the roughness stays approximately constant for varying line energies, its influence on the ratio of material that is included in the relative density but not in the load-bearing is higher for low strut thicknesses and relative densities. Especially for low relative densities, the value is overestimated. This leads to a slightly higher exponent $m$. A second possible explanation is an increased stiffness of the nodal points that is caused by their higher diameter compared to the actual struts. The same phenomenon was observed in

![Figure 4](image1)

**Figure 4.** Stress–strain curve of a sample ($\rho_{\text{rel}} = 2.3\%$) consisting of a cubic chiral unit cell with a low amplitude ($A = 0.6$ mm, $l = 5.0$ mm).

![Figure 5](image2)

**Figure 5.** Stress–strain curve of a sample ($\rho_{\text{rel}} = 2.5\%$) consisting of a cubic chiral unit cell with a high amplitude ($A = 2.0$ mm, $l = 5.0$ mm).
where SEBM manufactured struts were studied, too. Compared to the elastic moduli of Ti6Al4V cellular structures with similar density found in literature, e.g. a diamond lattice \([6]\) or a 3D re-entrant lattice structure \([23]\), the values for the cubic chiral structure are higher respectively lower.

Figure 7(b) shows the dependency of the elastic modulus on the amplitude of the struts: the higher the amplitude, the lower the elastic modulus. This can be explained by the lowered bending stiffness due to the higher initial bending of the individual struts. It can be shown that the elastic modulus of a bent strut of length \(l\) under the influence of a bending moment is inversely proportional to the amplitude \(A^2\):

\[
E \propto \frac{1}{A^n} \quad \text{with} \quad n = 2. \tag{4}
\]

The corresponding linear approximation in figure 7 fits quite well.

### 3.4. Poisson’s ratio

The Poisson’s ratio \(\nu\) for varying relative densities is shown in figure 8(a). A distinct variation cannot be observed. A linear fit of the measured values yields a Poisson’s ratio of \(-0.19\). Possibly, the covered range of relative densities is too small to show a de- or increase of the Poisson’s ratio with varying relative density. An increase in Poisson’s ratio was observed for buckling-induced lattices with increasing relative density in \([30]\).

The Poisson’s ratio in dependency of the amplitude of the strut can be seen in figure 8(b). The higher the amplitude, the more negative the Poisson’s ratio. The lower the amplitude, the broader is the error of the Poisson’s ratio. A lower amplitude means a stiffer sample. The behaviour of stiffer samples is strongly determined by the failure of individual struts due to defects in the lattice such as insufficient connection of powder particles. Due to the large error bars of the Poisson’s ratio in figure 8, it remains unclear how the Poisson’s ratio depends exactly on the amplitude of the strut. Unfortunately, the evaluation method only captures the first layer of the lattice. A tomographic recording during compression would help to locate the individual struts or nodal points that lead to deviating behaviour. In \([49]\) a Poisson’s ratio of \(-0.4\) was obtained via FEM simulation for an approximate amplitude of 1.4 mm. Compared to the numerical value, the experimental value differs by a factor of two. Possible reasons are the anisotropy of the mechanical properties of the struts and the accuracy of realisation of the cellular structures in the SEBM process. Furthermore, DIC is best suited for the analysis of two-dimensional changes. In the case under consideration, the nodal points may execute three-dimensional rotational movements as well.

The Poisson’s ratio depends significantly on the amplitude of the strut and stays approximately constant for varying relative densities.

Figure 6. Stress–strain curves of samples with different relative densities consisting of a cubic chiral unit cell with an amplitude \(A\) of 1.0 mm.

Figure 7. (a) Elastic modulus in dependency of the relative density. (b) Elastic modulus in dependency of the amplitude.
4. Conclusion

A three-dimensional chiral cellular structure exhibiting auxetic behaviour in all three cartesian directions was manufactured with SEBM. The samples were characterised with the help of compression tests. It was shown how the deformation mechanism changes from stretching to bending dominated by an appropriate choice of the amplitude of the strut. The amplitude of the struts has a strong influence on the elastic modulus and the Poisson’s ratio. A variation of the relative density leaves the Poisson’s ratio unchanged although the elastic modulus follows the well-known power-law relationship. This means that the mechanical properties of the studied unit cell can be tailored to potential applications by appropriate design of the unit cell parameters.

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Conflicts of Interest

The authors declare no conflict of interest.

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