Selective Electron Beam Melting: A New Way to Auxetic Cellular Structures

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Abstract

This paper is concerned with the build up and characterisation of well defined auxetic structures from Titanium alloys through Selective Electron Beam Melting (SEBM).The negative Poisson's ratio of auxetic structures make them interesting candidates for a wide range of applications (e.g. joining of dissimilar materials). Up to date auxetic cellulars have mainly been produced through volumetric compression of conventional foams. However, by using SEBM we are able to produce structures of any geometry in a well defined manner. This opens an almost limitless field for new cellular auxetics and the tuning of their properties. In the following we will introduce a simple self designed auxetic structure and show first results for the mechanical characterisation of that structure.

Introduction

Conventional materials under elastic compression along one axis will expand in the transverse directions. The relation between introduced deformation and resulting transverse deformation can be described by the Poisson's ratio. Poisson's ratio v is defined as $v_{ij}=-\varepsilon_j/\varepsilon_i$ with ε_j being the resulting transverse strain and ε_i the introduced strain. The bounds for Poisson's ratio following from elasticity theory for an isotropic material are between -1 and 0.5 [1] with larger values possible for anisotropic materials, however all engineering materials exhibit positive Poisson ratios. The only way to access negative Poisson's ratios for engineering purposes is through cellular materials with intricate internal structures. The principle is illustrated by Figure 1 for the case of a two dimensional honeycomb structure, where the inversion of the cell leads to a material exhibiting auxetic behaviour.

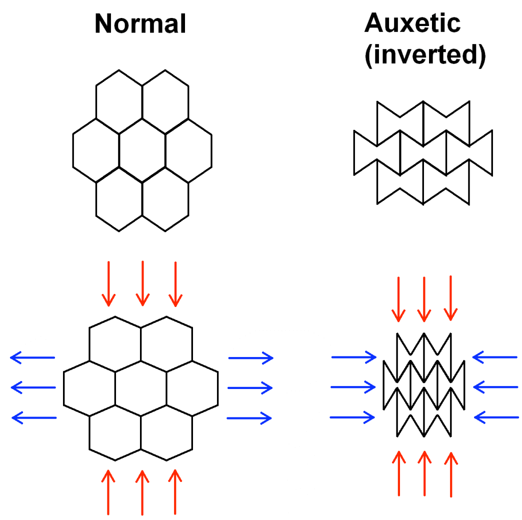

Figure1: The inversion of the honeycomb structure leads to auxetic behaviour (after [2]).

Such materials have been considered for a wide range of applications from improved seat cushions [3] to foam anchors [4] and impact resistant structures like bullet proof vest as they are expected to outperform conventional materials in several aspects. Poisson's ratio is just as significant for the mechanical performance of a material as Young's modulus. It has been postulated that negative Poisson's ratios lead to improved indentation resistance [5], shear resistance [6] and fracture toughness [7].
Until recently the only way to produce 3D auxetic cellular structures was through volumetric compression of conventional metallic and polymeric foams [8,9]. Compressing the foams leads to buckling of the struts within the structure and consequently to a cell inversion similar to the one illustrated in Figure1. However, the resulting auxetic foams face several limitations. The stochastic nature of the foams for example leads to very limited control of the resulting mechanical properties. The foams also show isotropic mechanical properties, which is an advantage for some applications but limits the range of accessible values for the Poisson's ratio. Here we will introduce a new route to auxetic structures using Selective Electron Beam Melting (SEBM). Using a rapid manufacturing technique has the significant advantage that structures can be build up in a controlled manner. This not only opens up an almost limitless field of possible new structures, but also allows for tailoring of the mechanical properties through controlled changes of the cell micro structure or graded structures. In the following we will first introduce our self-designed 3D auxetic structure and its fabrication in Ti-6Al-4V through SEBM and then show some results of the mechanical characterisation by compression testing.

Auxetic structure

A schematic building plan of our auxetic structure is shown in Figure 2. The basic element of the structure is an inverted tetrapod. These elements are joined together to first form building blocks and consequently planes. By stacking the planes on top of each other either by turning the second plane by 60° or by a parallel displacement of the plane, different structures can be derived (see Figure 2 structure A and B). Here we will limit ourselves to the structure entitled A in Figure 2 which is the result of a 60° rotation of the stacked planes relative to each other.

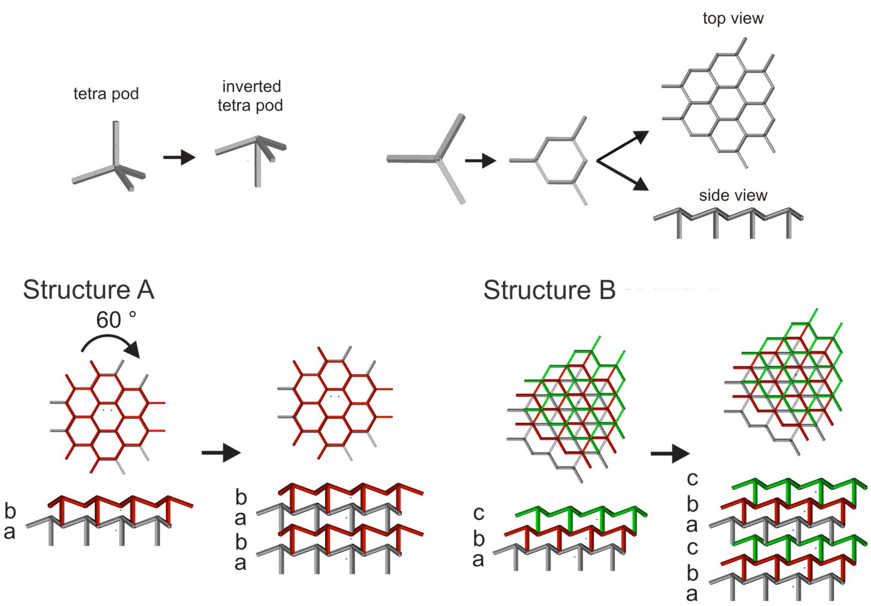

Figure 2: Two possible structures build up from inverted tetra pods.

As indicated in Figure 2 the stacking order of structure A is of the type ABAB. The structure is fairly complex and can be expected to be anisotropic. To help with picturing the structure and the coordinate system, which we will be referring to in the discussion of the mechanical properties of the structure, Figure 3 shows a block created in the above described manner with our chosen coordinate system. Also shown are projections of the blocks faces onto the respective coordinate planes.

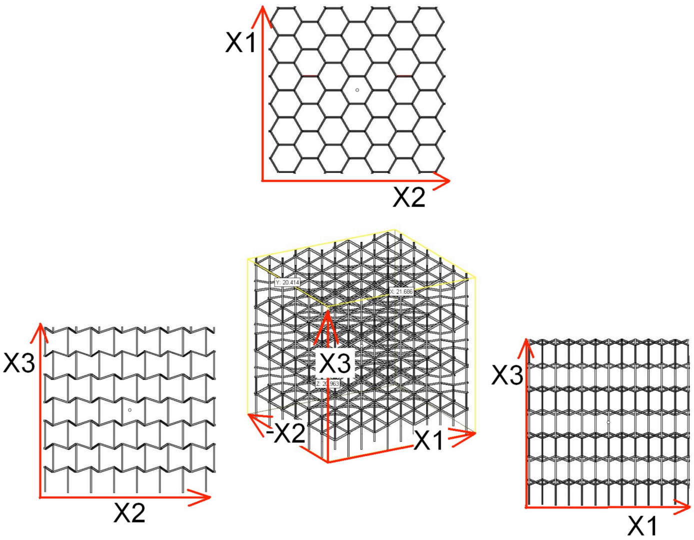

Figure 3: A block build up from Structure A with projections onto the coordinate system used to reference the system here.

The reference system was picked so that its vectors stand normal on distinctive planes of the structure, namely, on those planes where it is possible to "see through" the structure.

Experimental

Samples for compression testing were built in Ti-6Al-4V on an ARCAM A2 selective electron beam melting system. The Ti-alloy powder used had a mean particle diameter of 70µm and a maximum particle size of 105µm. During the process layers of 100µm thickness are deposited on top of a steel plate and successively locally molten to form the desired part. The electron beam gun used for melting the powder uses an acceleration voltage of 60kV. The process takes place under a low pressure Helium atmosphere and at elevated temperatures, leading to low impurity concentrations in the finished part and good material properties.
The geometrical data of the parts is given in form of CAD-models. In order to vary the relative density of the structures the amount of energy deposited per unit length was changed (constant scan speed of 160mm/s; three different beam current between 1.9 and 4 mA). A larger amount of energy leads to a larger melt pool and, hence, to thicker struts and larger relative densities. For a more detailed description of the procedure see [10].
Compression samples for the determination of Young's modulus E for three different orientations were made with slightly varying dimensions so as to not break the symmetry of the structure. The exact dimensions for the three different orientations are listed in Table 1 with the numbers corresponding to the long axis of the samples (the direction of compression).

Table 1: Dimensions of compression samples

Orientation	Height [mm]	Width [mm]	Thickness [mm]
Orientation 1	42.7	21.7	21.4
Orientation 2	42	20.7	21.4
Orientation 3	42	20.4	21.7

The dimensions of the single tetrapod as given in the CAD-file were A=2.5mm and B=2mm (see Figure 2). The samples were tested on a standard compression testing machine (Hegewald & Peschke; Inspekt Retrofit 100) with a crosshead speed of 1mm/min and strain was measured using an extensometers determining the relative movement of the two compression stamps.
The Poisson's ratio ν was determined on larger samples with a slightly coarser structure (A = 3.75 mm; B = 3 mm) as this allowed for better accuracy in the measurements. The samples were loaded up to 1.7 MPa which lay inside the elastic region for these samples. The transverse strains were measured with an extensometer attached to the sample by two sharp blades.
All samples (four samples per density) were built up in x3 direction to ensure comparability between the different orientations. The surfaces of the samples in contact with the compression stamps of the testing equipment were polished to achieve an even contact. A CT-scan (resolution ~20µm) was taken of one compression sample in order to assess the build quality.

Results and Discussion

Figure 3a shows the three samples corresponding to three different orientations that were used for determining Poisson's ratio. Samples of this type were used for the determination of *ν*. In 3b the CT scan of a compression sample is shown alongside the original CAD data used to create it. The geometry of the structure is nicely reproduced by the process. Strut thickness does not depend on the CAD file but on the energy used to create the structure.

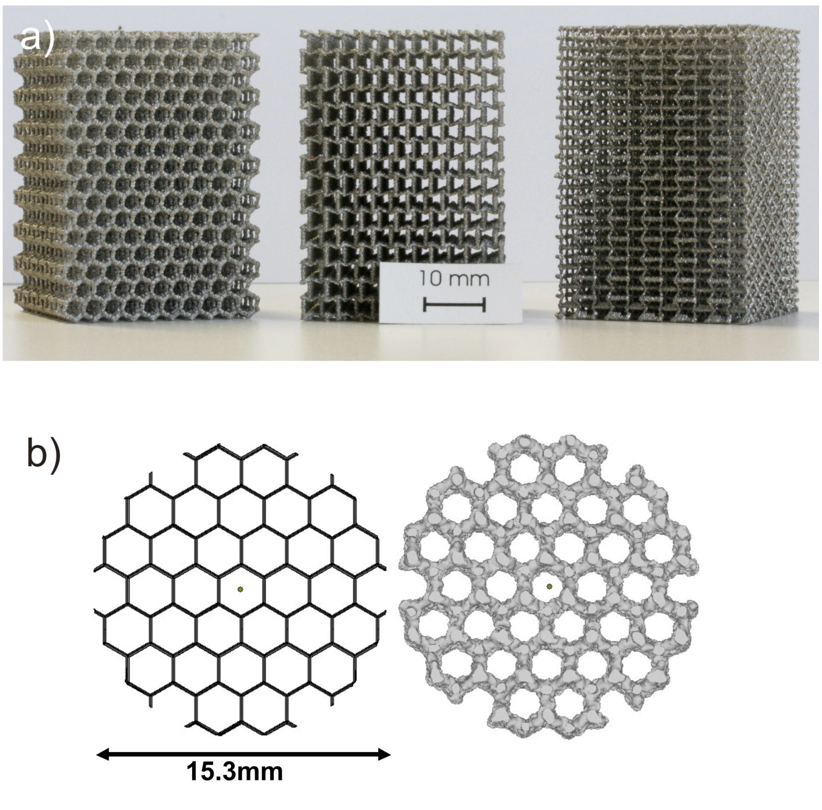

Figure 3: a) Samples used for measuring the Poisson's ratio and b) a comparison between original CAD-file and a CT-scan of the resulting structure.

Figure 4 shows a typical compression stress strain diagram for one of the samples. At first the sample deforms macroscopically elastic, then it enters a short phase of plastic deformation followed by a sudden stress drop. During the stress drop a single layer of the structure collapses and after the complete compaction of that layer the stress starts rising again until the next layer collapses.

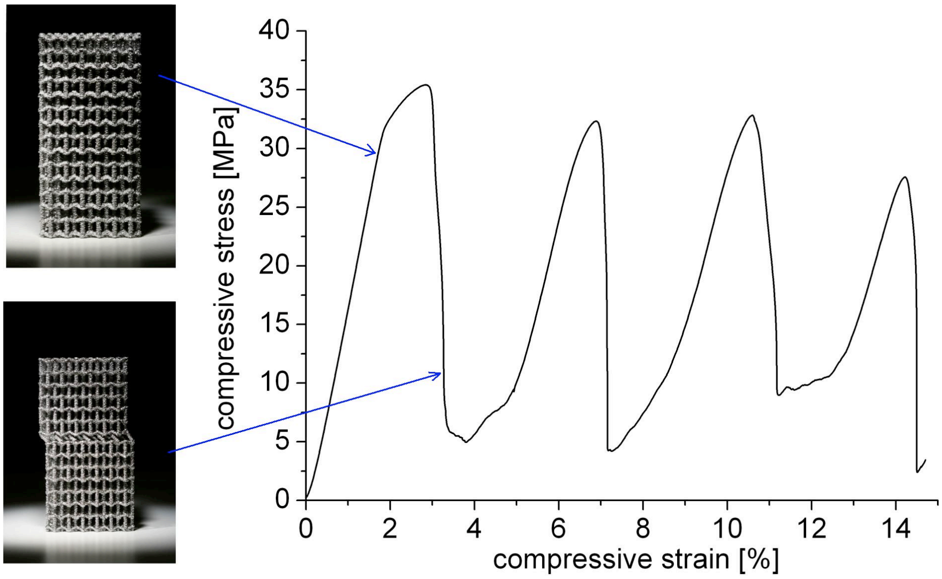

Figure 4: Typical stress-strain behaviour of a compression sample.

The Young's modulus of the structures strongly depends on the relative density (Figure 5a) and all three orientations show very similar absolute values for *E*. Towards low relative densities a drop off in stiffness can be observed. For samples in this density range a significantly larger amount of broken struts were found after the build process. Accordingly we contribute the reduction in stiffness to the fact that we are coming close to the limit in beam energy that still creates a continuous structure. This is further supported by the fact that trying to build structures with even lower energies at the powder-layer thicknesses used here (100 µm) does not result in structures that can be removed from the surrounding sintered powder without destroying them.

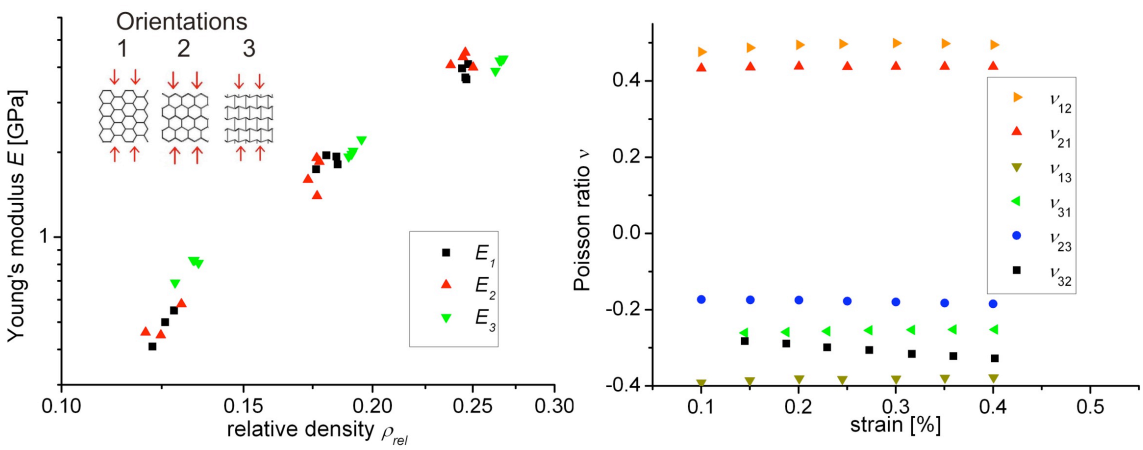

Figure 5 showing: left) Young's modulus vs. relative density and right) Poisson's ratio vs. strain for three different sample orientations.

Finally Figure 5b) presents the results for the Poisson ratio for the three different orientations in the elastic regime of the samples. In this relatively small strain window the Poisson's ratio does not depend appreciably on strain. In general a strain dependence of ν would be expected as the negative values are an effect of the geometry of the samples which is constantly changing during deformation. For most orientations we find a negative Poisson's ratio. Only when measuring the transverse strain on the x3-face do we find positive Poisson's ratios. These are the faces that resemble honeycombs in projection, however in the third dimension they posses a wavy structure. This means, that under compression in x3-direction the whole structure contracts, while in all other orientations one face shows expansion in the transverse direction of the applied compression.

Conclusions

We were able to build a well defined auxetic structure using SEBM. The ability to set a certain Young's modulus through change of the relative density of the structure was demonstrated. Further possibilities to adjust the mechanical properties of the structure should arise from the ability to freely change internal angles of the structure, which should directly influence its Poisson's ratio.

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