Selective Laser Melting of Honeycombs with Negative Poisson's Ratio

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Laser Freeform Fabrication allows additive manufacturing of functional parts from metallic powder materials. This yields potential for product innovations due to increased geometric degrees of freedom. Additional advantages are reduction of throughput time and economical manufacturing of small lot sizes. Hence, these processes are capable of producing structures of complex freeform geometry that cannot be manufactured at all with conventional processes [1]. This provides the possibility to manufacture designs that show a negative Poisson's ratio ν. It gives the relation of the negative transverse strain to the longitudinal strain of a material exposed to uniaxial tension or compression. The longitudinal strain occurs in the load direction, whereas the transverse strain is found normal to this axis. Typically, the Poisson's ratio is greater than zero, i.e. in tension a material's volume can increase or remain constant while the behaviour in compression is vice versa. However, some materials can exhibit negative values between –1 and 0 meaning that they show unexpected behaviour by expanding transversely under tensile forces and vice versa under compression.

This circumstance can be exploited in applications where parts are subject to compressive deformation but which are not allowed to expand laterally in order to not cause damage in adjacent components. Examples are crash impact absorbers and artificial intervertebral discs, etc. Experimental results were obtained from new honeycomb structures that were manufactured with Selective Laser Melting from stainless steel powder and tested in a universal testing machine under elastic, compressive deformation. Thus rules for successful design of honeycomb structures with negative Poisson's ratio were derived.

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1. Introduction

The strength of Laser Freeform Fabrication (LFF) processes for metallic engineering materials is the manufacture of low-volume parts of complex geometry in small lot sizes. Typically, such boundary conditions are encountered in medical applications where each part may be customized to the needs of the patient as it is the case for e.g. dental caps or endoprostheses. According process chains which involve the assessment of 3D CAD data from the patient by e.g. scanning or by computer tomography (CT), the conversion into manufacturable sliced part data and the one-step fabrication of according parts is close to being state-of-the-art at industrial level.

However, the mass fabrication of identical parts with LFF processes still seems out of reach since no suitable applications have been envisaged yet in this field. Therefore, it is suggested to use popular LFF processes such as Selective Laser Melting (SLM) for the production of products of high complexity which cannot be manufactured at all using conventional technologies such as subtractive machining, etc. or which can be manufactured only at excessive cost and time. A suitable field is one in which highly complex geometries allow to give materials new mechanical properties such that new applications can be developed. This is achieved by obtaining materials with negative Poisson's ratio, i.e. their transversal strain perpendicular to the direction of a uniaxial force behaves vice versa the expected direction with interesting engineering consequences which may be exploited.

2. Poisson's Ratio

2.1 Fundamentals

The Poisson's ratio ν gives a relation of the negative transverse strain to the longitudinal strain of a material exposed to uniaxial tension or compression. The longitudinal strain occurs in the load direction, whereas the transverse strain is found normal to this axis. The Poisson's ratio links the elastic moduli and can be found from the formulae in eqs. (1), (2) and (3) where E is Young's modulus, G is the shear modulus and K is the bulk modulus.

$$G = \frac{E}{2\cdot(1+\nu)} \tag{1}$$

$$K = \frac{E}{3\cdot(1-2\nu)} \tag{2}$$

$$\nu = \frac{3K-2G}{6K+2G} \tag{3}$$

In tension a material's volume can increase or remain constant while the behaviour in compression is vice versa. If quadratic strain terms are disregarded for small strains, then the relative volume change of the material is proportional to longitudinal strain by a factor of $(1–2\nu)$ due to thermodynamic considerations of strain energy [2]. Therefore, the Poisson's ratio of a material cannot exceed 0.5, typical values range between 0 and 0.5 where 0.5 is an incompressible material. Most metallic materials such as stainless steel, aluminum and titanium show values of 0.3, 0.33 and 0.34, respectively. However, some materials can exhibit negative values between –1 and 0 which can e.g. happen in the case of foam, sponge and specially designed materials. These are also referred to as auxetic materials. Table 1 summarizes typical materials which represent special cases of Poisson's ratio [3]. Values greater than 0.5 can occur if cells are elongated such that the cellular structure shows significant anisotropic mechanical properties. This might be the case in undeformed hexagonal honeycombs or strongly deformed foams [4]. Materials with a negative Poisson's ratio are envisaged in applications for artificial intervertebral discs or for the damping of vibrations and sound as well as impact energy [5].

2.2 Fabrication and experimental investigations

A negative Poisson's ratio in isotropic materials can be obtained in the following ways [6, 7, 8, 9]:

- non-affine deformation kinematics (i.e. unfolding of unit cells in foams and sponges),
- rotational degrees of freedom in lattice nodes connected by some ligaments of negative stiffness (due to pre-strain) or
- noncentrosymmetry (chirality) where a structure differs from its mirror image and has therefore no center of symmetry.

Negative Poisson's ratio materials can be manufactured from conventional metallic foams and sponges. The most investigated material is the so-called re-entrant structure where the cell walls or struts protrude rather inward than outward giving rise to a concave shaped unit cell. Since the theory of elasticity has no length scale a coarse cellular structure should not be required which allows to expect that even the transformation of microstructures smaller than 1 µm into re-entrant structures is possible. Their manufacture from conventional low-density foams and sponges made from random metallic materials incorporates permanent compression in three orthogonal directions. Some materials can be transformed by simple application of triaxial hydrostatic pressure, however, for ductile metal foams and sponges a subsequent uniaxial compression at room temperature is necessary until yield occurs. The major modifications induced are the formation of plastic hinges and the plastic buckling of cell walls or struts. The strain applied in each direction determines the alterations of the structure and thus the total volumetric compression ratio [10]. Another method was suggested [5] for closed-cell foams where the foam is exposed to a vacuum such that the cell walls stretch as the gas entrapped in the cells expands. The reintroduction of atmospheric or higher pressure causes the cell walls to buckle plastically, creating a re-entrant structure. It was observed that this method results in a negative Poisson's ratio along only one of three orthogonal axes. The most important parameters in transforming a foam or sponge into a re-entrant structure are temperature, time and volumetric compression ratio [4]. Typically, in testing of re-entrant materials the volumetric compression ratio is considered preferentially. A model was derived [11] for the theoretical Poisson's ratio at small linear elastic strains according to eq. (4) where φ is the angle of a specific cell strut pointing inwards into the unit cell at ranges of $0.25\pi < \varphi < 0.5\,\pi$ (45 to 90°). In this model theoretical volumetric compression ratios between 1.4 and 4.8 are required for the creation of re-entrant foams and sponges. According to the theory the lowest Poisson's ratio can be obtained at the highest volumetric compression ratio of 4.8 which is expected to be valid for elasto-plastic as well as brittle materials.

Table 1 Table 1 Extremal Poisson's ratios and their engineering consequences

Material	ν	Characteristics	Engineering consequences
Rubber	0.5	$\lim_{\nu\to 0.5}\left(K=\frac{2G(1+\nu)}{3(1-2\nu)}\right)=\infty$ $\lim_{\nu\to 0.5}\left(G=\frac{3K(1-2\nu)}{2(1+\nu)}\right)=0$	• incompressible • minimum shear strength
Cork	0	$\lim_{\nu\to 0}\left(K=\frac{2G(1+\nu)}{3(1-2\nu)}\right)=\frac{2}{3}G$ $\lim_{\nu\to 0}\left(G=\frac{3K(1-2\nu)}{2(1+\nu)}\right)=\frac{3}{2}K$ $\lim_{\nu\to 0}\left(E=2G(1+\nu)\right)=2G$	• shear strength exceeds compressibility • stiffness exceeds shear strength • transverse strain equals zero in tension and compression
Ideal re-entrant cellular material	-1.0	$\lim_{\nu\to -1}\left(K=\frac{2G(1+\nu)}{3(1-2\nu)}\right)=0$ $\lim_{\nu\to -1}\left(G=\frac{3K(1-2\nu)}{2(1+\nu)}\right)=\infty$ $\lim_{\nu\to -1}\left(E=2G(1+\nu)\right)=0$	• easy to compress • maximum shear strength • minimum stiffness

$$\nu = -\frac{\sin(\varphi - 0.25\pi)}{\cos(\varphi - 0.25\pi)} \qquad (4)$$

In some experimental investigations large scatter and no trend for the dependency of Poisson's ratio on relative density in the compression of conventional foams and sponges was observed [12]. However, it was noticed that Poisson's ratio reaches 0.5 for relative densities approaching zero and found that it decreases exponentially to the value of the bulk material towards relative densities near unity [13, 14].

Compressive tests were conducted [10] on a conventional open-cell copper sponge with initial relative density of 0.053 transformed into a re-entrant structure by triple uniaxial compression with a total volumetric compression factor of 1.7. Infered from the author's diagrams the conventional sponge showed yield stresses of roughly 0.25 MPa at 3.5 % elastic strain while the re-entrant structure failed only at 1 MPa stress and 15 % elastic strain with significantly reduced Young's modulus. The Poisson's ratio of the conventional copper sponge exhibited values of around 0.42, whereas the re-entrant sponge showed a value of –0.39 in the initial stages of compression with progressively increasing values as the magnitude of axial strain increased. More detailed results were obtained [7] and it was determined that strain-hardening does not occur with re-entrant foams and sponges in both tension and compression. Copper sponges with initial relative densities of 0.04, 0.08, 0.09 and 0.1 were transformed into re-entrant structures by sequential deformation in three orthogonal directions. The smallest Poisson's ratio obtained from these specimens was –0.8 at zero strain for the sponge with an initial relative density 0.1 and a volumetric compression ratio of 2.13. In the correlation of Poisson's ratio versus compression ratio at different relative densities the Poisson's ratio attains a minimum value at a specific volumetric compression ratio for each relative density. This specific compression ratio is the smaller the higher the initial relative density was. Young's modulus is influenced by the volumetric compression ratio such that compressive stiffness increases with volumetric compression while tensile stiffness behaves vice versa. The influence of volumetric compression ratio on yield strength was found to be similar. In conventional foams and sponges the yield strength in tension and in compression was mostly observed to be similar (see above). In re-entrant foams and sponges, however, the yield strength decreased under tensile load with the compression ratio and increased in compressive load. Explanations of the strength's decrease in tension rely on the weakness of the plastic hinges formed in the cell walls or struts while in compression the contact of cell walls or struts accounts best for the increase in strength.

At zero strain the Poisson's ratio of conventional foams and sponges will generally show a significant non-linear dependency on the amount and direction of strain. The Poisson's ratio drops in compression, however, remains greater than zero. In tension it will rise to a maximum close to 0.5 before it slightly decreases at continued strain. If the cell size is increased, the maximum Poisson's ratio should be obtained at smaller tensile strains. However, re-entrant structures on the other hand show their minimum Poisson's ratio at zero strain. Both compressive and tensile strain increase the Poisson's ratio which although remains below zero. If in the case of a re-entrant structure the cell size is increased, then the minimum Poisson's ratio decreases since the bending of cell walls or struts can occur more easily allowing e.g. concave cell struts to bulge out [4].

Negative Poisson's materials can also be obtained from specifically designed materials such as two-dimensional honeycombs. Structures comprised of squares or triangles connected at specific corners by hinges which allow them to rotate can give negative Poisson's ratio [17, 18]. The same can be achieved when connected squares are stretched [19]. Analytics show that depending on the geometry these designs can give Poisson's ratio theoretically as low as –1. Honeycombs with chiral structures were also investigated which yield theoretical minimum Poisson's ratios of -0.23 [20]. However, none of these sources describes the manufacture of such honeycombs except a more recent one which mentions the fabrication of auxetic honeycombs by means of Rapid Prototyping (RP) processes [21], i.e. freeform fabrication by additive layer manufacturing. These processes allow great freedom in producing virtually any two-dimensional honeycomb structure.

Table 1 as well as some material testing results give insight into the advantages of negative Poisson's ratio materials which are mainly high shear strength and high resilience. Besides these properties the resistance against indentation can also be maximized by applying materials with negative Poisson's ratio since indentation is proportional to the impinging pressure by the factor $(1-\nu^2)/E$ which equals zero in the case of $\nu = -1$ [2]. Likewise, the fracture toughness of negative Poisson's materials can be increased. An open-cell copper sponge was investigated and K_{Ic}-values of 120 kPa·m$^{0.5}$ were found for the conventional sponge with initial relative density of 0.08 and 180 kPa·m$^{0.5}$ were obtained for the re-entrant sponge after volumetric compression by the factor of 2.0 [15]. At volumetric compression ratios of 2.0, 2.5 and 3.0 the same re-entrant sponge delivered J_{Ic}-values of 1.4, 1.8 and 2.1 kPa·m while the conventional structure showed only 0.8 kPa·m. These experimental results document a clear rise of fracture toughness for re-entrant materials obtained from subsequent volumetric compression in three orthogonal directions with fracture toughness enhancements of up to 162.5 %.

3. Selective Laser Melting

3.1 Process characteristics

The LFF process that was used for the production of the specimens presented below is Selective Laser Melting (SLM). Like most other LFF processes involving powder material, the SLM process is based on a principle in such manner that the powder is applied in very thin layers on a building platform and melted due to the thermal energy induced by a laser beam. The powder particles have a statistical distribution of size from 5 µm to between 20 and 60 µm. Therefore, the thickness of each layer is at least 20 to 100 µm [16]. In each layer the laser beam exposes a cross-section area of the part that is built by melting and

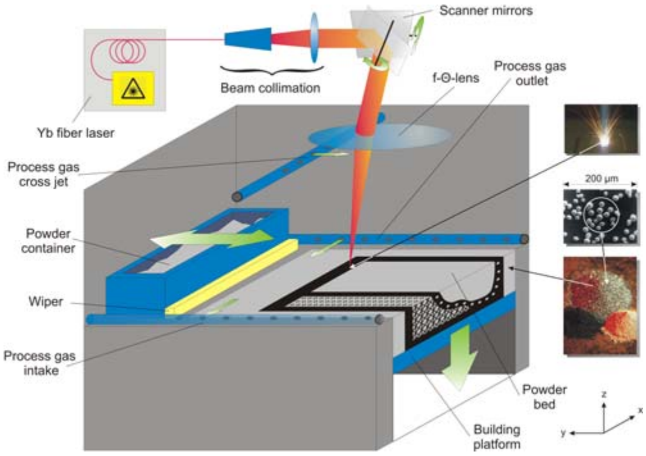

Fig. 1 Cross section through SLM process chamber

resolidification of the powder particles, before the building platform is lowered and coated with a new layer of powder. In order to achieve this, a coating device with a silicon wiper applies the new layer of powder onto the previous layer as shown in fig. 1.

The laser beam is being redirected across the surface of the powder bed (identified as the *x*-*y*-plane) by scanner optics (pivoted mirrors) in such a way that the powder particles can be selectively melted where desired. The surface tension of each powder particle changes due to melting which allows neck formation between adjacent particles, resulting in coalescence of the powder particles and creation of a solid layer attached to the previous one underneath.

3.2 Process chain

The SLM process is typically embedded in a process chain which consists of acquisition of 3D-CAD data, conversion of this data into a 2½-D representation in a sliced format, building the part from powder material and finishing the part according to the requirements. Thus, if the data preparation and the finishing are neglected, the part manufacturing is nearly a one-step process. This helps reduce the throughput time significantly.

3.3 Design options for SLM parts

Typically, design engineers optimize part designs for conventional processes such as subtractive machining, etc., i.e. parts are usually of solid design. However, with the introduction of Laser Freeform Fabrication technology they must learn how to exploit new geometric degrees of freedom. It gives them the possibility to apply solid freeform

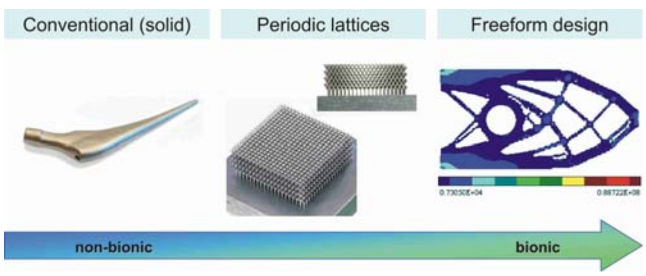

Fig. 2 Design options for SLM parts

shapes on one hand and parts with internal structures on the other hand. This allows to manufacture e.g. periodic lattice structures which excel the mechanic properties of metallic foams that are merely ordered stochastically. Such structures are well suitable for the purpose of universal or combined load situations. If, however, a part has to bear only unique and clearly foreseeable load situations its topology can be optimized in such a way that mass is only retained in places along which stresses concentrate. This process of topology optimization usually gives bionic freeform part designs which cannot be manufactured conventionally but with SLM. Altogether this leaves three design options for SLM parts [16] shown in fig. 2:

- solid freeform (conventional) design,
- internal periodic lattice structure design or
- bionic design, i.e. internal and external freeform network structures.

Of these options the second and third option are the most appealing in exploiting the possibilities of SLM.

4. Development of structures for negative Poisson's ratio

As shown in section 2.2 auxetic 2D honeycombs were analyzed in previous investigations. This paper reveals research on the SLM manufacturing route for some of these honeycombs as well as some newly developed ones containing structures not presented before. In order to achieve this the design rules for negative Poisson's ratio given in section 2.2 were applied. Fig. 3 shows two honeycomb designs where the rule of non-affine deformation kinematics was applied which implies the folding or unfolding of unit cells as the structure deforms. The structure on the left side is named decagonal honeycomb due to the shape of its unit cells of 10-sided polygons which were arranged in a 10x10 field. For improved clarity the unit cell design is depicted enlarged in the bottom right corner. The horizontal walls were provided for balanced distribution of

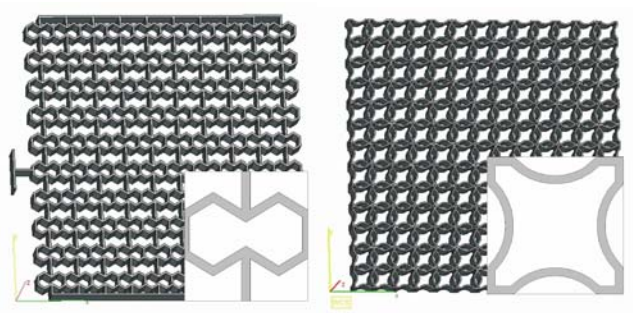

Fig. 3 Decagonal and cubic floral honeycomb

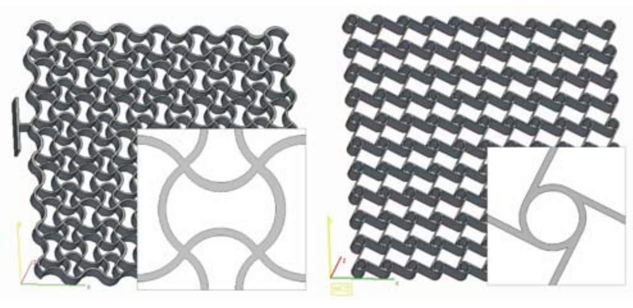

Fig. 4 Cubic sinus wave and cubic chiral honeycomb

compressive force and the small wall-piece at the left side for measuring the lateral strain. It was expected that this structure shows a Poisson's ratio of less than zero as the vertical struts fold together the remaining parts of the unit cells in such a way that they become more compact longitudinally as well as laterally. The structure on the right of fig. 3 was composed of unit cells with concave walls. In metallic foams e.g. cells with concave walls have clearly shown negative Poisson's ratio hence a similar behaviour was expected for this structure. Due to its appearance it was named cubic floral honeycomb which was arranged in a 13x13 field.

In contrast fig. 4 shows two designs according to the design rules of lattice nodes with rotational degrees of freedom and of chirality. On the left side a structure named after its cubic sinus waves unit cells was arranged in a 13x14 field. It was designed to show negative Poisson's ratio if external compressive force is applied to it, due to coiling of struts which gives lateral narrowing. In this structure the curvature of all cell walls, i.e. the lack of corners, is expected to reduce stress concentrations [21] and give a high strain range. The 10x10 structure on the right side, however, shows chiral unit cells without symmetry. Upon compressive external forces the nodes act as centers of rotation as well which cause the same effect of coiling of struts and hence the longitudinal and lateral compaction of unit cells. This cubic chiral honeycomb is also known as tetra chiral in the literature [20].

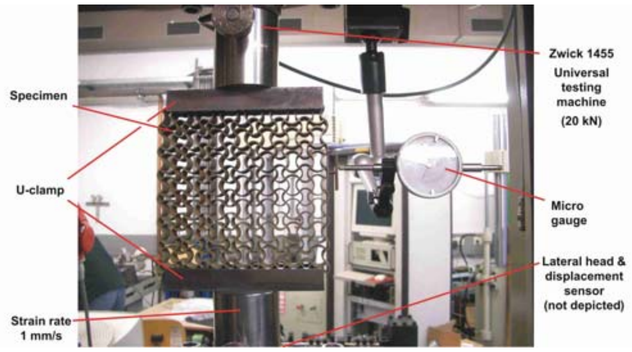

Fig. 5 Experimental setup of compressive tests

5. Experimental results

Specimens of all four honeycomb structures introduced above were fabricated with the SLM process with typical sizes not exceeding 170 mm in overall length and width and 20 mm in thickness to avoid buckling of the specimens. Fig. 5 shows the experimental setup that was provided to conduct compressive tests strictly in the elastic region in order to not destroy the specimens. Compressive specimens were chosen due to their higher expected strength compared to tensile specimens as stated above in section 2.2. In this context higher strength is beneficial due to an increased linear-elastic regime. The data which the longitudinal and lateral strain was derived from were taken from the unloading modulus of the stress-strain diagrams obtained during the tests. These were conducted on a Zwick 1455

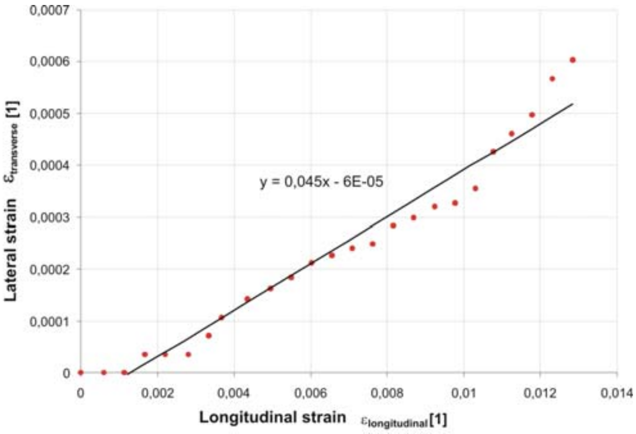

Fig. 6 Results for decagonal honeycomb

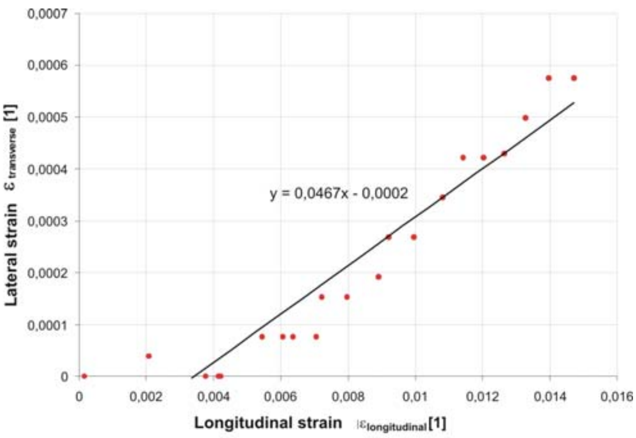

Fig. 7 Results for cubic floral honeycomb

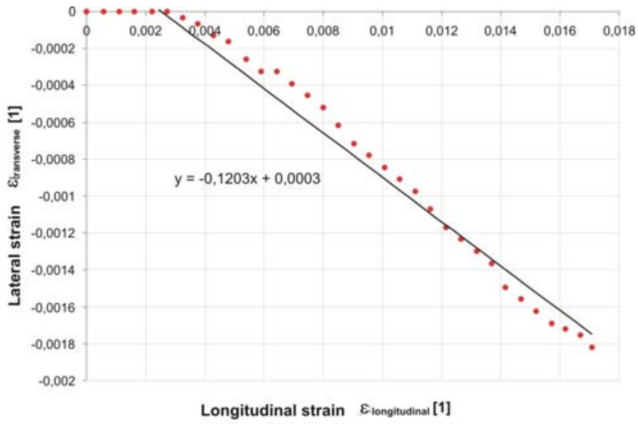

Fig. 8 Results for cubic sinus waves honeycomb

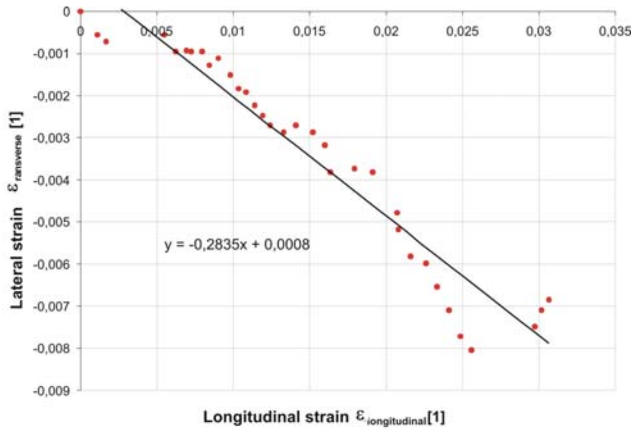

Fig. 9 Results for cubic chiral honeycomb

universal testing machine at a strain rate of 1 mm/s. The specimens were clamped in a lubricated U-shaped clamp. The longitudinal strain was recorded by a sensor in the lateral traverse while the lateral strain was recorded manually at fixed time intervals by using a micro gauge.

The results for all four different types of honeycombs are given in figs. 6 through 9 where the measured lateral strains vs. the longitudinal strains are shown. According to the literature [22] the Poisson's ratio can be directly derived from these diagrams based on engineering strain provided that only small strains apply. Additionally, the graphs contain best linear fits for the obtained data as suggested by the literature [23] and show the according equation in which the slope directly indicates the Poisson's ratio. Apparently, the decagonal and the cubic floral honeycomb show nearly zero, yet slightly positive Poisson's ratio while the cubic sinus waves and cubic chiral honeycombs show clearly negative Poisson's ratio.

6. Discussion

The results suggest that the design parameters of the honeycomb structures take significant influence on the results. Despite of the results for the decagonal structure it is still expected that this shape can show negative Poisson's ratio, however, the length and width of the unit cells have to be chosen very carefully. Compared to simpler honeycombs with non-affine deformation kinematics such as concave hexagonal shaped honeycombs, negative Poisson's ratio is more difficult to obtain.

The cubic floral honeycomb promotes the concept of negative Poisson's ratio found in predeformed foams which make re-entrant structures. However, this design did not succeed since, as opposed to metal foams, no support struts were provided to interconnect the unit cells. Instead the unit cells were directly adjacent to each other leaving no space for a preferred direction of lateral compaction. Therefore, this design needs to be improved.

In contrast, the cubic sinus waves honeycomb proved how successful rotational degrees of freedom are. A negative Poisson's ratio of –0.1203 was obtained. It was derived that this value can be further increased by changing the curvature of the unit cell walls. However, restrictions apply when the unit cells collide and rotational movements are stopped. An optimum structure would, therefore, compromise between these two factors. Generally, this structure is similar to the missing rib foam model [24, 25], however, the sinus waves structure should be considered superior due to avoidance of sharp edges which helps reduce stresses.

The cubic chiral honeycomb showed an even more negative Poisson's ratio of –0.2835. It was observed that the success is mainly dictated by the diameter of the nodes provided in the structure. The larger the diameter is the more negative the Poisson's ratio becomes. However, the length of the struts connecting the nodes must be balanced to this diameter to ensure such results.

Future work that is planned involves the simulation of honeycomb structures using appropriate software for multi-body systems. This would help optimize the obtainable Poisson's ratio and minimize the experimental effort.

7. Summary

Four honeycomb structures of which some were newly developed were investigated experimentally towards their mechanical behaviour in elastic compression. Two of these structures named cubic sinus waves and cubic chiral honeycomb clearly showed negative Poisson's ratio with values of –0.1203 and –0.2835. The remaining two structures show slightly positive values close to zero. The structures with negative Poisson's ratio are desired for applications in which materials are required to show high compressibility, i.e. minimum resistance to compression, and possess high shear strength. Examples are e.g. crash impact absorbers, bullet proof vests or artificial intervertebral discs.

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