Experimental study of auxetic behavior of cellular structure

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Abstract. The uniaxial tension of two-dimensional auxetic cellular constructions is studied experimentally. Samples were made of nonauxetic polyethylene terephthalate (PET-A amorphous) and subjected to monotonous uniaxial tension until the last moment when they still remained plane. As a result of the experimental data analysis, comparison of the mechanical properties is given for a faultless sample and constructions in which one horizontal or vertical element in the central area of the sample was removed. It is shown that the lack of one horizontal element of the construction has little influence on the auxetic properties of these constructions unlike the structures with one vertical element being absent.

1. Introduction
Poisson’s ratio for isotropic materials varies in the range from −1 to 0.5 [1]. This ratio characterizes the relation of transverse deformations to longitudinal deformations. The majority of the known materials have positive values of Poisson’s ratio. In [2], the polymeric foam with negative Poisson’s ratio was obtained for the first time. The very name of auxetics was attributed to materials with negative Poisson’s ratio [3]. Recently, we observe a certain increase in the number of studies on the physical and mechanical properties of auxetics [4–6]. The main directions of these studies are the studies of auxetic crystal materials [7–23], creation of auxetic structures [24–29], and production of composites with effective negative Poisson’s ratio [30, 31]. Note that there are over four hundred crystal auxetics known at the moment. The greatest number (more than three hundred) were found among cubic crystals. For example, monocrysalts of lithium, potassium, calcium, nickel, iron, gold, silver, etc. possess auxetic properties (see [16 17]). It was for the first time in [24, 25], where the concave hexagon was suggested as a cell of the auxetic two-dimensional plane for creation of auxetic structures. In [24], the auxetic two-dimensional framework consisting of concave hexagons was considered, and calculations of the average elastic characteristics were given. In [25], a two-dimensional construction comprised of concave hexagons was also proposed, and the geometrical parameters at which Poisson’s ratio is observed to be equal to −1, were calculated. In [27, 28], the concave hexagon in which a part of straight elements is replaced with curvilinear ones was suggested. An experimental analysis of such two-dimensional construction showed that Poisson’s ratio can reach −0.6. The two-dimensional and three-dimensional auxetic polymeric planes were experimentally studied in [29], where the dependence of their Poisson’s ratio on the real deformation was calculated.
Figure 1. Three plane cellular samples with central area 28 \times 24 \times 0.7 \text{ mm}: faultless sample \text{zz} (a); sample with one horizontal element being absent \text{zzH} (b); sample with one vertical element being absent \text{zzV} (c).

Figure 2. Variation in the transverse displacement $\Delta l_x$ versus the longitudinal displacement $\Delta l_y$.

The present paper considers an experimental study of uniaxial tension of two-dimensional auxetic cellular constructions consisting of concave hexagons which contain defects in the central part of the samples.

2. Methods

The mechanical tests were performed on samples which were obtained from nonauxetic polyethylene terephthalate (PET-A amorphous) 0.7 mm thick by the femtosecond laser cutting method. The laser machine carried out displacements of the billet with micron accuracy. The duration of radiation impulses was 500 fs. The energy of an impulse was 120 $\mu$J, and the radiation power in an impulse reached 240 MW. The average power of radiation was 3 W. As a result of laser cutting, three plane cellular samples with dimensions $112.5 \times 24 \times 0.7 \text{ mm}$ with central area $28 \times 24 \times 0.7 \text{ mm}$ were obtained (figure 1): a faultless \text{zz} sample (figure 1a), \text{zzH} sample with one horizontal element being absent (figure 1b), and \text{zzV} sample with one vertical element being absent (figure 1c). The transverse size of elements of the cellular construction was equal to the thickness of the initial plate.

All three samples were subjected to monotonic uniaxial tension on a universal uniaxial setup (MTS Synergie 400) at 1 mm/min loading rate, with simultaneous registration of displacements and forces. The samples were stretched until the last moment when they still remained plane. The changes of the sample geometry were registered in the 12-Megapixel photo and video images taken during the experiment by Dahua IPC-HF81200E camera. The force and displacement of the cantilever-moving beam of the upper grip were also registered by the built-in sensors of the setup. The displacements and deformations in the plane of the sample were calculated later after decoding the video into separate frames by digital image correlation (DIC) method using Ncorr software package [32]. A random two-color pattern was applied to the initially transparent samples to enable tracking of specific areas by DIC post-processing.

Based on the force-displacement data, the experimental dependence of equivalent longitudinal stresses acting in the transverse section of the sample on longitudinal deformation can be calculated. The initial stage of almost linear deformation is related to the elastic reaction of the structure elements. At the next stage, the plastic deformation develops in curved elements and straight parts connecting them, the in-plane rotations is performed. At the last stage, the rigidity of the structure is restored.
Figure 3. Photographs of sample zz at different stages of deformation $\varepsilon_x = 0$, $\varepsilon_y = 0$ (a), $\varepsilon_x = 0.110$, $\varepsilon_y = 0.172$ (b), $\varepsilon_x = 0.319$, $\varepsilon_y = 0.400$ (c); sample zzH at different stages of deformation $\varepsilon_x = 0$, $\varepsilon_y = 0$ (d), $\varepsilon_x = 0.118$, $\varepsilon_y = 0.188$ (e), $\varepsilon_x = 0.287$, $\varepsilon_y = 0.365$ (f); sample ssV at different stages of deformation $\varepsilon_x = 0$, $\varepsilon_y = 0$ (g), $\varepsilon_x = 0.098$, $\varepsilon_y = 0.210$ (h), $\varepsilon_x = 0.218$, $\varepsilon_y = 0.395$ (i); the axis $y$ corresponds to the tension direction, and the axis $x$ corresponds to the transverse direction.

3. Result and discussion
Variations in the transverse displacement $\Delta l_x$ versus the longitudinal displacement $\Delta l_y$ for three cellular samples are shown in figure 2. The sample with one vertical element being absent (zzV sample) is extended much stronger as compared to other samples. The maximum change of longitudinal displacement was 9.6 mm for sample zz, 10.3 mm for sample zzH, and 11.7 mm for sample zzV. The lack of one horizontal element in sample zzH led to a longer time till the loss of stability as compared to sample zz. Thus, in the monotonous tension, sample zzH was extended slightly stronger as compared to the faultless construction. The lack of one vertical element in sample zzV leads to its poor extension in the transverse direction during the experiment.
Figure 4. Poisson’s ratio as a function of (a) longitudinal deformations $\varepsilon_y$ and (b) transverse deformations $\varepsilon_x$ for three samples.

as compared to the two other samples. The maximum changes of transverse displacements reached 6.4 mm for sample zz, 6.9 mm for sample zzH, and 5.3 mm for sample zzV. The pictures of three studied samples at different stages of deformation are given in figure 3.

Poisson’s ratio in elasticity theory in the case of small deformations is determined by the formula

$$\nu = \frac{-\varepsilon_x}{\varepsilon_y},$$

where $\varepsilon_x$ is the transverse deformation and $\varepsilon_y$ is the longitudinal deformation. The variability of Poisson’s ratio for three cellular samples was studied by analogy with this formula. In this case, $\varepsilon_y = \Delta l_y/L_0$ is the longitudinal deformation, $L_0 = 28$ mm is the length of the central area, $\varepsilon_x = \Delta l_x/l_0$ is the transverse deformation, and $l_0 = 24$ mm is the width of the central area.

The dependence of Poisson’s ratio on longitudinal and transverse deformations for three cellular samples is given in figure 4. Figure 4a shows that samples zz and zzV experience large longitudinal deformations as compared to sample zzH. In the case of transverse deformations (see figure 4b), the lack of one vertical element leads to the fact that sample zzV has significantly smaller transverse deformation as compared to the two other samples. The maximum longitudinal and maximum transverse deformations reached 40% and 32% for sample zz, 36% and 29% for sample zzH, and 41% and 22% for sample zzV, respectively).

Conclusions

Poisson’s ratio for sample zz varies in a wider range (from $-0.40$ to $-0.81$) as compared to the two other samples. In the case of sample zzH, the range of Poisson’s ratio is reduced to values from $-0.54$ to $-0.79$. The lack of one horizontal element in the cellular plane (sample zzH) has weak influence on the mechanical properties. Distinctions in Poisson’s ratio take place at longitudinal deformations up to 13%. The narrowest range of Poisson’s ratio variations is for sample zzV (from $-0.40$ to $-0.54$). This is related to the fact that this sample extends stronger with less widening as comparison to sample zz and sample zzH (figure 2).

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