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Auxetics materials: classification, mechanical properties and applications

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Abstract. In contrast to classical materials, auxetic materials (from the Greek word αὐξητικὸς / auxetikos) possess negative Poisson’s ratios, thereby exhibit reverse deformation mechanism. Under a tensile force applied in the longitudinal direction, auxetics expand in the perpendicular transverse direction. Consequently, auxetic materials possess various useful properties for potential applications. This review contains the classification of auxetic materials according to different criteria: the type of structure, cell geometry and scale, mechanical characteristics, methods of their production, and engineering applications. The aim of this work is to sum up structural information on auxetics.

Auxetics (from Greek word αὐξητικὸς / auxetikos) are materials or structures with negative Poisson’s ratios [1], most often resulting from the structural geometry of their cells, with sizes varying from nano to macro scales depending on the type of material [2]. Figure 1 illustrates a general classification of auxetic materials. Auxetic materials exist in nature in two forms: biological and mineral. Depending on the deformation direction, synthetic or man-made auxetic materials under mechanical load may be subdivided into two main groups: two-dimensional and three-dimensional. The most known natural auxetic materials are presented on figure 1 [3-9]. In this paper, much more attention is given to synthetic structures (figure 2), and their deformation mechanism [10-23]. The most studied two-dimensional geometry is the hexagonal unit cell (figure 2, c), with two parallel sides, while the left ones form re-entrant folds symmetrically [12]. Structures with this type of geometry exhibit auxetic behavior when a tensile or compressive force is applied at the re-entrant connection points. Another similar geometry can be obtained based on triangular unit cells with one re-entrant rib. In this case, the negative Poisson’s ratio results from displacements of the connection points.

The two-dimensional re-entrant configurations described above can be implemented into three-dimensional structures. In the first case, it is necessary to join perpendicularly trough their bending points two similar hexagonal re-entrant unit cells (figure 2, b) [13], and for the second one similar combination of unit cells is applied. There is also a configuration of auxetic materials based on two- or three-dimensional rotating units. A typical example with such a structural configuration is the rotating square unit structure (figure 2, c). In this case, the Poisson's ratio value is almost -1 [14]. For this configuration, rectangles, rhombuses or triangles can be used instead of squares. The three-dimensional mechanism of this type of structure is based on rotating tetrahedrons (figure 2, d) [15]. Another type of mechanism is the chiral mechanism. The auxetic behavior in this case results from the rotation of the connecting nodes. For the two-dimensional configuration, the motif consists in a chiral...
arrangement of unit circles and ribs tangentially attached to them (figure 2, e) [16]. The auxetic behavior occurs when a tensile or compressive load is applied in the connecting nodes. The circle unit then rotates in a certain direction and pulls or pushes the adjacent circular units through ribs connected in a different direction to the load direction. In this case, the Poisson’s ratio could approach values close to -1. The three-dimensional configuration of this type of mechanism is made out of cubic joints and deformable ribs (figure 2, f). As the number of unit cells increases, the Poisson's ratio decreases from a positive value to a negative one, and the structure itself becomes inclined to size effects [17].

![Figure 1. General classification of auxetic materials.](image)

Besides autonomous use, auxetics could be used as reinforcing components. The utilization of auxetic fibers as a filler enhances the interfacial adhesion under tensile load in composite materials [18]. There are four manufacturing techniques of auxetic composites: using a matrix with negative Poisson’s ratio, using auxetic fibers and an ordinary matrix, or both components auxetic, or by layering ordinary composite layers in predetermined directions. In all these cases, the fracture toughness increases during the manufacturing process, what makes these materials suitable for many applications. The fracture toughness depends on Poisson's ratio value and increases as it approaches closely to -1. This feature has been demonstrated as an example in composites reinforced with carbon fibers [18]. Indentation resistance, energy absorption and toughness can be enhanced in sandwich-panels by means of auxetic layer, reducing their weight at the same time [19]. Auxetic honeycomb displays synclastic curvature through a relatively small number of manufacturing steps in contrast to traditional materials, and also possess enhanced out-of-plane bending resistance and stiffness. This is due to the perpendicular arrangement of ribs to the curved surface. Auxetic re-entrant honeycombs possess various mechanical characteristics. Chiral honeycombs in truss-core assemblies are very effective for adaptive lifting devices, since the cylinders stiffness is increased during the out-of-plane compression, and tangentially linked connections increase their resistance in case of out-of-plane shear [19].

The two-dimensional configuration is exclusively represented by auxetic perforated plates with ordered or randomly oriented notches, and lattices with missing-rib type cell. In the first case, the most known structure is the one with perpendicular notches, which imitates the mechanism of rotating square units (figure 2, g) [11]. Perpendicular notches can be replaced by rhombus-shape or star-shape perforations (rotating triangle). Plates with randomly oriented cuts also exhibit auxetic behavior. The
missing-rib type cell is obtained by perpendicularly fastening the midpoints of two identical ribs, and connecting again perpendicularly to their ends additional rods, building an unfinished square (figure 2, h). This model effectively describes behavior of auxetic polyurethane foam [10].

Figure 2. Unit sells and structures of synthetic auxetic: (a) re-entrant unit cell, (b) 3D re-entrant unit cell [13], (c) structure with rotating units [14], (d) 3D structure with rotating units [2], (e) chiral unit structure, (f) 3D chiral unit structure [17], (g) perforated plates [11], (h) missing-rib type model [10], (i) porous foam structure [20], (j) crumpled sheet type structure [21], (k) entangled single wire type [23], (l) Miura-ori folded structure [22].
The three-dimensional auxetic configuration is common for foams, crumpled structures, entangled single wire models and miura-folded structures. Microporous polytetrafluoroethylene (PTFE) with disk-like particles as node points in fibrillar network possess a large negative value of Poisson’s ratio (figure 2, i) [20]. As a result of tensile load, the fibrils in the microstructure network lead to the rotation of anisotropic disk-like particles that expand the material in the transverse direction and lead to low Poisson's ratios value, that can reach -12. Such elasticity theories as Cosserat theory and micropolar elasticity models, take into account the existence of micro-rotational degrees of freedom as those that have been seen in this microstructure [20]. The auxetic behavior of crumpled materials occurs due to the unfolding mechanism, common feature for graphene foils. Crumpled materials are of interest due to their low density and simple manufacturing process. (figure 2, j) [21]. The Poisson's ratio of entangled single wire models slowly decreases under tensile load and lingers in the region of zero, and under compression, the coefficient becomes positive (figure 2, k) [23]. Transverse expansion during longitudinal tension or compression of entangled single wire occurs due to spiral segments and the steric effect, which helps to reduce or enhance local rotations. This property makes an entangled single wire model suitable over other auxetics in the manufacture of anchor devices, since it results in enhanced adhesion under tensile or compressive loads [23]. The structure of the Miura-ori cells is formed by zigzag folds of the sheet, which are regulated depending on the desired auxetic effect (figure 2, l). For the Miura-ori sheet, the Poisson’s ratios for in-plane and out-of-plane deformations are of opposite sign. For in-plane deformations auxetic behavior is observed, and under bending it deforms into a saddle-shaped configuration characteristic of a positive Poisson’s ratio. These Poisson’s ratios are found to be equal and opposite. A metamaterial that expands/contracts uniformly can be created by stacking together individual Miura-ori sheets layer by layer in a three-dimensional structure [22]. Classification of auxetics by the production methods is presented on figure 3.

![Fabrication methods of synthetic/man-made auxetic materials](image)

**Figure 3.** Fabrication methods of auxetic materials.

Due to the negative Poisson's ratio, auxetic materials have enhanced mechanical properties (Tab. 1) [27-38], most of which are superior to similar properties of non-auxetic materials, and some of them unique. Auxetic materials are suitable for many practical applications [18, 19, 31, 34, 37-48]. The main existing and potential applications of auxetic materials are presented in Tab. 2.

Reference to the above reasoning shows that there are a lot of papers devoted to auxetic materials, however, the majority of them deal with the internal structure of auxetics, experimental determination of Poisson’s ratios, as well as with the description of features of different auxetics [1-51]. However, papers discussing the mathematical models describing the behavior of viscoelastic auxetics are rare, and there are practically no studies devoted to the solution of boundary-value dynamic problems with such materials [52-55]. With the accelerated progress in studies of auxetics made in last few years,
there are new potential opportunities for researchers. Anisotropic auxetic materials are still in developing stage and require intensive research via creating new mathematical models which could adequately describe their properties [56, 57].

| Mechanical properties                    | Description                                                                 |
|------------------------------------------|-----------------------------------------------------------------------------|
| Increased Energy Absorption              | As it is shown by experimental results, auxetic materials exhibit a better damping and sound absorption (ex: Porous auxetic foams) [27] compared to conventional materials |
| Enhanced Indentation Resistance          | This property is the result of two main reasons: high shear stiffness, and the fact that when an impactor touches their surfaces, auxetic materials move to regions where the impact is applied, what increases the density of these regions. Many studies have been carried out on materials with re-entrant unit cells, polymeric and metallic foams, and composite sandwich panels [28-30] |
| High Shear Stiffness                    | From the well know relation between the Poisson’s ratio (ν), the Young’s modulus (E), shear modulus (G), the following conclusion could be made: at negative magnitudes of the Poisson’s ratio, the shear modulus becomes higher. When the value of the Poisson’s ratio approaches close to -1, the shear modulus tends to infinity, and the shear resistance gets significantly larger. Researches on this property have been carried out on structures with re-entrant and chiral unit cells [31, 32] |
| High Fracture Toughness                 | Conducted studies have shown that it requires more energy to propagate a crack in auxetic material, and that toughness could be changed as the Poisson’s ratio varies, and therefore the material becomes very tough if the Poisson’s ratio gets close to -1. Many studies have been conducted on structures with re-entrant unit cells, composite sandwich panels and solid foams [33-35] |
| Synclastic Curvature in Bending         | Under bending load applied on two opposite sides, auxetic surfaces undergo synclastic deformation. This property allows the manufacturing of structures with different shapes through a relatively small number of machining steps, avoiding the waste of material, and consequently with low manufacturing cost. This feature is most typical for structures with re-entrant unit cells [2, 36] |
| Variable Permeability                   | Porous auxetic materials are suitable for varying permeability. This property allows to control the permeability of filters. When a load is applied in a certain direction, the size of their pores changes. In case of tensile load, their size increases. This variable permeability can be used from macroscale to nanoscale materials. All porous auxetic materials exhibit this property [37, 38] |
Table 2. Applications of auxetic materials.

| Field                | Application (existing and potential)                                                                 |
|----------------------|-----------------------------------------------------------------------------------------------------|
| Aerospace            | Aircraft engine vanes, aircraft thermal protecting system, fasten belts, wing (enhanced shear resistance) panel, aircraft nose-cones, rivet, sounds and vibration absorber [19, 31, 38] |
| Military (defense)   | Lighter protective materials, blast curtains, vehicle armor for ballistic protection, helmet, bullet proof vest, protective gear, knee pad, protective gear (better impact resistance) [31, 40, 41] |
| Automotive           | Energy absorption devices, cushion, thermal protection, jounce bumper, vehicle armor for ballistic protection, fastener [19, 42] |
| Composite            | Composite reinforcement (better adhesion between fiber and matrix) [18, 34, 40, 43] |
| Biomedical           | Stents, surgical implants, arterial prostheses, bandage, wound pressure pad, auxetic scaffolds, health monitoring sensors, artificial skin, prosthetic linings, sutures and ligament/muscle anchors [44, 45] |
| Building industry    | Reinforcement of masonry walls with an auxetic layer. The auxetic foams used in this case, due to their negative Poisson's ratios, increase the toughness of the wall [46] |
| Sensors/actuators    | Piezoelectric devices and composites, sensors/ hydrophone (higher sensitivity and higher resistance variation in the sensor) [19, 47] |
| Textile industry     | Comfortable textiles with reduced clothing pressure, textile fibers, functional fabric, threads industry, color-change straps, or fabrics [37, 44, 48] |

Conclusion
This review provides a coherent classification of synthetic auxetic materials, including the most studied types of structures and geometries of their unit cells, expected mechanical properties, their main manufacturing methods, and their existing and potential applications. This review will help researchers and engineers interested in auxetic materials to get a general representation of these interesting materials, and their unique characteristics and properties.

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