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Review Article

An investigation on auxetic feature and its applications

Umut Aksu [a], ***M. Seha Tatlıer*** [b*]

[a]*Osmaniye Korkut Ata University, Department of Mechanical Engineering, Osmaniye, Turkey*
[b]*Osmaniye Korkut Ata University, Department of Mechanical Engineering, Osmaniye, Turkey*

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ABSTRACT

The technology aims to respond to ever-increasing needs day by day is in a progressing development. One of the basic and most important components of technology is material. Nowadays, as an alternative to conventional engineering materials, multi-functional new generation competitive materials are obtained by adding new features to existing materials or developing new materials in order to meet the demands of the present and future. In this respect, the negative Poisson's ratio (auxetic) materials are one of the most widespread research subjects recently. The auxetic structure and materials, originally found in nature, have been observed to separate from traditional (positive Poisson's ratio) materials with various mechanical properties, mainly deformation mechanisms, thanks to their unique microstructures. In this study, auxetic feature is investigated and researches for adaptation of the auxetic feature to various science and technology fields are compiled.

1. Introduction

Materials have various mechanical properties according to the characteristic of their microstructures. These properties, which guide the behavior of materials, play an important role in many stages from design to manufacturing method and product development. Many of the mechanical behaviors of materials have been expressed numerically with the formulas. The Poisson's ratio, which is one of the most important formulas in engineering, can be defined as the negative ratio of the transverse strain to axial strain [1]. The Poisson's ratio is given by Equation (1)

$$\nu = -\frac{\left(\frac{\Delta y}{y_0}\right)}{\left(\frac{\Delta x}{x_0}\right)} = -\frac{\varepsilon_y}{\varepsilon_x} = -\frac{\varepsilon_{transverse}}{\varepsilon_{axial}} \qquad (1)$$

It's a physical phenomenon known by experiences that conventional materials expand in the direction they are stretched and contract in other directions. In this case, the Poisson's ratio values of conventional materials are considered as positive. However, due to their unique microstructures, some materials and structures which are different from conventional materials, by the way of expanding as they are stretched or contracting as a result of compression, are a continuing research subject. These materials have negative Poisson's ratio values due to the deformation mechanism they exhibit. Materials with negative Poisson's ratio have been called "auxetic" which is a Greek word "auxetikos" meaning "tend to increase". The term "auxetic" was first used in 1991 by Professor Ken Evans [2]. The deformation mechanisms of both auxetic and conventional materials are shown in Figure 1. Researches that have been conducted over 30 years include various purposes such as the understanding of the mechanism leading to auxetic behavior, designing and production of auxetic materials and examination and development of mechanical properties of auxetic materials [3]. In this study, the auxetic feature is investigated and the researches on the adaptation of auxetic feature to technology are compiled.

2. Auxetic Structures and Materials

Auxetic behavior is the feature that independent from the dimensional scale, so can be observed in various sizes

* Corresponding author. Tel.: *+90-328-827-10-00 (3457)* :
E-mail addresses: umutaksu@osmaniye.edu.tr , sehatatlier@osmaniye.edu.tr
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from molecular level to bulk structures (Figure 2) [4].

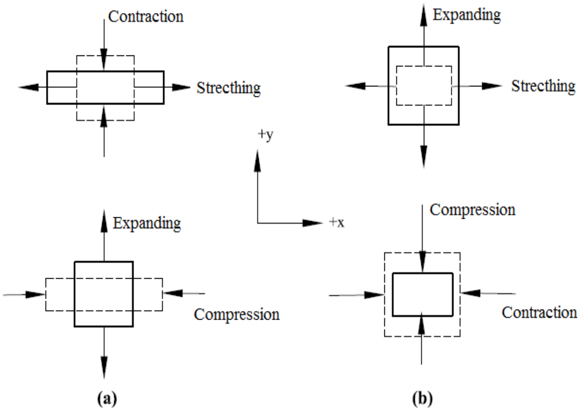

Figure 1. Deformation mechanisms of (a) a conventional and (b) an auxetic structure [5]

The first natural material at the molecular level being observed to exhibit auxetic behavior was cubic monocrystalline iron pyrite (iron sulphide) (Poisson's ratio value $\nu = -0.14$), discovered at the beginning of 1900's. It was observed that iron pyrite exhibits auxetic behavior due to its twin crystal structure [6]. Ledbetter et al. [7] have found that YBa2Cu3O7 (yttrium barium copper oxide) exhibits auxetic behaviour. Milstein et al. [8], then Baughman et al. [9] reported that cubic crystal structures exhibit auxetic behavior at a rate of 69% on the (110) plane. Other natural auxetic materials which have been discovered through researches and take place in literature are thermal graphite [10], rocks with micro cracks in the structure [11,12], arsenic with single crystalline structure [13] and cadmium [14], α-cristobalite silica crystal with multi-crystalline structure [15]. There are also examples of biological structures in which the auxetic feature is observed such as cancellous bone in human [16], cow teat skin [17], cat skin [18] and salamander skin [19].

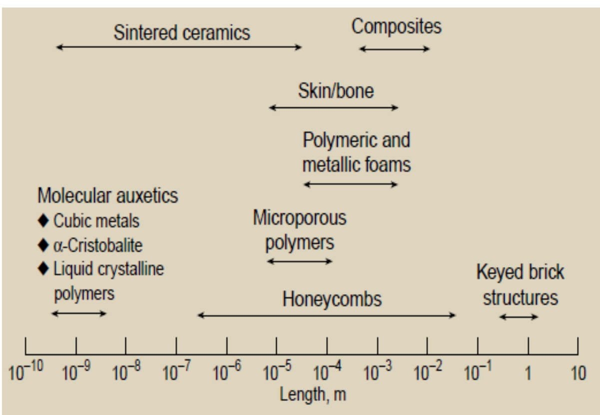

Figure 2. Auxetic structures and materials in various levels [4]

The first designed structure which auxetic deformation mechanism obtained was a 2D anisotropic "re-entrant honeycomb" model (Figure 3). The structure designed by Gibson et al. [20] was also manufactured using silicon-rubber and aluminum.

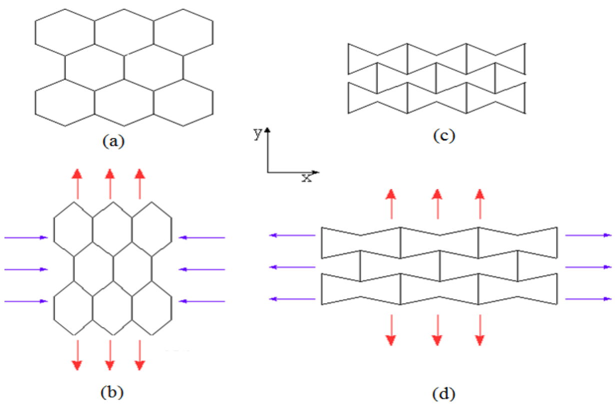

Figure 3. Conventional honeycomb model (a) in the free state (b) in the deformation state and auxetic anisotropic honeycomb model (c) in the free state (d) in the deformation state [20]

Almgren [21] purposed a three-dimensional re-entrant honeycomb model. It was observed that shear stress occurred in plane in case of axial stretching or compressing. In this study, springs were placed between the collars on the vertical beams of the honeycomb structure. Very large shear stress ($G = \infty$) was obtained with this structure for Poisson's ratio$\nu = -1$. The model is elastically isotropic (Figure 4).

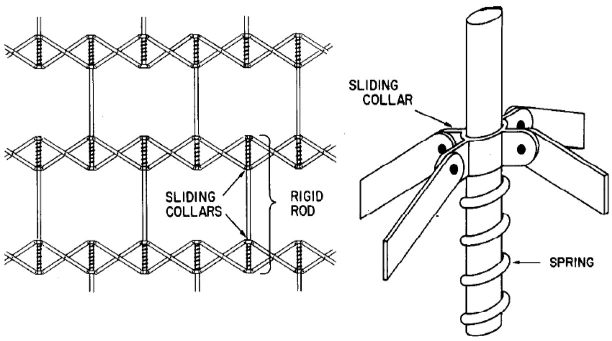

Figure 4. Auxetic isotropic honeycomb model [21]

Lakes [22] successfully produced the first auxetic open-pore isotropic polyurethane foam with his own method. Conventional open-pore, low-density polyester foam was compressed volumetrically to make pores of the foam re-entrant. Later, the foam was heated to a temperature slightly above its softening temperature after placing to pattern. Finally, the foam was allowed to cool at room temperature. Through experiments with different values of production parameters, negative Poisson's ratio value ($\nu = -0{,}7$) was obtained. Auxetic foam was observed to be more flexible than conventional foam. Figure 5 shows the microstructures of both conventional and auxetic foams.

Friis et al. [23] produced auxetic foams using conventional open-pore thermoplastic (polyester urethane), thermoset (silicone rubber) and copper foam through the method developed by Lakes. They observed that the elasticity modulus of auxetic foams produced was lower than that of conventional foams.

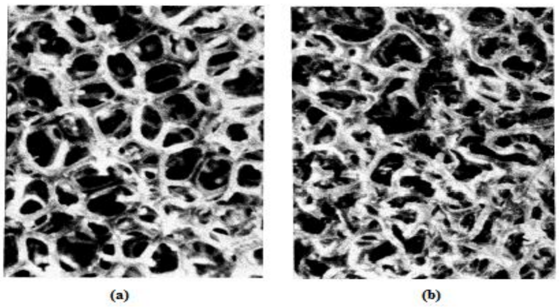

Figure 5. Microstructures of (a) a conventional foam and (b) auxetic foam [22]

Caddock et al. [24] produced an expanded form of polytetrafluoroethylene (ePTFE), a microporous anisotropic auxetic polymer (Figure 6). The Poisson's ratio values of auxetic ePTFE varied up to $\nu = -12$.

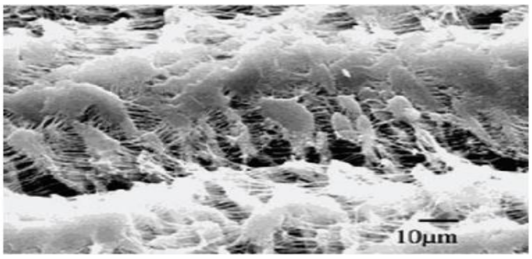

Figure 6. Microstructure of ePTFE in expanded form with auxetic feature [24]

Evans et al. [25] designed a 2–dimensional model to observe the mechanism that leads to auxetic behavior in ePTFE. The designed model was compatible with the experimental results (Figure 7).

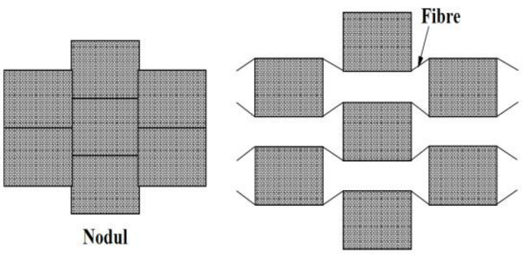

Figure 7. 2–dimensional model of auxetic ePTFE [25]

Choi et al. [26] studied on parameters affecting auxetic foam production. In their study, parameters such as material type, temperature, process time, humidity, permanent volumetric compression ratio, relative density and pore sizes were investigated through experiments with industrial polymer foams (Scott foam and gray polyurethane-polyester foam) which have the same density. In addition, they revealed the relation between permanent volumetric compression ratio factor–Poisson's ratio and elasticity modulus–shear modulus. They also observed that for the auxetic foams they obtained, there was a direct proportional relation between the applied permanent volumetric compression ratio and fracture toughness. In the auxetic foam materials they produced, they obtained $\nu = -0.7$ Poisson's ratio value. Also for another study, they obtained Poisson's ratio of $\nu = -0.8$ with re–entrant porous copper foams [27]. Choi et al. [28] compared the results of numerical analysis performed on the 3-dimensional ideal foam cell model (Figure 8) and the results of experimental studies with conventional and auxetic open-pore foam materials previously produced. The generated 3D model was found to be successful in explaining the deformation mechanism and mechanical behaviors of the both foams.

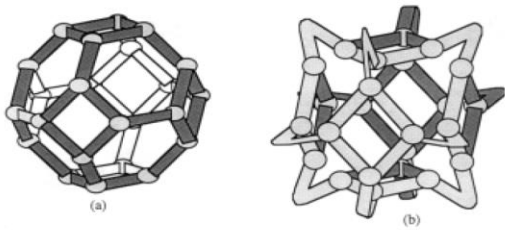

Figure 8. (a)An ideal conventional foam cell model, (b) an ideal auxetic foam cell model [28]

He et al. [29] designed a model of molecular–level structure to adapt auxetic feature to polymer materials. The proposed model is formed by placing rigid rod–shaped molecules at a distance on the fluid crystalline polymer chain with linking elements. In unloaded state, the rigid rod-like molecules oriented parallel to the chain of the polymer they are on (Figure 9(a)), come to the perpendicular position to the polymer chain by rotating around their centers with stretching (Figure 9(b)). Auxetic feature has been observed with this mechanism. In this model, the dimensions of the rigid rod molecules and the length of the fluid crystalline polymer chain are parameters that affect the auxetic feature.

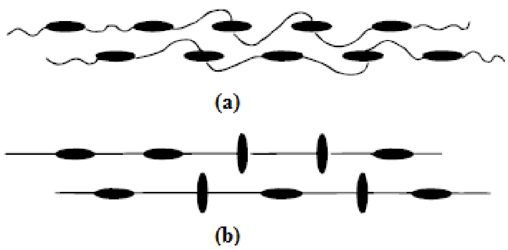

Figure 9. Fluid-crystalline polymer chain model of auxetic polymers (a) before stretching and (b) after stretching [29]

Larsen et al. [30] observed auxetic behavior with both 2–dimensional numerical model formed from arrowhead unit cells (Figure 10), generated through the numerical topology optimization method, and a prototype they produced. The prototype of this structure was fabricated through silicon surface micromachining technique. With the numerical model, the Poisson's ratio $\nu = -0.8$ was obtained. Also, for the prototype fabricated by through silicon surface micromachining technique, the Poisson's ratio $\nu = -0.92$ was obtained.

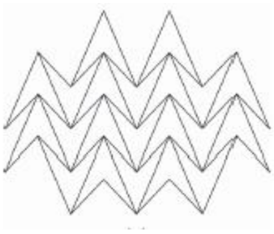

Figure 10. Structure of a unit cell with periodic arrowheads in which auxetic behavior observed [30]

Prall et al. [31] investigated the relationship between the geometric structure and mechanical properties of the 2–dimensional hexagonal asymmetric model (Figure 11) they designed with numerical and experimental studies. For this model, they obtained the Poisson’s ratio $\nu = -1$ in plane regardless of strain.

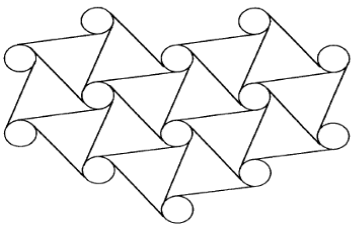

Figure 11. Auxetic 2D asymmetric hexagonal model [31]

Smith et al. [32] developed a 2–dimensional numerical model to help to evaluate the strain-dependent Poisson's ratio values and stress–strain behavior of the first polyurethane auxetic foam (Figure 12). Compared with the previously generated honeycomb model, for this model, results of numerical analysis are found to be more compatible with experimental results with auxetic foam.

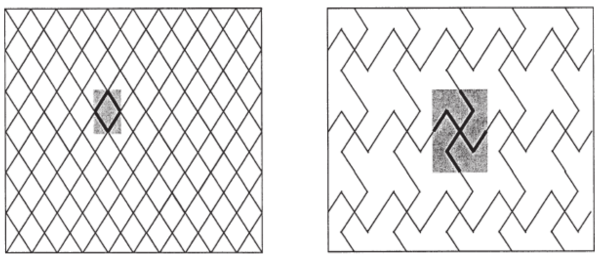

Figure 12. Model developed to explain and evaluate the experimental results of polyurethane auxetic foam [32]

Grima et al. designed 2–dimensional isotropic microstructure models consist of rigid square cells [33], rectangular cells [34] and triangular cells [35] to examine and explain the deformation mechanism of such structures as, crystalline inorganic materials [33], silica, zeolites, fluid crystalline polymers [34], the ABW and JBW zeolites [35], at which auxetic behavior was observed (Figure 13).

Tatlıer et al. examined the adaptability of the auxetic feature to fiber network structures. They investigated the effects of the structural parameters of the fiber network

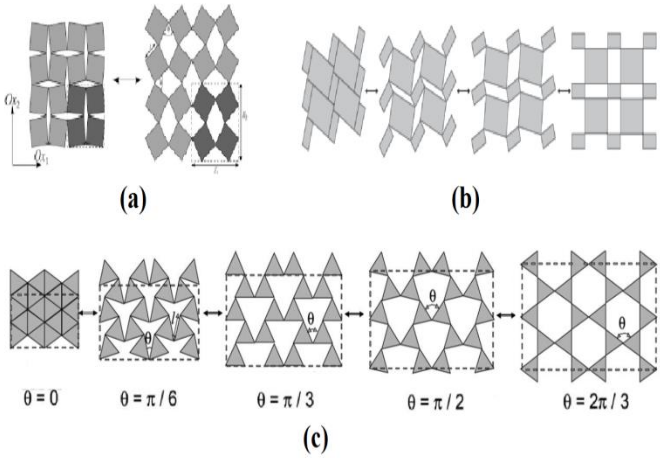

Figure 13. The auxetic microstructure models consist of (a) moving square cells, (b) rotating triangular cells and (c) rectangular cells [33–35]

and the applied axial compression, on auxetic feature with numerical method [36,37]. Also, experimental results obtained from tensile tests, applied to a pre–compressed stainless steel fiber network, provided consistency with numerical analysis’ results [36].

Since negative Poisson’s ratio has also emerged at nanostructures such as multi–layer orthorhombic arsenic [38], black phosphorus [39], single–layer graphene [40] and single–layer molybdenum disulphide (MoS_2) [41], recent studies have addressed to the researching and development of auxetic engineering nanomaterials. One of the determining features governing the mechanical properties of nanomaterials is their inherent large surface–to–volume ratio (in 3D), or their large edge–to–area ratio (in 2D), which causes surface stress [42]. Results obtained from studies on designing such auxetic nanomaterials as nanoscale metal (001) plates [43], metal [100] nanowires and nanotubes [44] have been verified this theory.

Alderson et al. [45] developed 3 different analytical molecular constructions consisting of SiO_4 tetrahedron molecules for investigating into deformation mechanisms and mechanical properties of α–cristobalite. The model incorporating tetrahedral a–axes rotation to act concurrently with both tetrahedral c–axes rotation and dilation exactly fit with the experimental results [15].

Valente et al. [46], for the first time, researched into the optical properties of micro and nanoscale auxetic plasmonic metamaterials (planar re-entrant honeycombs with Poisson ratio between –0.3 and –0.5) they fabricated by nanomembrane technology.

3. Auxetic Feature and Its Applications

The most distinguishing characteristic of auxetic structures and materials is the mechanical behaviour, which is different from the conventional engineering materials due to the negative Poisson's ratio. In addition, negative Poisson's ratio accompanies many mechanical features through auxetic structure and materials. Thus, various application areas for auxetic structures and materials have been emerged.

According to the elasticity theory, the relationship between elasticity modulus (E), shear modulus (G), volume modulus (K) and Poisson's ratio (ν) of the parameters that play a role in determining the mechanical properties of isotropic materials is like in Equation (2) and Equation (3) [38--47].

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

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

3–dimensional isotropic, linear elastic materials have a theoretical Poisson's ratio in the range of $-1 \leq \nu \leq 1$ and 2–dimensional isotropic, linear elastic materials have a theoretical Poisson's ratio in the range of $-1 \leq \nu \leq 0.5$ [48]. Considering Equation (2) and Equation (3), it can be seen that the bulk modulus value is much larger than the shear modulus value (G << K) for the materials with Poisson's ratio of 0.5 or close to this value. However, it can be seen that the value of the shear modulus for the materials with a Poisson's ratio of –1 and close to this value is much larger than the volume modulus value (K << G). For example, magnox nuclear reactor built in England in the 1950s, designed so that the reactors can move freely in order to ensure the safety of the reactor against the effects of the horizontal components of the loads (shear stress) that may occur because of earthquake, thermal expansion/contraction, etc. (Figure 14). This structure was regarded as one of the first auxetic structures, since the highest shear stress carrying capacity for the structure would be the case for $\nu = -1$ [49].

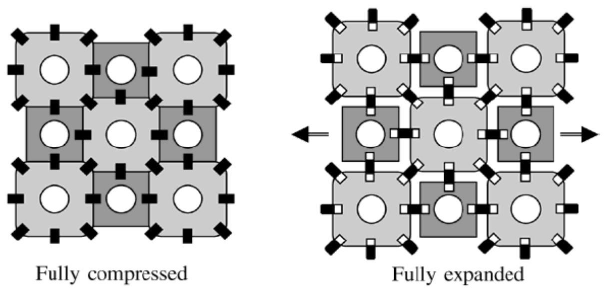

Figure 14. Structure of magnox reactor [49]

For auxetic foams, it has been demonstrated with experiments that fracture toughness is a function of the permanent volumetric compression ratio [48]. As a result of experimental works by Choi et al. [26] has shown that auxetic foam has better fracture toughness properties when compared to conventional polyurethane–polyester foam. Auxetic materials also have high crack resistance. If there is a crack in the auxetic material, so the material will expand as it stretched and close the crack [48].

The materials resists to plastic deformation due to the hardness they have. The measure of this resistance is the degree of indentation on the surface of material when the pressure applied to the material. The indentation resistance (rigidity) for isotropic materials is given in Eq. (4) [49].

$$\mathbf{H} \propto \left[\frac{\mathbf{E}}{(\mathbf{1}-\boldsymbol{\nu})^{2}}\right]^{\gamma} \tag{4}$$

Accordingly, the indentation resistance for Poisson's ratio of –1 and 1 has the highest value. However, considering that the Poisson's ratio value for isotropic materials cannot exceed 0.5, the indentation resistance will have the highest value for the Poisson's ratio values of –1 or closest. Thus, given the fact that auxetic materials tend to contraction in all directions when compressed, the density and therefore the indentation resistance at the point where the compression is applied will increase. Conversely, in non-auxetic materials, the density decreases so does the indentation resistance at the point where the pressure is applied (Figure 15) [49].

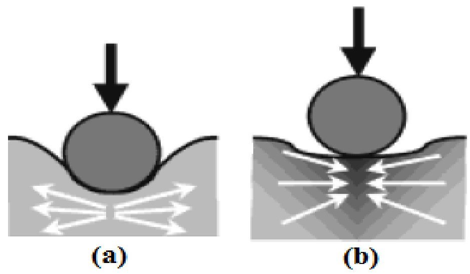

Figure 15. Indentation resistance in (a) conventional and (b) auxetic materials [49]

Smith et al. [50] observed that auxetic foams, regardless of bulk density and bulk modulus, had better indentation resistance than conventional foams. In addition, Alderson et al. [51] have found that, for lower loads, the auxetic UHMWPE (ultra-high molecular weight polyethylene) has better indentation resistance compared to conventional UHMWPE.

Compared to conventional materials, auxetic materials have superior ability to absorb energy (such as acoustic, ultrasonic, vibration, impact) [48]. Scarpa et al. observed that auxetic foams have better sound absorption [52] and better dynamic crushing resistance properties [53] than non-auxetic foams. Howell et al. [54] tested of sound absorption capability of auxetic polyurethane auxetic foam for a frequency range of 100–1600 Hz. Alderson et al. [55] conducted experimental studies for comparison of sound absorption capability of auxetic, compacted and sintered and conventional UHMWPE's at ultrasonic frequencies. It was concluded that sound absorption ability was enhanced along with degree of auxeticity. Scarpa et al. [56] studied on utilizing the auxetic feature to reduce the effects of especially human exposure to hand-arm vibration. They proposed the idea of anti-vibration gloves made from auxetic polyurethane (PU) foams. Transmissibility tests, conducted to determine the anti-vibration characteristics of auxetic polyurethane (PU) foams, also determine the foam manufacturing parameters. Within the tests, transmissibility was found to be greater than 1 in the frequency range from 10 to 31.5 Hz, while it was less than 1 for the frequencies greater than 31.5 Hz. Applicability of auxetic feature to vibration case has been satisfied with some structures reinforced with auxetic materials, like sandwich composites embedded with auxetic layers [57], anti-tetrachiral honeycomb structure with embedded metal rubber particles [58] etc. Lira et. al. [59] designed, manufactured and tested the auxetic band-graded core model in order to provide a decrease of the dynamic modal displacements and the first three natural frequencies within the admissible frequency range and reduction of the total mass (by 35%) of the aero engine fan blades.

Hook et al. [60] introduced the auxetic helical yarn, a multifilament structure consisting of a relatively thicker, low-stiffness core filament wrapped around by a narrower and stiffer one, both of which are non–auxetic. In case of longitudinal stretching, the stiffer filament straightens while the softer core wrap around it, and the structure thickens (Figure 16). Auxetic effect can be observed in this way. Sloan et al. [61] investigated into the effects of the geometric parameters of filaments on the mechanical characterization of auxetic helical yarn, experimentally. They stated that the starting wrap angle had the major effect on auxetic behavior of the structure. Besides, the diameter ratio of wrap to core filaments and the filaments' inherent Poisson's ratio were found to be related to auxetic performance. The other products, such as low modulus auxetic composites [62] and blast-proof curtains [63] also have been developed by utilizing inherently auxetic helical yarn structure.

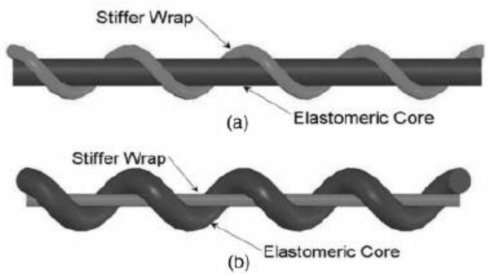

Figure 16. Structure of auxetic helical yarn in (a) unstretched, (b) stretched status [60]

Ugbolue et al. [64] proposed a novel structural model similar to the auxetic helical yarn. This structure consisted of wales of chain and inlaid yarns. The wales, low-stiffnes thicker filaments, are knitted from open loops and the high-stiffness filament is inlaid around the underlap loops (Figure 17).

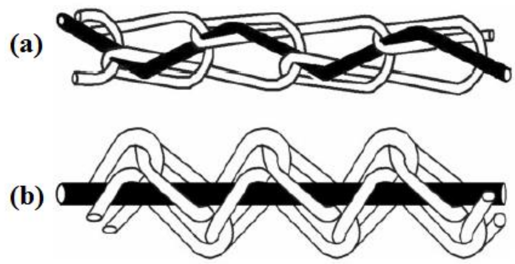

Figure 17. Structure of warp knit consisted of wales of chain and inlaid yarns (a) unstretched, (b) stretched status [64]

The auxetic feature can be employed for various filtration processes (Figure 18). When porous auxetic filtering material is stretched, it enlarges so do the pores. Thus, it can be avoided of pressure increase in the filter and efficiency degradations due to clogging of the pores of filters [65]. Also, breathable fabrics can be produced by utilizing this property of porous auxetic structures. Adjustable pore size level can facilitate air circulation. This feature can be utilized in sportswear where comfort is important [3].

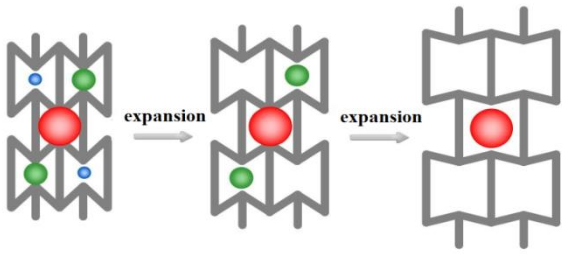

Figure 18. Smart filtering with auxetic feature [66]

Conventional structures and materials take a shape like "saddle" (anticlastic) when they are forced to bend, while auxetic structures and materials have been observed to become dome-shaped (synclastic) (Figure 19). This property can be used in the aerospace industry for the design and production of the nose cone parts and wing panels of air vehicles [49].

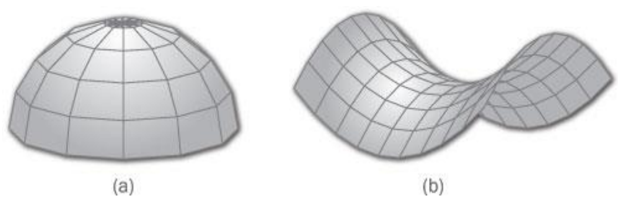

Figure 19. (a) Dome-shaped (synclastic) form of auxetic materials and (b) saddle-shaped (anticlastic) form of conventional materials [67]

Auxetic structures and materials are used in a variety of applications in the biomedical field, also. Flexible auxetic (ePTFE) vessel dilators used in surgeries like angioplasty, suture anchors, smart bandages, artificial muscles and blood vessels [49], polymeric bone stent for tubular fractures [68] are some of the examples (Figure 20).

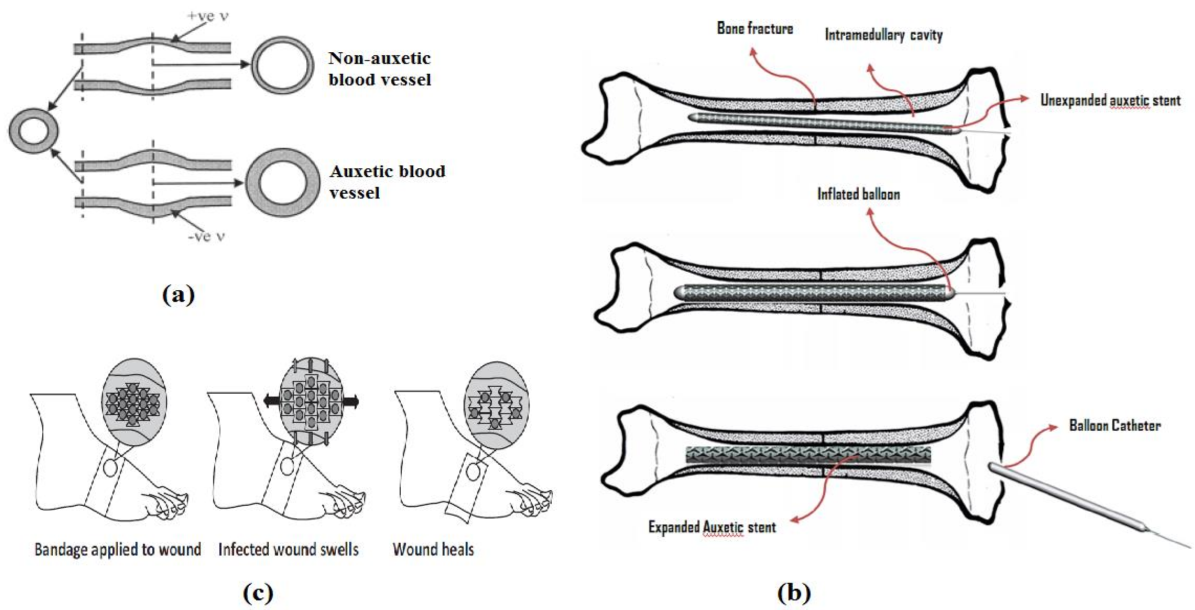

Figure 20. **(a)** Non-auxetic and auxetic blood vessels [49], **(b)** polymeric bone stent for tubular fractures [68], **(c)** smart bandages [69]

4. Discussions

The Poisson's ratio, one of the equations widely used in engineering, expresses how materials respond as deformation to the applied loadings. Materials with positive Poisson's ratio contract laterally while elongate in longitudinal direction. However, auxetic materials and structures exhibit an expansion behavior due to stretching or exhibit contraction with compression, as well. Technology, keep developing to increase quality of life, ensure and maintain life safety, needs better materials than that are today's. These materials are classified as multifunctional, smart materials. Recently, auxetic materials were included in this class. In view of the negative Poisson's ratio, primarily due to their unusual deformation mechanism and mechanical properties, auxetic structures and materials can be used as a subsidiary or alternative to conventional materials.

Compared to conventional materials with the same modulus of elasticity, some mechanical properties of auxetic materials have been observed to be superior. Some of them are;

- increased planar strain resistance [70],
- increased indentation resistance [70],
- increased shear modulus [71],
- increased fracture toughness [72],
- better energy absorption capacity and superior acoustic properties [73],
- controllable porosity-permeability [65],
- dome-shaped (synclastic) bending [74]

The auxetic feature was first discovered in nature in the early twentieth century. However, auxetic materials had not drawn attention until the first isotropic auxetic foam was produced from open-pored conventional foam by Lakes in 1987. Then, various investigations on auxetic properties were made, various auxetic structures and materials were discovered, synthesized and produced. In Available auxetic structures and materials with various application fields are demonstrated in Table 1 [48].

The auxetic feature can be observed due to the porous structure in the materials. It was reported that the auxetic feature might not be able to be encountered in materials with less than 40% porosity, except for natural auxetic structures and materials [75]. High porosity, while making the auxetic property noticeable, causes a decrease in material density and restricts the use of auxetic materials in applications where high strength is required. This limitation can be overcome by the production of reinforced composite materials with auxetic fibers or honeycomb structures, layers etc. [76].

5. Conclusions

Studies have been conducted to develop for such better materials as smart materials, multi-functional materials etc. for the future's requirements. Novel classes of materials have been achieved by such methods as modifying, reverse engineering and discovery of intrinsically different kind of materials. As being one these, an outstanding kind of material, the auxetics, despite being already discovered first in nature, hadn't drawn much attention until the first auxetic polyurethane foam was produced. By definition, the term "auxetic", which applies to the Poisson's ratio, describes a deformation behavior that exhibits expanding while stretched axially or exhibits contraction with compression in a direction, in contrast to materials with a positive Poisson's ratio. Auxetic behavior is a size-independent feature. The stimulant factor of auxetic behavior is the unique microstructure. Based on this, a variety of microstructural models have been designed to achieve the auxetic behavior. As the researches have continued, variety of outstanding properties accompanied auxetic behavior have emerged, such as higher shear modulus – lower volume modulus, increased planar strain crack resistance, higher stiffness resistance, higher fracture toughness, greater energy absorption capacity, superior acoustic properties, a controllable porosity-permeability and the ability to take a shape like dome-shape (synclastic) in case of bending, when comparing auxetic polymeric materials with those of non–auxetic with the same modulus of elasticity. However, auxetic materials have lower modulus of elasticity than their conventional counterparts due to their porous structure. For this reason, auxetic materials are not suitable enough for the applications that require strength. This limitation can be overcome by improving design of microstructures, or by adaptation of auxetic feature to the conventional structures and materials which are stiffer.

Table 1. Various applications for auxetic materials [48]

Application area	***Applications***
Industry	Reinforcement fibers, air filter, cord and rope, gaskets, fishing nets, rivets, seat belts, vehicle cushions, earphone cushions, shock absorbers and sound dampers
Aeronautics and space	Wing panels, nose cones of aircrafts, curved body parts
Protection	Helmets, bulletproof vests, knee and elbow protectors, gloves, protective clothing, vehicle bumpers, explosion-proof curtains
Biomedical	Bandage, wound pressure pad, drug release, muscle/ligament anchors, dental floss, artificial blood vessel, artificial skin, surgical sutures
Sensors and actuators	Hydrophone, miniaturized sensors, piezoelectric devices
Textiles	Functional fabrics, auxetic fibers, color-change straps and fabrics, threads, yarns

Nomenclature

E	: Modulus of elasticity
P	: Modulus of shear
H	: Hertzian pressure
K	: Bulk modulus
Δx	: Displacement in direction of x axis
Δy	: Displacement in direction of y axis
ε_x	: Strain in direction of x axis (axial strain)
ε_y	: Strain in direction of y axis (transverse strain)
ν	: Poisson's ratio
γ	: Hertzian pressure constant

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