Auxetic material in biomedical applications: a systematic review

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ABSTRACT

This study reviews and analyzes the different auxetic materials that have been developed in recent years. The search for research articles was carried out through one of the largest databases such as ScienceDirect, where 845 articles were collected, of which several filters were carried out to have a base of 386 articles. There are a variety of materials depending on their structure, composition, and industrial application, highlighting biomedical applications from tissue engineering, cell proliferation, skeletal muscle regeneration, transportation, bio-prosthesis to biomaterial. The present paper provides an overview of auxetic materials and its applications, providing a guide for designers and manufacturers of devices and accessories in any industry.

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1. INTRODUCTION

Innovative products to fulfill the new customer's requirements are increasingly demanded, for designers and manufacturers must propose solutions, develop prototypes, compare mechanical properties with design specifications, and required service conditions. For this, the choice of the material has been a priority task, considering each component and the type of material that fits its profile, so an analysis of the material used is required to determine its most important characteristics, as well as its processing where a detailed knowledge of the properties at different temperatures and loading conditions is performed. Traditional engineering materials, that is, metals, wood, ceramics, which, whether they are brittle or ductile, will tend to irreversibly deform in response to small strains, either by fracturing or flowing plastically. Softer materials such as rubbers, gels, and biological tissues can often withstand moderate amounts of strain without reaching a material limit, and so they can reversibly withstand elastic instabilities without permanent deformation, exhibiting geometric nonlinearities by bending, buckling, wrinkling, creasing, and crumpling. An example is longitudinal elastic deformation produced by a single tensile stress or a compressive stress with lateral deformation occurring simultaneously, where some interesting structures exhibit negative poisson ratios.

The auxetic property is the focus of this literature review. The negative poisson rate was also considered as a similar description because some articles relate this second concept. All fields of application, design proposals, development, and production were considered. The query was made in the digital database Science direct of all the results published during the years 2014 to 2020. The keywords used in the study were "auxetic" and "Poisson negative rate". Research, review, and patent publication articles were selected. Book chapters, lectures, and other types of reports were discarded. The focus of the review was to identify the different auxetic materials and their behavior, for this the articles related to structure, metamaterial, composite and properties were filtered.

A review of auxetic materials developed in recent years is presented in the article, classify their behavior and designs, and show the different proposed industrial applications. The rest of this document is organized. Section 1 presents the introduction. Section 2 describes research method, section 3 auxetic materials according to their properties, behaviors and identifies different types of materials. Section 4 presents the applications in the different fields of industry. Section 5 concludes the investigation.

2. PROPOSED METHOD

The systematic review was developed following three phases: planning, execution, and reporting. The planning phase included the problem identification to be investigated, proposing i) research questions and ii) search equation and keywords, taking into account the inclusion and the exclusion criteria. The execution process was performed by systematic search in selected databases, then a filter based on exclusion criterion. Finally, the results were reported in the results and discussion section.

3. METHOD

Planning and execution: systematic review began defining the area of knowledge to work; particularly, the research topics are focused on the study of material and biomaterials, specifically auxetics structures and auxetics structures biomedical applications. Based on this analysis the searching process started with the research questions definition: i) why research regarding auxetic structures and materials has increased?, ii) what are auxetic material applications?, and iii) which are the requirements to design and fabricate technologies for biomedical applications?.

Inclusion and exclusion criteria: the following criteria were considered taking into account the definition of the research problem: i) inclusion criteria: studies published between 2014 and the present, studies in English languages, publication types: research article, studies related to materials and ii) exclusion criteria: publications outside the established time range, publication types: conference and book (or chapter). The concepts that fall under auxetic materials are presented in Figure 1, identifying the area and subarea of the concept, the fundamental characteristics, and additional exclusions.

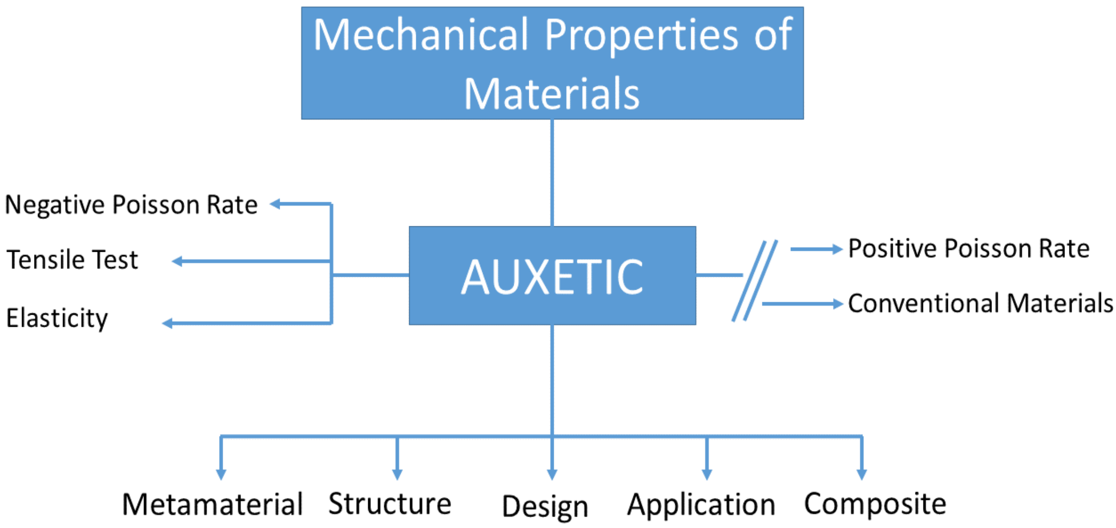

Figure 1. Conceptual mentefact of auxetic material

4. RESULTS AND DISCUSSION

The information search process was done in Science Direct databases, multiple searches carried out, establishing specific words that match with the title, abstract, or keywords of the articles; these were established in English. The keywords used in the study were “auxetic” and “Poisson negative rate”. Research, review, and patent publication articles were selected. Book chapters, lectures, and other types of reports were discarded. The focus of the review was to identify the different auxetic materials and their behavior, for this the articles related to structure, metamaterial, composite, and properties were filtered.

Auxetic material behavior: properties: engineered elastic constants such as young's modulus, poisson's ratio, mass modulus, and shear modulus are found by analytical methods [1]. Poisson's ratio is an important mechanical property that expresses the deformation patterns of materials. A positive poisson's ratio is a characteristic of the majority of materials. However, some materials show negative poisson's ratios [2]–[5], known as auxetics, which flexible structures deform, where stretching in some direction involves lateral widening, rather than lateral shrinking [6] or extending in all directions under tensile load in one direction [7]. Given this counterintuitive behavior, they are expected to possess high shear, fracture and indentation resistance, and superior damping. The lack of natural isotropic auxetics has promoted an effort to design structures that mimic this behavior [8], and have broad applications in biomedical, aeronautical and structural fields, though manufacturing is often limited to 2D [9].

Auxetic material behavior: structures: solids that exhibit a negative poisson's ratio are called auxetic materials [10], a metamaterial engineered through special microstructure design, where the mechanical properties can be adjusted over a wide range and have significant auxetic behavior [11]–[13], the property of expanding contracting transversely while being tensioned compressed in the longitudinal direction [8], [14]–[16]. Improves various yields due to its unusual property [17]–[22] isotropic [23], has been the subject of intensive research, where several different auxetic systems have been commonly based on designing special geometry of the material microstructure [24]–[32] show better indentation resistance, impact shielding capability, and enhanced toughness [33], [34], as well as various design techniques based on finite elements have been developed to achieve auxetic materials with specific effective properties, mainly in a linear deformation regime [35].

Auxetic material behavior: metamaterials: mechanical metamaterials are man-made structures with counterintuitive properties that originate from the geometry of their unit cell rather than the properties of each component, generally associated with the four elastic constants mentioned above [36], [37], spanning a wide range of anomalous systems that arise primarily from their structure rather than their composition. This unique characteristic gives them an advantage over many natural or readily available materials and makes them suitable for a variety of custom applications [4] and their unique deformation behavior [38]. These artificial composites consist of a series of periodically arranged microstructures that may not be readily found in nature [39] rationally designed that can provide extraordinary effective properties [40]. Three of these lattices (reentrant hexagon, chiral diamond, hexachiral lattice) are auxetic metamaterials, since they show a negative poisson's ratio [41], some annular cellular structures composed of graduated auxetic metamaterials were also studied [42] and were manufactured [43]. Auxetic materials and structures as a class of metamaterials have been studied and evaluated extensively from any application [44], [45], The influence of various structural and material parameters on auxetic and mechanical properties were investigated [46].

Auxetic material behavior: composites: auxetic composites are non-conventional materials [47] with a specific arrangement of composite reinforcing structures [48]. Several composites have been proposed and manufactured to mimic the improved relative static and dynamic properties of auxetics [8], meta-biomaterials [49], hybrid materials consisting of auxetic (material with negative poisson´s ratio) and non-auxetic phases [50], The elastic deformation patterns of gels with different structural and mechanical properties are depicted [51] tendons are highly anisotropic and behave in a very unconventional manner when stretched, and exhibit a negative poisson´s ratio (auxeticity) in some planes when stretched up to 2% along their length, i.e. within their normal range of motion [52], auxetic systems [53].

Auxetic material behavior: applications: auxetic materials or structures have attracted great attention due to their unprecedented mechanical behaviors in recent years. If rationally designed structures can be made from high- performance materials the specific properties, This has been exploited in diverse industrial applications and academic research: cellular solids [54], functionally graded orthotropic materials [55], stent geometries, composites, sensors and satellite components [53], shape memory polymer (SMP) periodic cellular structures [56], bone implants [57], double shear lap-joint (DSLJ) damper as an alternative method for vibration damping [58], braided composites for civil engineering applications [46], [59], polymeric fibers and yarns [60], [61], personal protection materials, such as cut resistance fabrics, bullet proof vest, helmets [62], airframe morphing [63], [64], an architectural system life form structure (LFS) with the ability to change its shape according to the environment conditions [65], fused filament fabrication (FFF) 3D printing of thermoplastic polyurethanes [66], metallic glass chiral nanolattice (MGCN) [67], nanotruss networks [68], for load-bearing biomedical applications [69], [70], functionally graded rectangular and skew plates (FGPs) for airplane wings [71], compress or stretch-twist coupled smart actuators, biomechanical devices, and micro sensors [72], [73] lightweight parts to enhance the passive safety of automobiles and reduce the fuel cost consumption [74], patient-specific medical implants [75], morphing skin [76], electromagnetic shielding [77], ceramic for harsh temperature environments [78], vibroacoustic engineering fields [79], Piezoelectric nanogenerator (PENG) [79]. Some auxetic structures have been developed from unit cells or the combination of substructures, some cases are presented in Table 1.

Table 1. Auxetic structures

Structure	Obtaining Procedure	Application	Ref.
Tessellating arrowhead motif	Locating cylinders at each junction connecting 4 tangentially attached ligaments in the arrowhead geometry	Alternative cylinder-ligament honeycomb comprising cylinders	[28]
3D re-entrant cellular structure	The structure can be represented by the unit cell	Wide range of mechanical property control	[80]
Spider's web	Add small hexagons at the centers of the cells of a hexagonal lattice and connect adjacent vertices by straight beams	Hierarchical fractal-like honeycombs	[81]
Unit cell structure	The unit cell possesses a horizontal, vertical and central symmetry	Two-dimensional morphing	[82]
Unit cell structure	Adding a narrow rib in re-entrant structure	Honeycomb-like structure	[83]
Unit cell structure	Composed by two parts that provide separate in-plane and out-of-plane deformations contributions.	Large out-of-plane deformations and morphing.	[84]
Cellular structure (AuxHex) made using Kirigami	Combination of cells with different shapes that interlock with each other. Origami only allows folding, while Kirigami includes sharp cut slits and, if needed, material removal.	Synclastic as well as anticlastic behavior	[85]
Chiral three-dimensional	Material was designed by orthogonal assembling based on chiral two-dimensional honeycomb with four ligaments	Influence of geometries on the equivalent elastic parameters	[86]
Graded structure	Improved model for banana peel varying wall thickness	Energy absorbers design for elevator cabin	[87]
In-plane graded	In-plane gradient is introduced by changing the thickness of each cell wall of honeycomb unit cell along its side length.	The crushing behavior and energy absorption capacity	[88]
Re-entrant	Deformation styles in crushing	Energy absorbing structure	[89]
Re-entrant hexagonal	Incorporation and reinforcement of the rhombic configuration to the normal reentrant hexagonal honeycomb (NRHH).	Critical buckling strength are significantly improved	[90]
Re-entrant hexagonal	Use of narrow ribs and rhombuses embedded in each cell of the NRHH	Improving the in-plane stiffness	[22]
3D double-V	Inclined beams are defined as stuffer and tensor respectively	Quasi-static collapse stress	[91]
Tetrachiral, trichiral, hexachiral	Circular loops and square loops, respectively, with inclined rods connecting the neighbor layers	Priory mechanical properties under large deformation	[92]
Hexagonal chiral structure	A composite metamaterial structure is inserted into the bulk into a chiral base structure	Attenuation of mid to low frequency elastic waves	[93]
Hierarchical	Replacing each three-edge vertex of a regular hexagonal honeycomb by a smaller hexagon	Fractal-like honeycombs with self-similar hierarchy	[94]
Quasi-hexagon structure	Integrating triangular tubes with sinewave corrugated plates	Triangular tube reinforced corrugated honeycomb	[95]
Structures	Symmetry imposition and post-processing for stress avoidance using the penalty isotropic solid microstructure method.	Morphing skin applications	[76]
Chiral	Connecting neighbor chiral honeycomb layers by inclined rods	3D metamaterial	[96]
Half re-entrant	Mirroring the horizontal series-connected parallelograms along the vertical direction	Elastic behavior	[97]
Pre-folded	Conventional honeycomb with a pre-folded trace, composed of multi-layer regular hexagonal oblique prisms	Energy absorption devices	[98]
Rectangular-shaped cells	The use of alternating bimaterial strips to form rectangular cells in triangular array	Triangular array	[99]
Re-entrant hierarchical	Replacing the cell walls of re-entrant honeycombs with regular hexagon substructure (RHH) and equilateral triangle substructure (RHT)	Exhibit an improved crushing performance, and RHT provides the highest energy absorption capacity among all specimens.	[100]
Re-entrant star-shaped	Combining the re-entrant honeycomb and the star-shaped honeycomb	Energy absorption	[101]
Star-arrowhead (SAH)	Adding DAH cells into star-shaped honeycomb (SSH)	Higher energy absorption capacity	[102]
Structures	Different diameters of elementary cells	Crashworthiness properties, wall-thickness	[103]
Variants of HC structure	The role of ligament orientation on their effective elastic, piezoelectric and dielectric properties	3-3 piezoelectric metamaterial networks	[104]
Cylindrical DAH	Composed of several layers and each layer is obtained by organized unit cells	Elastic mechanical properties	[105]
DAH	Representative DAH patterns under low velocity impact in z direction	Energy absorptions	[106]
Star-triangular (STH)	The horizontal and vertical ligaments of the star honeycombs (SH) are replaced with triangular structures	Energy absorption	[107]
Unit cell structure	Four kinds of mechanical metamaterials with unit cells of triangle and honeycomb configurations	Triangle and honeycomb (a) regular triangle, (b) regular honeycomb, (c) arrow like reentrant triangle, (d) reentrant honeycomb	[108]
Vertex-based hierarchical	Substitution of each vertex of the regular honeycomb using triangular lattices	Crushing behaviors	[109]

Regarding biomedical applications, it was found that auxetic material are applied in tissue engineering, cell proliferation, skeletal muscle regeneration, transportation, bioprothesis and biomaterial, the summary is presented in the Table 2. In the future, other unit cell designs can be used. For example in the form of a cross [110], or the inclusion of asymmetries to modify the resonance of the elements [111].

Table 2. Scaffold design

Kind	Application	Ref.	Year
Nanometric features	tissue engineering	[112]	2015
Tunable	tissue engineering and programmable flexible electronics	[113]	2020
Tubular	tissue engineering and soft robotics	[114]	2020
Laser-made 3D Auxetic Metamaterial	tissue engineering	[115]	2020
Composites	tissue engineering	[116]	2020
Tunable	cartilage repair in tissue engineering	[117]	2021
poly(D, L-lactic-co-glycolic acid) (PLGA)	cell proliferation	[118]	2016
Hybrid	cell proliferation	[119]	2016
Tunable	cellular differentiation	[120]	2017
Multi-layered, cell-laden	cell growth, tissue interaction	[121]	2017
PLGA	cell proliferation	[122]	2017
Tunable	cellular differentiation.	[123]	2018
Cell-laden auxetic	proliferation of human Schwann's cells	[124]	2020
Resorbable	skeletal muscle regeneration	[125]	2020
Cellular solids	transportation and medical industries	[126]	2021
Composite semi resorbable armored	bioprosthesis	[127]	2016
Out-of-plane auxetic nonwoven	meta-biomaterials	[128]	2020
Multi-scale and tunable	biomedical	[129]	2021

5. CONCLUSION

The growing interest in developing materials with superior properties is an important sign that this field is fertile ground for future research that can make significant theoretical and practical contributions both within and beyond materials science and engineering. This article aims to investigate the current state of development of auxetic materials. Using a systematic review methodology, a total of 845 full-text references were screened to answer the research questions "Have auxetic materials been used to date?" and "How have these materials been designed, developed and applied to date?" respectively. The results of the review showed that design studies and development of auxetic materials have increased exponentially, proposing new forms, structures, combination of materials and new applications to obtain properties superior to traditional materials, especially for biomedical applications. This suggests that the evolution of engineering materials will have auxeticity as a fundamental aspect in order to obtain superior performance.

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