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REVIEW

An Interesting Material: Auxetic Metamaterial

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ABSTRACT

Metamaterials are a class of periodic or aperiodic artificial microstructures with unusual physical properties. Their unique and controllable properties provide rich design inspiration for human technology products. Negative Poisson's ratio (NPR) metamaterial, also known as auxetic metamaterial, is a kind of mechanical metamaterial that can produce NPR effect different from common materials in nature, and has a long history of development and a wide range of application scenarios. This paper mainly reports the basic characteristics, development process and research content of auxetic metamaterial, and makes corresponding analysis and prospect, aiming to popularize its concept and explore its development potential in the field of mechanics. However, it should be noted that with the development of new technologies such as additive manufacturing and artificial intelligence, the future of auxetic metamaterial is still full of uncertainties. To this end, the design of new configurations, the coupling of new functions and the implementation of new applications may become concerns, which will make auxetic metamaterials more interesting.

KEYWORDS

Mechanical Metamaterials, Auxetic Metamaterials, Negative Poisson's Ratio (NPR), Mechanical Properties, Microstructures.

INTRODUCTION

In 1968, Veselago [**1**] conceived a novel material with negatively refractive electromagnetic phenomena at the theoretical level and put forward the concept of "left-handed material". In 1996, Pendry [**2**] designed a periodic metal wire array with a negative dielectric constant, setting a precedent for the realization of anomalous physical properties in artificial materials. In 2000, at the annual spring meeting of the American Physical Society (APS), Walser [**3**] called this artificial material, which possessed extraordinary physical properties not found in natural materials a "metamaterial". In the same year, Smith [**4**] produced "electromagnetic metamaterials" with negative refraction phenomenon, which announced to the world the possibility of designing metamaterials with novel functions. Around 2012, the study of metamaterials in mechanics gradually broke free from the constraints of electromagnetism, optics and acoustics, and became a new category called "mechanical metamaterials" [**5,6**]. In less than sixty years, metamaterials have been transformed from a hypothesis to a reality in the field of electromagnetism, and have rapidly penetrated and multiplied in other disciplines, triggering a technological revolution in new materials, with far-reaching implications for the scientific and engineering communities.

Since the concept of "metamaterial" was proposed in 2000, it has attracted widespread attention from all walks of life. Internationally, in 2008, *Materials Today* (an international journal) named the metamaterial as one of the top ten breakthroughs in 50 years of materials science [**7**]. In 2010, *Science* (an international journal) selected metamaterials as one of the top ten scientific and technological breakthroughs that will affect humanity in the 21st century [**8**]. At present, metamaterials with anomalous properties have appeared in many scientific fields, such as mechanical metamaterials with negative Poisson's ratio (NPR) effect (also called auxetic metamaterials) [**9,10**], acoustic metamaterials with negative equivalent density [**11**], information metamaterials with the ability of digital encoding [**12**], and robotic metamaterials in the field of artificial intelligence [**13**] and so on, which are attributed as shown in **Fig. 1**. These metamaterials make up for the shortcomings of conventional materials in nature and are characterized by multidisciplinary crossover and tunable properties, occupying an important position in cutting-edge science and technology. Mechanical metamaterials are a new branch derived from metamaterials that exhibit anomalous mechanical behaviours or novel mechanical properties [**5,6**], and are constantly refreshing the physical phenomena that cannot be achieved by conventional materials or structures in the field of mechanics.

Metamaterials are helping to solve the challenging problems of programmable impact energy absorption, lightweight and high-strength load-bearing, directional vibration transmission and multi-tasking, and are supporting the development of important frontier needs such as the key technologies of aerospace impact protection [**14**], medical assistive devices [**15**] and composite amours [**16**]. This review focuses on mechanical metamaterials in metamaterials, in particular auxetic metamaterials in mechanical metamaterials, highlighting their concept, history and current research progress, as well as the outlook for their future development.

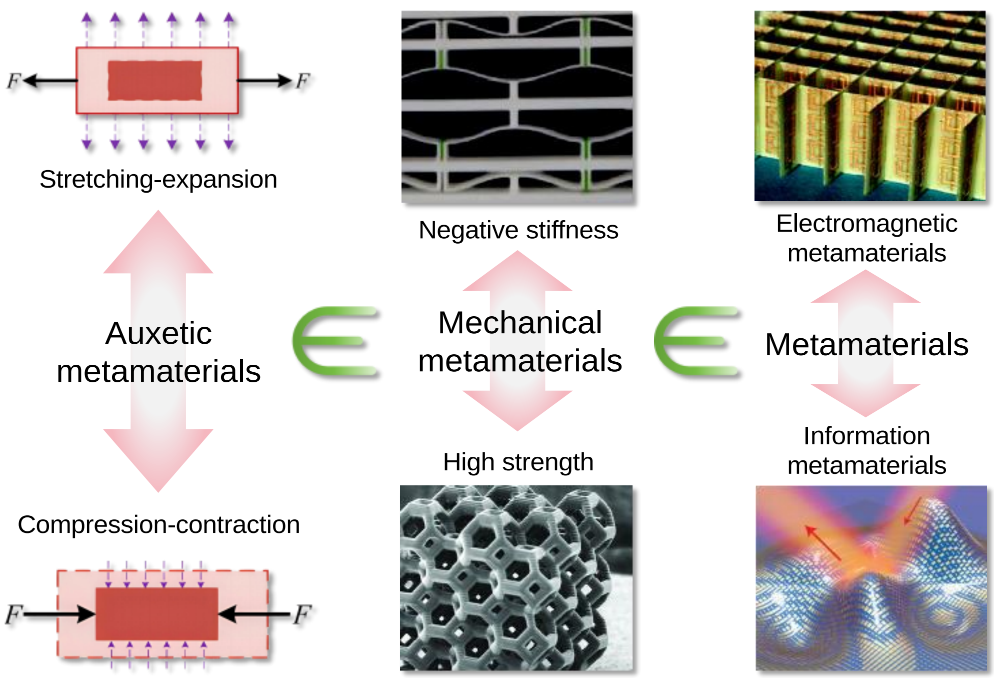


Fig. 1. Relationships between auxetic metamaterials and other metamaterials **[17,18,19,20]**.

CONCEPT OF AUXETIC METAMATERIALS

NPR metamaterials, also known as auxetic metamaterials, can generate the novel phenomena of compression-contraction and stretching-expansion [**9,10**], as shown in **Fig. 1**, which is the earliest origin and the most classical type of mechanical metamaterials. Of note, the basic mechanical behaviours of stretch, compression, bending, torsion and shear of auxetic metamaterials are controlled by the materials, components and configurations of the unit, and they have the unique properties of being designable, tunable and self-determining [**10**]. For example, shear behaviour can be induced by unit wall deformation, rotation, buckling and fracture, which can be used to design five-mode metamaterials [**21**], quasi-fluid metamaterials [**22**]. Poisson's ratio is one of the elastic constants of a material and is defined as the inverse of the ratio of the transverse strain to the axial strain when the material is subjected to unidirectional tensile or compressive stress, also known as the transverse deformation coefficient [**23**]. The Poisson's ratio of a material is usually positive, between 0 and 0.5. Therefore, NPR is unusual, which means that the transverse and axial deformation modes of the material are the same under uniaxial loading, corresponding to the compression-contraction or tension-expansion deformation characteristics, where the two characteristics are often referred to as the NPR effect or auxetic effect.

DEVELOPMENT HISTORY

Auxetic materials were introduced earlier than metamaterials and their original name is NPR materials, i.e., they are different from the common positive Poisson's ratio materials found in nature. Research on auxetic metamaterials includes the discovery of phenomena and mechanisms, the design of materials and structures, and the study of properties and applications. However, only representative studies have been selected for illustration here, based on timeline and importance.

Interpretation of the negative Poisson's ratio

As early as 1944, Love [**24**] proposed the elastic mechanics hypothesis of the existence of "negative Poisson's ratio". In 1982, Gibson *et al.* [**25**] proved theoretically and experimentally the NPR phenomenon in honeycomb. In 1987, Lakes [**26,27**] prepared NPR foam materials. Thereafter, in 1991, Evans *et al.* [**28**] renamed NPR materials as "auxetic materials" based on the tensile-expansive phenomenon. These studies have a profound influence on subsequent development. During this period, people were keen on discovering the NPR phenomenon, explaining the NPR mechanism and preparing NPR materials. In 1969, Popereka *et al.* [**29**] discovered the NPR phenomenon in ferromagnetic thin films, and subsequently NPR phenomena were reported on *α*-quartz, composite laminates, point-wire structures, face-centred cubic metallic materials and woven fabrics [**30**]. It was not until 1987 that Lakes [**26,27,31**] and others successively prepared artificial NPR polymeric and metal foams to reveal the microscopic re-entrant porous structure that causes NPR and its mechanism of realization. Later, Caddock *et al.* [**32**] even prepared auxetic porous foam materials with NPR values as high as -12. Wei *et al.* [**33**] proposed a theory of three-dimensional auxetic polymers and even at the micro-level. With the continuous updating of the NPR material library, such as laminates, crystalline materials, porous foams and polymers, the NPR phenomenon gradually came into the view of scientists. However, in the light of the new NPR phenomenon, the focus of the problem at that time was to discover, prove and prepare new materials with NPR effect.

Properties of the auxetic materials

Later, the NPR, derived from the elastic constant of the material attracted more dynamicists, which led to the mechanical properties of auxetic materials being studied extensively. As can be seen from the research trend in **Fig. 2(a)**, the development of auxetic metamaterials is currently at its peak. According to the material scale, the related studies can be divided into two categories: equivalent to homogeneous materials and considering the microscopic structure, the former only need to consider the effects and phenomena caused by the Poisson's ratio becoming negative in the mechanical equations. For example, Lipsett [**34**] carried out a basic linear elastic dynamic theoretical analysis for NPR homogeneous materials, pointing out the characteristics of free surface reflection, Rayleigh wave propagation and transverse vibration of plates and beams in this unconventional material. Lakes [**35**] carried out a study of the Saint-Venant end effect for homogeneous NPR materials, pointing out that NPR leads to faster stress decay. Homogeneous NPR materials are relatively easy to study, but many auxetic materials are not homogeneous and often have a microstructure, as shown in **Fig. 2(b)**.

For this reason, considering the effect of microscopic unit walls, Lakes *et al.* [**36**] studied the indentation resistance of conventional foams and re-entrant NPR foams, pointing out that NPR foams have higher yield strength and energy absorption, but lower stiffness. Later, they also investigated the viscoelastic behaviour, nonlinear behaviour and fracture toughness of NPR foams, and expressed the advanced ideas of NPR materials towards NPR structures [**37**]. Evans *et al.* [**38**] investigated the static and dynamic modulus of polyethylene auxetic foams, revealing rate- and strain-dependent material behaviours. Subsequently, they also carried out studies on the tensile, compression, shear and creep properties of NPR foams, and the results showed that the mechanics of NPR material under tensile and compression loading were not exactly the same, and that the static and dynamic shear modulus could increase with increasing NPR [**39,40**]. Lowe and Lowe [**41**] tested the cushioning performance of NPR foam cushions and found that the re-entrant foam performed better in controlling the maximum pressure. In a study to improve NPR materials, Scarpa *et al.* [**42**] investigated the mechanical, acoustic and electromagnetic properties of auxetic foams coated with magnetic fluids.

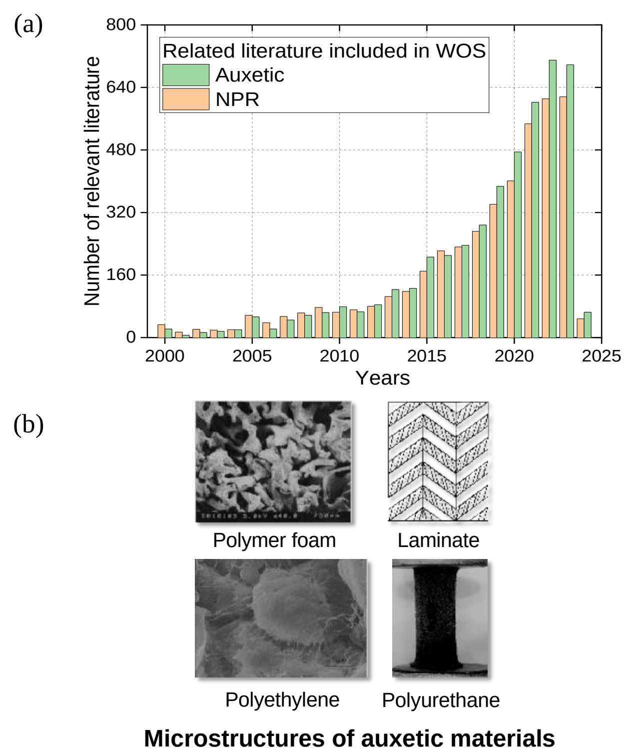


Fig. 2. State of research on auxetic materials: (a) number of relevant literatures in the last two decades, and (b) microstructures of typical NPR materials **[26,37,38,39]**.

It can be noted that in the early stages of mechanical research on auxetic materials, there have been more studies on porous foams and laminates, which are easy to manufacture and have a wider range of raw material sources.

However, there have been relatively few studies on the microstructure, engineering applications and multidisciplinary interactions of auxetic materials.

Traditional auxetic metamaterials

Later, stimulated by the re-entrant honeycomb structure and the microstructure of porous foam, the auxetic materials started to develop towards macrostructures in the form of re-entrant structures [**43**]. Around 2012, these periodic auxetic structures with artificial structures that produce peculiar mechanical phenomena were classified as mechanical metamaterials [**5,6**], which led to the rapid development of auxetic metamaterials. Initially, auxetic metamaterials appeared in the form of auxetic structures with only a single load input-output processing capability, often referred to as traditional auxetic metamaterials, which is different from the later new auxetic metamaterials with multi-step deformation [**44**], programmed control and intelligent response [**45**]. **Fig. 3** lists some typical traditional auxetic metamaterials.

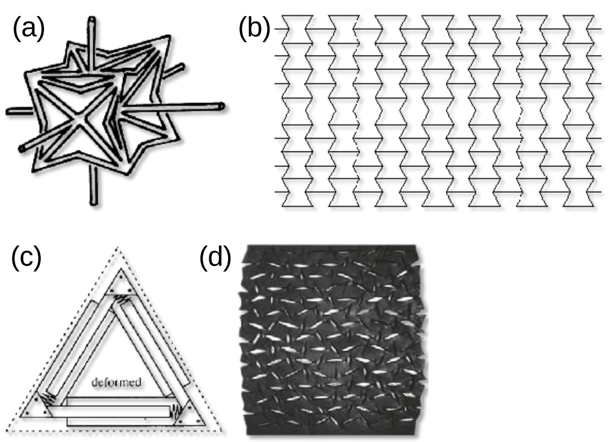


Fig. 3. Conventional auxetic metamaterials. (a) re-entrant lattice unit [**26**], (b) re-entrant hexagonal honeycomb [**25**], (c) triangular spring-loaded sleeve [**49**], and (c) perforated plate rotary block [**52**].

Regarding the re-entrant structure, Gibson *et al.* [**25**] showed in 1982 by theoretical and experimental methods that the NPR phenomenon occurs when the hexagonal honeycomb unit wall is re-entrant instead of externally convex, and this work laid the foundation for later theoretical studies on auxetic structures. Almgren [**46**] used rods, hinges, and springs to design a two-dimensional re-entrant structure with a Poisson's ratio value of -1, and pushed the two-dimensional structure into three dimensions. Masters *et al.* [**47**] established a theoretical model of the elastic constants at the macro-level for the bending, stretching and hinging deformations of the re-entrant honeycomb unit, and pointed out the influence of the three deformation mechanisms on the elastic constants. Lu *et al.* [**48**] investigated the microscopic mechanics of two-dimensional re-entrant NPR materials and proposed a macroscopic constitutive model.

Under the key ideas of compression-contraction and tension-expansion, NPR structures with non-reentrant configurations have also been developed, such as NPR truss structures proposed by Rothenburg *et al.* [**49**] based on spring sleeves, two-dimensional chiral honeycombs proposed by Prall *et al.* [**50**]. In 2005, Grima *et al.* [**51**] clearly pointed out that the auxetic behaviour is scale-independent, and the same geometric or deformation mechanism can achieve the NPR effect at macro, micro, nano and molecular levels, and proposed rotating square auxetic materials [**52**].

Conventional auxetic metamaterials are a step further from auxetic materials such as porous foams, with more controllable mechanical behaviours, more varied microscopic configurations, and easier design and preparation, and thus closer to practical applications. However, to some extent, the injection of the ideas of multi-properties, multi-functions and multi-dimensionality has been neglected.

New auxetic metamaterials

With the development of metallic and non-metallic additive manufacturing technology, one of the top ten breakthrough technologies in the world in 2013 [**53**], new complex auxetic metamaterials have been rapidly developed. Compared with traditional auxetic metamaterials, the new auxetic metamaterials have the characteristics of multiple input-output relationship, non-contact response and intelligent autonomy, which are more in line with the development trend of modern metamaterials. Early novel auxetic metamaterials are mainly innovations in deformation and load output, for example, Hassan *et al.* [**54**] prepared a new concept NPR structure using a shape memory alloy core, so it has different deformation modes at different temperatures. Schenk [**55**] proposed miura origami auxetic metamaterials, which is a fusion of auxetic metamaterials and origami metamaterials. Functional fusion of metamaterials can also be achieved by clever structural design, such as positive and negative Poisson's ratio transformations [**56**]. The relevant configurations are shown in **Fig. 4**.

In recent years, multi-modal, multi-property, and tunable auxetic metamaterials have been rapidly developed. Hu *et al.* [**57**] designed a reprogrammable 3D dilating metamaterial based on the origami strategy, and pointed out its potential applications in mechanical computing, robotics and deformable frames. Intelligent auxetic metamaterials are structural products of smart materials, and these smart materials can produce different deformation patterns under different external stimuli, thus changing the properties of the metamaterials. Based on the programming of ferromagnetic domains, Kim *et al.* [**58**] achieved mechanical metamaterials with controllable deformation modes with auxetic effect. Alapan *et al.* [**59**] prepared a substrate by embedding ferromagnetic particles in a soft material, and then oriented the domains by applying a magnetic field, allowing three-dimensional programming of metamaterials for reconstruction and auxetic behaviour. In 2024, McHale *et al.* [**60**] converted auxetic metamaterials into superhydrophobic surface materials, and Li *et al.* [**61**] designed a new 3D auxetic metamaterial with high elasticity and mechanical hysteresis based on springs, which expanded the research field of auxetic metamaterials.

Functional integration, controllable performance and intelligent response are the current and even future trends in the development of metamaterials, as evidenced by **Table 1**. In fact, as a kind of cutting-edge new materials, metamaterials have infinite possibilities, and so do the auxetic metamaterials, as demonstrated by the above studies. Obviously, smart metamaterials are not satisfied with the NPR effect, the innovation of auxetic configurations has reached a bottleneck, and the engineering applications are constantly making new demands, which leads to the need to expand and improve the traditional auxetic metamaterials. Therefore, how to explore new mechanisms, control new phenomena and realize new functions around the inherent properties of auxetic metamaterials has become an urgent issue to be considered.

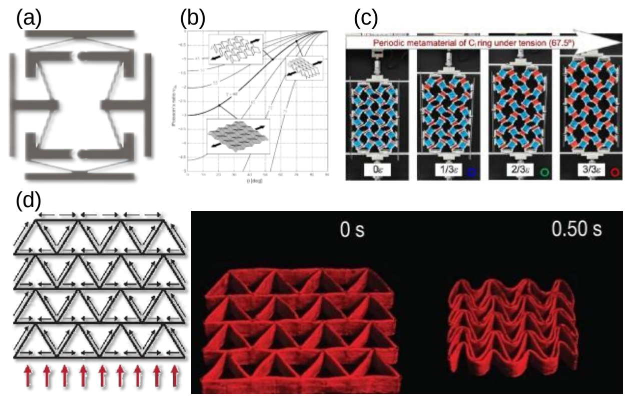
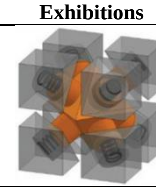
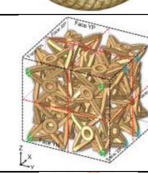
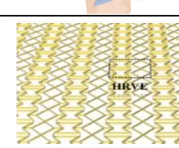
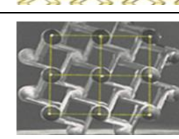
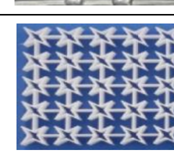


Fig. 4. New auxetic metamaterials. (a) positive and negative Poisson's ratio transformable metamaterials [**56**], (b) origami auxetic metamaterials [**55**], (c) shape-programmable auxetic metamaterials [**57**], and (d) smart auxetic metamaterials [**58**].

Table 1. The latest researches focused on auxetic metamaterials.

Types	Properties	Applications	Exhibitions
3D auxetic tiled metamaterials [**61**]	High resilience, large mechanical hysteresis, ideal isotropy, and a unique coupled auxeticity and twisting behavior	Soft robotics, mechanical actuators and dampers	
Curved re-entrant configuration [**62**]	Impact energy absorption, synclastic behaviour	Helmet liner	
Combined-auxetic-mechanism structures [**63**]	Multi-step deformation, load-bearing, and energy absorption	3D multifunctionality	
Curved re-entrant honeycomb structures [**64**]	Auxetic effect and synergistic effect	Soft strain sensors	
Architected metamaterials [**65**]	Tunable positive and negative Poisson's ratios	Programmable mechanical properties	
Body centered cubic 3D auxetic [**66**]	Stiffness, Poisson's ratio, and instability load	Morphing wings and localized impact	
Classical re-entrant honeycombs [67]	Shape recovery and energy absorption	Reusable energy absorbers	

CONCLUDING REMARKS AND OUTLOOKS

Nowadays, mechanical metamaterials are products of cutting-edge science and technology supported by modern industry, and their properties are expressed by designable artificial units that are interdisciplinary, multifunctional and tunable. According to the signal processing capability, the current research on mechanical metamaterials can be broadly classified into three categories, i.e., traditional mechanical metamaterials with load input and deformation output, new mechanical metamaterials with load input and deformation or information or waveform output, and intelligent and robotic metamaterials with (contactless) temperature or magnetic or electric or optical or acoustic field input and deformation or information or waveform or load output. Among them, the development of traditional auxetic mechanical metamaterials has entered a stable stage, remaining in structural optimization [**68**], etc. New mechanical metamaterials with the ability to process load input signals are being developed, such as mechanical computational metamaterials [**69**], Fourier transform metamaterials [**70**], etc. Intelligent and robotic metamaterials that sense multiple signal inputs and react accordingly are just beginning, e.g., coded information representation for temperature control [**71**], laser-induced realization of dynamic diagnostics [**72**], etc.

The excellent mechanical properties of auxetic metamaterials are expected to overcome some of the challenging problems in aerospace, naval, biomedical and railway engineering, and are mainly used in blast resistance, automotive crashworthiness, new energy vehicle battery protection and submarine noise reduction. However, most of these functions depend on the indentation resistance of auxetic metamaterials, and compressive loading typically induces local deformation, leading to the overall bending instability and the collapse. The predominance of two-dimensional and less three-dimensional shapes of conventional auxetic metamaterials and their controlled mechanical behaviour make them unsuitable for multi-functional, multi-tasking, programmable and complex loading requirements, highlighting the future research directions.

In addition, with regard to auxetic metamaterials, the structural optimization to achieve the extreme properties, the advanced fabrication process for complex auxetic microstructures, the material behaviour in various extreme environments, the standardization of research methods, and the intelligent material responses will be the potential research directions. Especially in the context of global sustainable development, it's an important way to develop auxetic metamaterials with recyclable and environmentally friendly materials. On this basis, more new problems will arise and need to be addressed.

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CONFLICT OF INTEREST

There are no conflicts to declare.

REFERENCES

1. Veselago, V.G.; *Soviet Physics Uspekhi*, **1968**, *10*, 509-514.
2. Pendry, J.B.; Holden, A.J.; Stewart, W.J.; Youngs, I.; *Phys. Rev. Lett.*, **1996**, *76*, 4773.
3. Walser, R.M. APS March Meeting: Session Z5.001 - Metamaterials, Minneapolis, MN, Friday morning, March 24, **2000**.
4. Smith, D.R.; Padilla, W.J.; Vier, D.C.; Nemat-Nasser, S.C.; Schultz, S.; *Phys. Rev. Lett.*, **2000**, *84*, 4184.
5. Nicolaou, Z.; Motter, A.; *Nat. Mater.*, **2012**, *11*, 608-613.
6. Wegener, M.; *Science*, **2013**, *342*, 939-940.
7. Wood, J.; *Mater. Today*, **2008**, *11*(1-2), 40-45.
8. Yu, J.J.; Xie, Y.; Pei, X.; *Journal of Mechanical Engineering*, **2018**, *54*(13), 1-14.
9. Liu, Y.; Zhao, C.; Xu, C.; Ren, J.; Zhong, J.; *Eng. Res. Express*, **2023**, *5*, 042003.
10. Zhong, J.; Zhao, C.; Liu, Y.; Ren, J.; Yang, C.; Zhang, Z.; *Fibers Polym*, **2024**, *25*, 395-406.
11. Liu, Z.; Zhang, X.; Mao, Y.; Zhu, Y.Y.; Yang, Z.Y.; Chan, C.T.; Sheng, P.; *Science*, **2000**, *289*(5485), 1734-1736.
12. Cui, T.J.; Liu, S.; Zhang, L.; *J. Mater. Chem. C*, **2017**, *5*, 3644-3668.
13. Brandenbourger, M.; Locsin, X.; Lerner, E.; Coulais, C.; *Nat. Commun.*, **2019**, *10*, 1-8.
14. Zhong, J.L.; Zhao, C.F.; Chen, C.Q.; Lai, W.L.; Wang, Q.; *Eur. J. Mech. A-Solid*, **2025**, *109*, 105454.
15. Sun, M.; Hu, X.; Tian, L.; Yang, X.; Min, L.; *Orthop. Surg.*, **2024**, *16*, 1801-1815.
16. Zhao, C.F.; Zhong, J.L.; Wang, H.X.; Liu, C.; Li, M.; Liu, H.; *Mater. Des.*, **2024**, *246*, 113295.
17. Hua, J.; Zhou, Y.; Chen, C.Q.; *Int. J. Mech. Sci.*, **2024**, *272*, 109170.
18. Zheng, X.Y.; Lee, H.; Weisgraber, T.H.; Shusteff, M.; DeOtte, J.R.; Duoss, E.B.; Kuntz, J.D.; Biener, M.M.; Ge, Q.; Jackson, J.A.; Kucheyev, S.O.; Fang, N.X.; Spadaccini, C.M.; *Science*, **2014**, *344*, 1373-1377.
19. Smith, D.R.; Pendry, J.B.; Wiltshire, M.C.; *Science*, **2004**, *305*, 788-792.
20. Ni, X.; Wong, Z.J.; Mrejen, M.; Wang, Y.; Zhang, X.; *Science*, **2015**, *349*, 1310-1314.
21. Bückmann, T.; Thiel, M.; Kadic, M.; Schittny, R.; Wegener, M.; *Nat. Commun.*, **2014**, *5*, 4130.
22. Zhang, H.K.; Kang, Z.; Wang, Y.Q.; Wu, W.J.; *Adv. Theor. Simul.*, **2020**, *3*, 1900182.
23. Zhao, C.F.; Zhou, Z.T.; Liu, X.X.; Tang, Z.R.; Zhang, K.B.;, Zhang, P.; Ren, J.; Liu, Z.L.;, Le, G.G.; Zhong, J.L.; *J. Alloys Compd.*, **2020**, *859*, 157840.
24. Love, A.E.H.; *Nature*, **1944**, *105*, 511-512.
25. Gibson, L.J.; Ashby, M.F.; Schajer, G.S.; Robertson, C.I.; Proceedings of the Royal Society of London, A. Mathematical and Physical Sciences, *Vol. 382*, 25-42, **1982**.
26. Lakes, R.S.; *Science*, **1987**, *235*, 1038-1040.
27. Lakes, R.S.; *Science*, **1987**, *238*, 551.
28. Evans, K.E.; Nkansah, M.A.; Hutchinson, I.J.; Rogers, S.C.; *Nature*, **1991**, *353*, 124-124.
29. Popereka, M.Y.; Balagurov, V.G.; *Fizika Tverdogo Tela*, **1969**, *11*(12), 3507-3513.
30. Ren, X.; Das, R.; Tran, P.; Ngo, T.D.; Xie, Y.M.; *Smart Mater. Struct.*, **2018**, *27*, 023001.

31. Friis, E.A.; Lakes, R.S.; Park, J.B.; *J. Mater. Sci.*, **1988**, *23*(12), 4406-4414.
32. Caddock, B.D.; Evans, K.E.; *J. Phys. D Appl. Phys.*, **1989**, *22*, 1877-1882.
33. Wei, G.Y.; *J. Chem. Phys.*, **1992**, *96*(4), 3226-3233.
34. Lipsett, A.W.; Beltzer, A.I.; *J. Acoust. Soc. Am.*, **1988**, *84*(6), 2179-2186.
35. Lakes, R.S.; *J. Appl. Mech.*, **1992**, *59*(4), 744-746.
36. Lakes, R.S.; Elms, K.; *J. Compos. Mater.*, **1993**, *27*(12), 1193-1202.
37. Lakes, R.S.; *Adv. Mater.*, **1993**, *5*(4), 293-296.
38. Evans, K.E.; Alderson, K.L.; *J. Mater. Sci. Let.*, **1992**, *11*(24), 1721-1724.
39. Chan, N.; Evans, K.E.; *Journal of Cellular Plastics*, **1999**, *35*(2), 130-165.
40. Chan, N.; Evans, K.E.; *Journal of Cellular Plastics*, **1999**, *35*(2), 166-183.
41. Lowe, A.; Lakes, R.S.; *Cell. Polym.*, **2000**, *19*(3), 157-167.
42. Scarpa, F.; Smith, F.C.; *J. Intell. Mater. Syst. Struct.*, **2004**, *15*(12), 973-979.
43. Lakes, R.S.; *J. Mater. Sci.*, **1991**, *26*(9), 2287-2292.
44. Meng, Z.Q.; Liu, M.C.; Yan, H.J.; Guy, M.G., Chen, C.Q.; *Sci. Adv.*, **2022**, *8*, eabn5460.
45. Liu, C.; Zhang, X.; Chang, J.; Lyu, Y.; Zhao, J.; Qiu, S.; *Front. Mater.*, **2024**, *11*, 1361408.
46. Almgren, R.F.; *J. Elast.*, **1985**, *15*, 427-430.
47. Masters, I.G.; Evans, K.E.; *Compos. Struct.*, **1996**, *35*(4), 403-422.
48. Lu, Z.X.; Zhao, Y.B.; *Journal of Beijing University of Aeronautics and Astronautics*, **2006**, *32*(05), 594-597.
49. Rothenburg, L.; Berlin, A.A.; Bathurst, R.J.; *Nature*, **1991**, *354*(6353), 470-472.
50. Prall, D.; Lakes, R.S.; *Int. J. Mech. Sci.*, **1997**, *39*(3), 305-307, 309-314.
51. Grima, J.N.; Alderson, A.; Evans, K.E.; *Phys. Status Solidi B*, **2005**, *242*, 561-575.
52. Grima, J.N.; Mizzi, L;. Azzopardi, K.M.; Gatt, R.; *Adv. Mater.*, **2016**, *28*, 385-389.
53. Hines, K.; *MIT Technology Review*, April 26th, **2013**.
54. Hassan, M.R.; Scarpa, F.; Mohammed, N.A.; Ancrenaz, Y.; ASME International Mechanical Engineering Congress and Exposition, Proceedings of the ASME Aerospace Division, 451-456, **2005**.
55. Schenk, M.; Guest, S.D.; *PNAS*, **2013**, *110*(9), 3276-3281.
56. Farzaneh, A.; Pawar, N.; Portela, C.M.; Hopkins, J.B.; *Nat. Commun.*, **2022**, *13*, 1041.
57. Hu, X.; Tan, T.; Wang, B.; Yan, Z.M.; *Nat. Commun.*, **2023**, *14*, 6709.
58. Kim, Y.; Yuk, H.; Zhao, R.R.; Chester, S.A.; Zhao, X.; *Nature*, **2018**, *558*(7709), 274-279.
59. Alapan, Y.; Karacakol, A.C.; Guzelhan, S.N.; Isik, I.; Sitti, M.; *Sci. Adv.*, **2020**, *6*(38), eabc6414.
60. McHale, G.; Alderson, A.; Armstrong, S.; Mandhani, S.; Meyari, M.; Wells, G.G.; Carter, E.; Ledesma-Aguilar, R.; Semprebon, C.; Evans, K.E.; *Small Struct.*, **2024**, *5*, 2300458.
61. Li, T.; Li, Y.; *Adv. Mater.*, **2024**, *36*(15), 2309604.
62. Mohammad, H.Z.; Mohammad, H.R.; Mohsen, M.; *Int. J. Solids Struct.*, **2025**, 113240.
63. Yang, H.M.; Yang, L.; Zheng, X.R.; Xu, S.H.; Zhang, Y.; *Int. J. Mech. Sci.*, **2025**, 109981.
64. Zhu, W.B.; Mo, X.J.; Wang, Z.; Liu, H.Q.; Chen, J.; Wang, L.; Shou, D.H.; *Chem. Eng. J.*, **2025**, 159539.
65. Yin, P.; Li, B.; Hong, J.; Jing, H.; Li, B.; Liu, H.; Chen, X.; Lu, Y.; Shao, J.; *Adv. Sci.*, **2024**, *11*, 2307279.
66. Antonio, M.C.; Alessandro, A.; Nejc, N.; *Smart Mater. Struct.*, **2025**, *34*, 015050.
67. Liu, Y.Z.; Zhao, C.F.; Xu, C.; Ren J.; *Compos. Struct.*, **2025**, *352*, 118708.
68. Zhang, J.; Xiao, M.; Gao, L.; Alú, A.; Wang, F.; *Nat. Commun.*, **2023**, *14*, 4041.
69. Mei, T.; Chen, C.Q.; *Nat. Commun.*, **2023**, *14*, 5204.
70. Lin, X.; Pan, F.; Ma, Y.; Wei, Y.; Yang, K.; Wu, Z.; Guan, J.; Ding, B.; Liu, B.; Xiang, J.; Chen, Y.; *PNAS*, **2023**, *120*(37): e2305380120.
71. Zhang, M.; Pal, A.; Zheng, Z.; Gardi, G.; Yıldız, E.; Sitti, M.; *Nat. Mater.*, **2023**, *22*, 1243-1252.
72. Kai, Y.; Dhulipala, S.L.; Sun, R.; Lem, J.; DeLima, W.; Pezeril, T.; Portela, C.M.; *Nature*, **2023**, *623*, 514-521.

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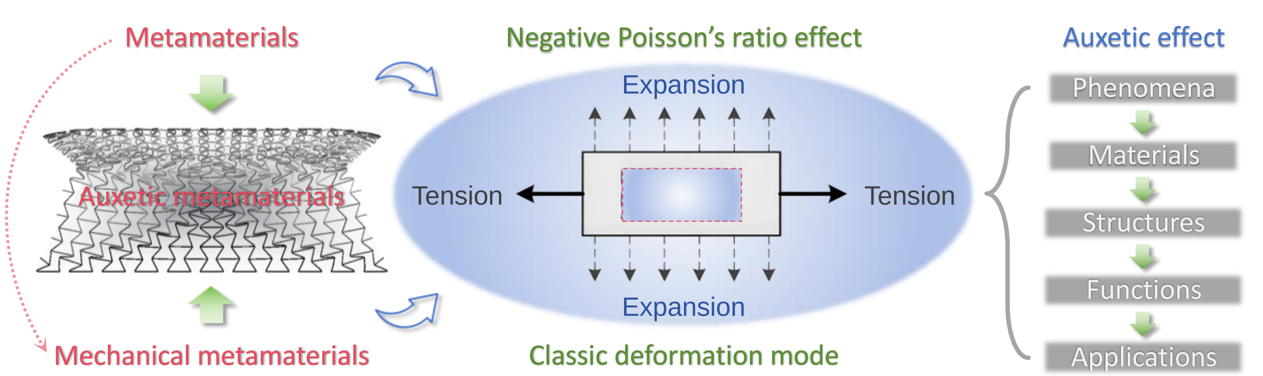
GRAPHICAL ABSTRACT



Category of auxetic metamaterials and their interesting auxetic effect.