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Literature Review: Materials with Negative Poisson's Ratios and Potential Applications to Aerospace and Defence

Q. Liu

Air Vehicles Division
Defence Science and Technology Organisation

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ABSTRACT

An auxetic material exhibits exceptional features, which are different from a conventional material. That is, the auxetic material gets fatter when it is stretched, or becomes smaller when it is compressed, because it has a negative Poisson's ratio. This report briefly reviews the latest advances in research work in auxetic materials, structural mechanisms, properties and applications, particularly in aerospace and defence.

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Executive Summary

Modern technology requires new materials of special properties. One of the reasons for interest in materials of unusual mechanical properties comes from the fact that they can be used as matrices to form composites with other materials of other required properties, e.g. electric, magnetic, etc. A new field of endeavour is to study materials exhibiting negative Poisson's ratio (NPR). These types of materials get fatter when they are stretched, or become smaller when compressed, in contrast to conventional materials (like rubber, glass, metals, etc.). Large-scale cellular structures with NPR property were first realised in 1982 in the form of two-dimensional silicone rubber or aluminium honeycombs deforming by flexure of the ribs (Gibson, et al, 1982 & 1988). In 1987, Lakes first developed the NPR polyurethane foam with re-entrant structure (Lakes, 1987a and 1987b). This polymeric foam had a Poisson's ratio of -0.7. These new types of materials were named **auxetics** by Evans (Evans, et al, 1991). "A*uxetics*" comes from the Greek word *auxetos*, meaning "that which may be increased".

Studies and experiments have demonstrated that auxetic materials (i.e., materials with NPR) can improve mechanical properties, including shear resistance, indentation resistance and fracture toughness, compared to conventional materials from which they are made. These auxetic materials also offer very good sound and vibration absorption and could have many potential applications to aerospace and defence areas.

This report briefly reviews the latest advances in research work in auxetic materials, structural mechanisms, properties and applications, particularly in aerospace and defence. Indeed, these new types of materials have a lot of potential applications to Defence such as personal protective equipments (e.g., protective clothing, body armour, bullet-proof vest, etc) and others (e.g., "smart" sensors, sonar, panels etc). Also, these materials could potentially be used to build completely new structures with special functions. However, more research work needs to be done for further understanding of these materials and applications to real components. Also, for future work it is necessary to collaborate with researchers from textile, chemical & biological areas to explore the potential applications for protecting military personnel from injury, or chemical and biological attacks.

Authors

Qianchu Liu
Air Vehicles Division

Qianchu Liu joined Defence Science and Technology Organisation (DSTO) in 1999. After completing his PhD in 1991 at the Vienna University of Technology, Austria, he held various academic positions at the University of Technology Vienna and the University of Sydney. Currently, he is currently a senior research scientist in Air Vehicles Division, DSTO. His main research interests include fatigue, fracture and corrosion of metallic materials, life extension or enhancement, repair of damaged materials and components of aircraft, material joining, surface treatments, laser processing and Non-destructive inspections.

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1. Introduction

Modern technology requires new materials of special properties. One of the reasons for interest in materials of unusual mechanical properties comes from the fact that they can be used as matrices to form composites with other materials of other required properties, e.g. electric, magnetic, etc. A new field of endeavour is to study materials exhibiting negative Poisson's ratio (NPR). Large-scale cellular structures with NPR property were first realised in 1982 in the form of two-dimensional silicone rubber or aluminium honeycombs deforming by flexure of the ribs (Gibson, et al, 1982 & 1988). In 1987, Lakes[1] first developed the NPR polyurethane foam with re-entrant structure (Lakes, 1987a and 1987b). This polymeric foam had a Poisson's ratio of -0.7. These new types of materials were named **auxetics** by Evans[2] (Evans, et al, 1991), which, in contrast to conventional materials (like rubber, glass, metals, etc.), expand transversely when pulled longitudinally and contract transversely when pushed longitudinally. "A*uxetics*" comes from the Greek word *auxetos*, meaning "that which may be increased". In this report, the term 'auxetic' will be used.

People have known about auxetic materials for over 100 years, but have not given them much attention. This type of material can be found in some rock and minerals, even animal such as the skin covering a cow's teats. To date, a wide variety of auxetic materials has been fabricated, including polymeric and metallic foams, microporous polymers, carbon fibre laminates and honeycomb structures. A typical example is a well-known synthetic polymer-polytetrafluorothylene (PTFE), which has been in use for many years. Other materials possess the NPR property such as microporous ultra high molecular weight polyethylene (UHMWPE), polypropylene (PP) (Caddock & Evans, 1989; Picklrs, et al, 1996; Alderson, et al, 2000), several types of rocks (Nur & Simmons, 1969). However, their special characteristics are largely ignored. Only up until recently, Lakes, Evans and other scientists' work has attracted more attention to these auxetic materials.

These auxetic materials are of interest due to the possibility of enhanced mechanical properties such as shear modulus, plane strain fracture toughness and indentation resistance (Lakes, 1987a; Evans, 1990). Therefore, studying these non-conventional materials is indeed important from the point of view of fundamental research and possibly practical applications, particularly in medical, aerospace and defence industries. In fact, some materials with such anomalous (i.e. NPR) properties have been used in applications such as pyrolytic graphite for thermal protection in aerospace, large single crystals of Ni_3Al in vanes for aircraft gas turbine engines, and so on.

The main objective of this report is to conduct a literature review of the research work in this field and to provide useful information for potential Defence applications of this type of material. The result of the program could lead to a new research area, which may be beneficial to the Australian Defence Force and other areas.

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[1] A professor from the University of Iowa, USA.

[2] A professor from the University of Exeter, UK.

2. Mechanism, Structure and Functions of Materials

2.1 General

It is well known that Poisson's ratio[3] is defined by the ratio of the transverse contraction strain to the longitudinal extension strain in a simple tension condition (Fung, 1968; Beer, et al, 2001), i.e.,

$$\nu = -\frac{\varepsilon_{yy}}{\varepsilon_{xx}} \tag{1}$$

Since most engineering materials become thinner in cross section when stretched, as shown in Figure 1 (a), Poisson's ratio in this situation is positive, typically around 0 to +0.5. The reason is that the inter-atomic bonds realign with deformation. However, some materials or structures contract in the transverse direction under uniaxial compression, or expand laterally when stretched, see Figure 1 (b). These materials or structures are said to have negative Poisson's ratios (NPR). A typical example is a novel foam structure or an auxetic material, where a material gets fatter when stretched. This behaviour does not contradict the classical theory of elasticity: based on the thermodynamic considerations of strain energy, the Poisson's ratios of isotropic materials can not only take negative values, but can have a range of negative values twice that of positive ones (Fung, 1968). That is, the Poisson's ratio is bounded by two theoretical limits: it must be greater than -1, and less than or equal to 0.5, i.e.,

$$-1 < \nu \leq 0.5 \tag{2}$$

The upper bound of the Poisson's ratio corresponds to rubber-like materials with an infinite bulk modulus (Lakes, 1987), while the lower bound stands for an infinite shear modulus.

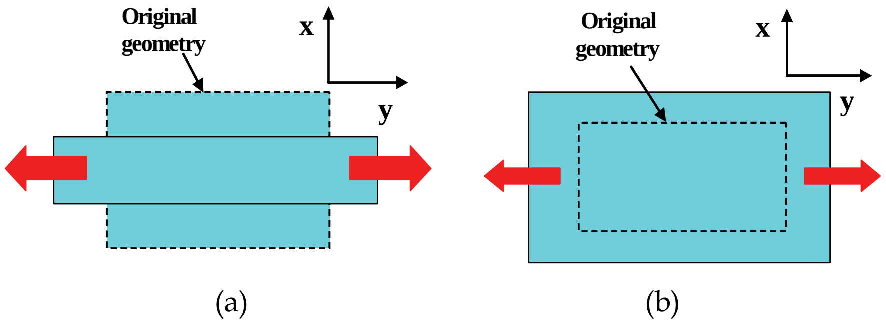

Figure 1 (a) A material deformation with positive Poisson's ratio and (b) A material deformation with negative Poisson's ratio when stretched.

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[3] Named after the French mathematician, Simeon Poisson (1781-1840).

2.2 Mechanism and Structure

As stated above, a material with NPR expands (gets fatter) when stretched, as opposed to most materials, which tend to get thinner. A typical mechanism is shown in Figure 2. When a force pulls the structure in one direction (e.g., here vertically), the structure opens up or expands in the perpendicular direction (here, horizontally), i.e., the structure gets fatter. Based on this simple mechanism, a network-like structure can be built up, as shown in Figure 3, where a 2D structure of such a material consists of a regular array of rectangular nodules connected by fibrils (Burke, 1997). Deformation of the structure is by 'hinging' of the fibrils. For the 'open' geometry, the cells elongate along the direction of stretch and contract transversely in response to stretching the network, giving a positive ν (refer to Figure 3 (a)). However, the structure is modified to adopt a re-entrant[4] geometry, Figure 3 (b), and the network now undergoes elongation both along and transverse to the direction of applied load. In other words, this is an auxetic structure.

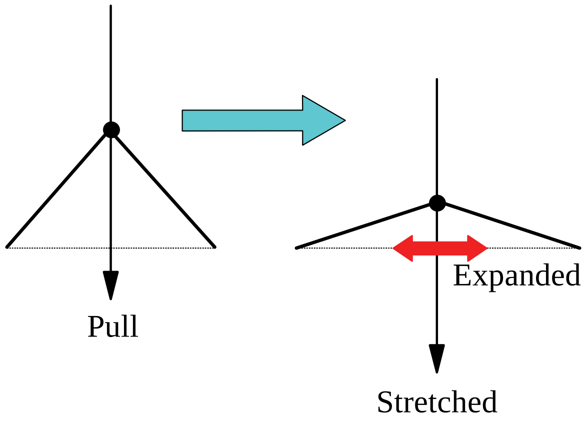

Figure 2 Schematic of basic deformation mechanism in auxetic material.

Figure 4 shows the variation in width plotted against length variation for two polypropylene (PP) fibres stretched axially. Fibre 1 is a conventional PP fibre and shows a contraction in width as it is extended, corresponding to a positive Poisson's ratio (ν). Fibre 2 is processed using extruder temperatures[5], which lead to the nodule-fibril microstructure. Its width now increases upon stretching - it displays auxetic behaviour.

For auxetic honeycombs, which are a special subset of auxetic materials, the NPR effect is due to the geometric layout of the unit cell microstructure, leading to a global stiffening effect in many mechanical properties such as in-plane indentation resistance, transverse shear modulus and bending stiffness. Figure 5 shows the deformation mechanism of the auxetic honeycombs along with conventional honeycomb structure. For a conventional hexagonal geometry (Figure 5 (a)), under the stretch in the y direction the cells elongate

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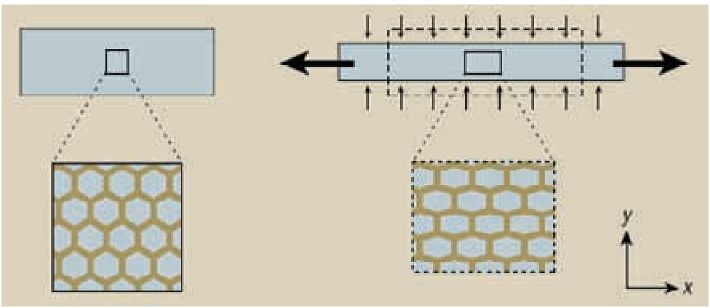
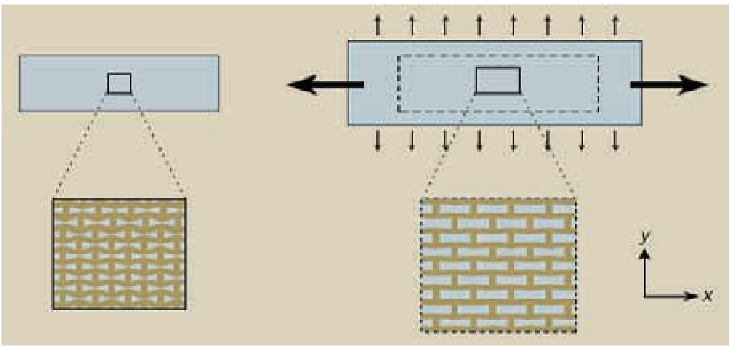
[4] Re-entrant is also named as auxetic by Evans et al.

[5] Extruder temperature is a temperature during continuous forming of a material (e.g. rubber) by forcing through a die.

along the y-axis and close up in the x direction, leading to a positive Poisson's ratio. However, for an auxetic structure, the cells undergo elongation both parallel and perpendicular to the direction of the applied load.



(a)



(b)

Figure 3 *Comparison of deformation behaviours: (a) non-auxetic and auxetic material (after Alderson, 1999; Evans & Alderson, 2000; Lakes, 2001).*

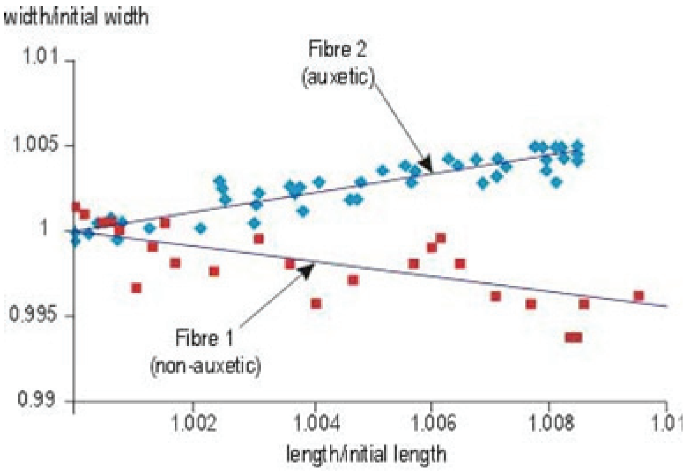
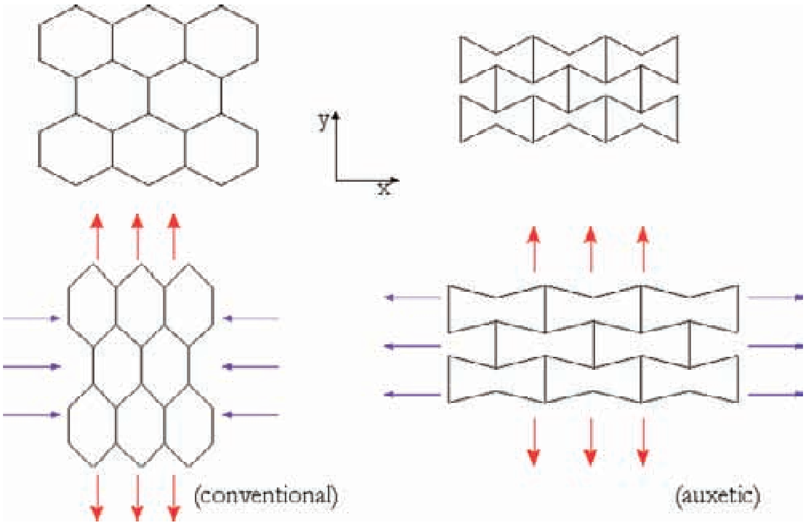


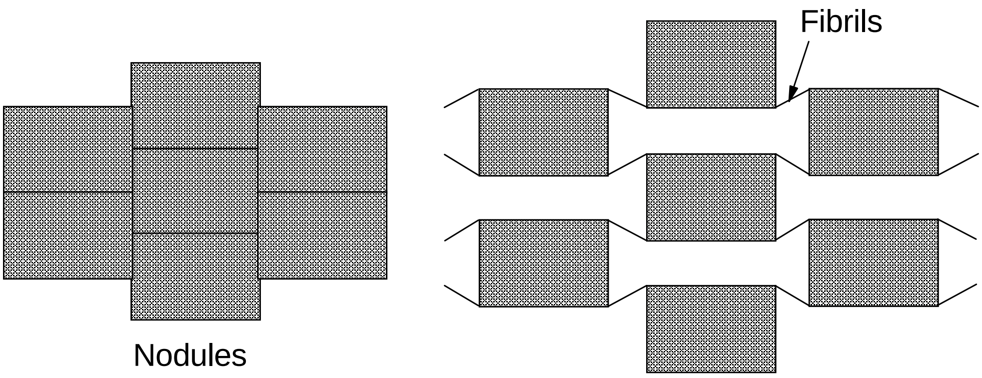
Figure 4 *Width as a function of length variations for polypropylene fibres (after Stott, et al, 2000).*



(a) (b)

Figure 5 Two-dimensional deformation mechanisms, which are subjected to loading in the y-direction: (a) Conventional honeycomb structure (b) Auxetic honeycomb structure (after Evans & Alderson, 2000a; Evans & Alderson, 2000b).

For auxetic microporous polymer, the characteristics of the microstructure can be interpreted by a simple 2D model, as shown in Figure 6. This basically consists of an interconnected network of nodules and fibrils. If a tensile load is applied, the fibrils cause lateral nodule translation, leading to a strain-dependent negative Poisson's ratio.



(a) (b)

Figure 6 Schematic of the microstructure of a typical auxetic polymer. (a) The polymer at rest and (b) The polymer at the tensile load (After Caddock & Evans, 1989; Evans & Caddock, 1989).

2.3 Classifications and Types

Materials with NPR expand in all directions when pulled in only one, therefore behaving in an opposite manner compared to conventional materials. Foams and honeycombs are a special subset of auxetic materials. The NPR effect is due to the geometric layout of the unit cell microstructure, leading to a global stiffening effect in many mechanical properties such as in-plane indentation resistance, transverse shear modulus and bending stiffness. Under compression, the increase of relative density leads also to an enhanced mechanical behaviour. Auxetic honeycomb cores can be also used effectively to manufacture curved sandwich panels because of their synclastic curvature feature due to the NPR effect.

A variety of auxetic materials and structures have been discovered, manufactured or synthesised within about the last twenty years, ranging from the molecular level, up through the microscopic, and right up to genuinely macroscopic level. Figure 7 shows that the major classes of materials (polymers, composites, metals and ceramics) now exist in auxetic form and that natural and synthetic auxetic materials are known over several orders of magnitude of stiffness, or Young's modulus, E. The detail of the review from naturally to man-made auxetic materials can be seen in Evans & Alderson’s paper (2000b).

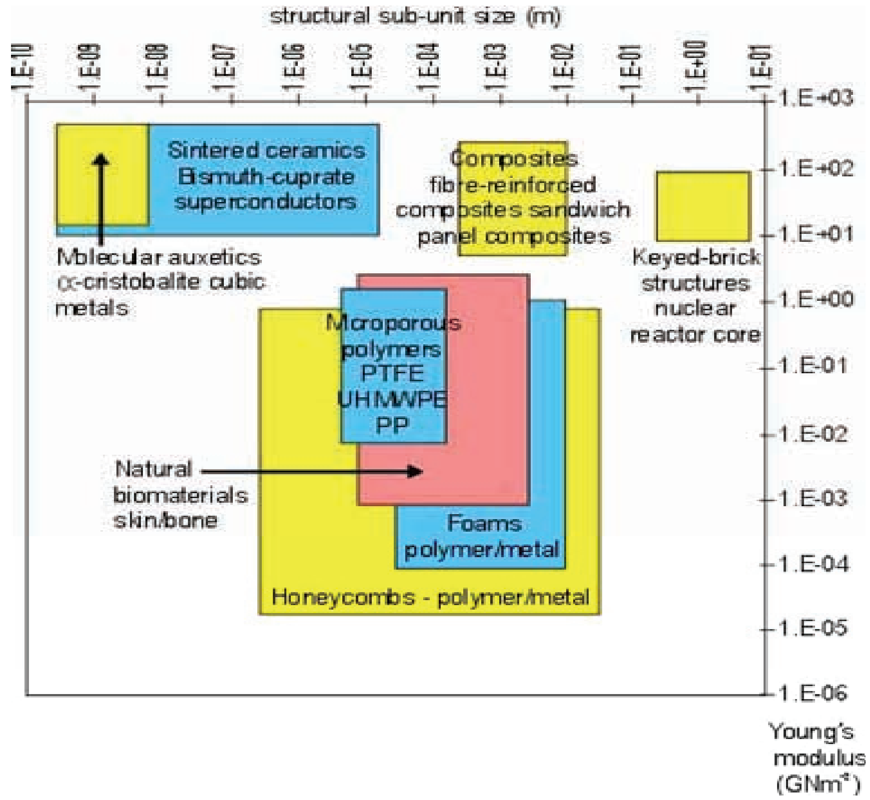


Figure 7 Classes of materials in auxetic form (after Stott, et al, 2000).

Nearly, all conventional materials, including foams, exhibit a positive Poisson's ratio. Recently, Lakes created a new type of foam material that exhibits a NPR (Lakes, 1987a & b). This material was produced by transformation of the conventional cell structure (Figure 8 (a)), so that the cell ribs protrude inward rather than outward, i.e. a re-entrant structure, as shown in Figure 8 (b). When the vertically protruding ribs are under tension, the ribs in the lateral directions will tend to move out, leading to lateral expansion. However, when compression is applied, the ribs will bend inward further, thus resulting in lateral contraction in response to axial compression. Based on this model, polymeric foams with NPRs could be made.

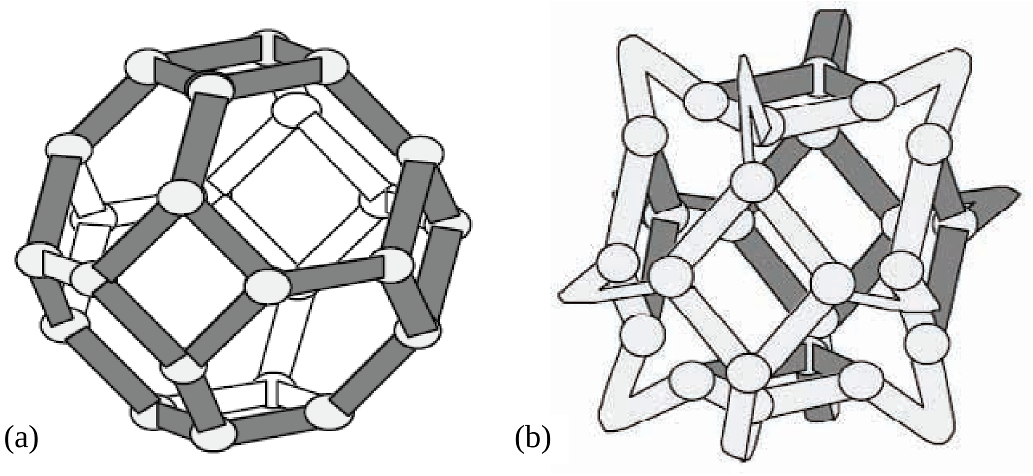


Figure 8 Idealised models for foam cells. (a) Conventional cell. (b) Re-entrant cell (after Lakes & Witt, 2002).

3. Properties of Materials

Materials with NPRs have the following special properties:
(1) High in-plane indentation resistance;
(2) Good fracture toughness;
(3) High transverse shear modulus; and,
(4) High dynamic properties.

3.1 Young's and Shear Moduli

Another special feature of auxetic materials is to have higher resistance to shear strain, caused by twisting or tearing forces. Shear resistance is particularly important in structural components such as sheets or beams in buildings, cars and aircraft. This feature can be qualitatively explained by the relations among the shear (or rigidity) modulus G, the Young's modulus E, and bulk modulus K (the inverse of the compressibility) and Poisson's ratio (ν). For isotropic material, the relations are (Fung, 1968; Beer, et al, 2001):

$$\mathrm{G} = \frac{3\mathrm{K}(1-2\nu)}{2(1+\nu)} \tag{3}$$

and

$$E = 2G(1+\nu) = 3K(1-2\nu)\,. \tag{4}$$

In conventional isotropic materials, Young's modulus (E) is at least twice the shear modulus (G). However, when the Poisson's ratio becomes negative, the two moduli become close until, at ν = -0.5, they are equal. In other words, the material becomes highly compressible but difficult to shear; its bulk modulus and Young's modulus are much less than its shear modulus. Beyond ν = -0.5, the shear modulus actually exceeds the elastic modulus (Choi & Lakes, 1992). For example, a solid with ν = -1 would be difficult to shear but easy to deform volumetrically: G>>K. However, if the Poisson's ratio approaches the positive 0.5, as in rubbery solids, the bulk modulus (K) greatly exceeds the shear modulus (G) and the material is referred to as incompressible: G<<K.

However, Young's modulus is affected by the permanent volumetric compression ratio[6] in this type of material. Generally, Young's modulus decreases monotonically with permanent volumetric compression under tension, as shown in Figure 9. The effect of volumetric compression ratio on Young's modulus under tension and compression is different, as shown in Figure 10. Under compression, Young's modulus increases with volumetric compression ratio.

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[6] The permanent volumetric compression ratio is defined by the ratio of the initial volume to the final volume.

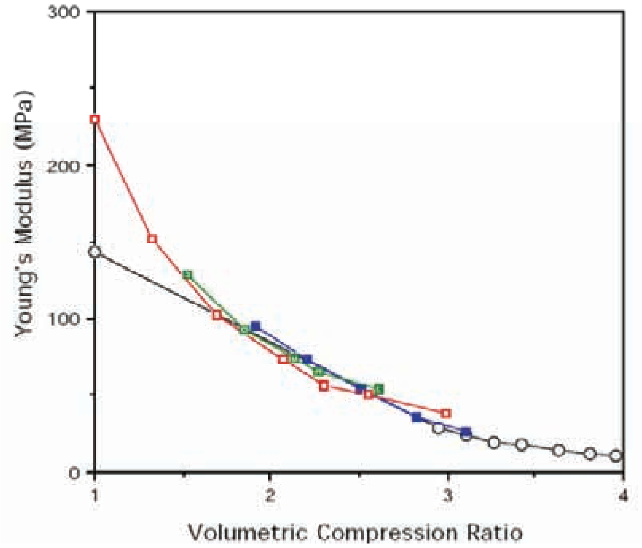


Figure 9 Young's modulus as it depends upon initial relative density and upon volumetric compression ratio; initial relative density. Solid squares - 0.1; open diamonds - 0.09; solid diamonds - 0.08; open squares - 0.04 (after Choi & Lakes, 1992).

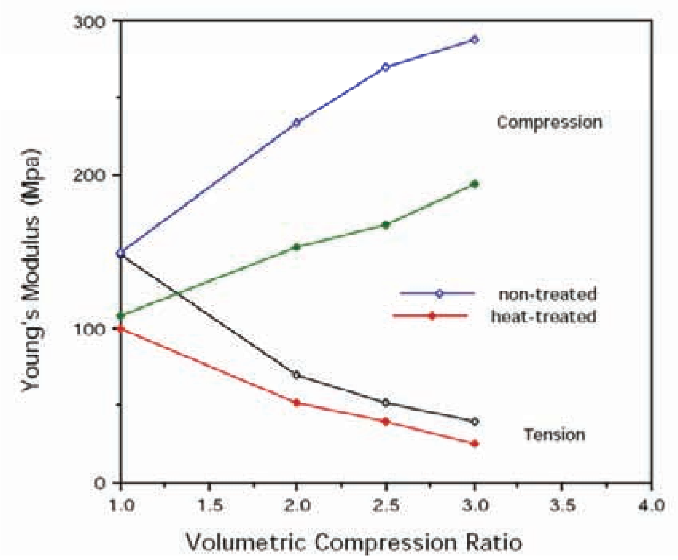


Figure 10 Young's modulus as a function of permanent volumetric compression ratio for annealed and non annealed copper foam at a strain of 0.5%; non-treated, non-annealed; heat treated, annealed (after Choi & Lakes, 1992).

3.2 Indentation Behaviours

Auxetic materials do not dent as easily as non-auxetic materials and so have more resistance to indentations. When a non-auxetic material is subjected to impact loading, the force compresses the material, and the material is compensated by spreading in directions perpendicular to and away from the direction of the impact (see arrows in Figure 11 (a)). However, when an object hits an auxetic material and compresses it in one direction, the auxetic material also contracts laterally — material 'flows' into (compresses towards) the vicinity of the impact, as shown in Figure 11 (b). This creates an area of denser material, which is more resistant to indentation. The investigation showed that re-entrant foams had higher yield strength (σ_y) and less stiffness (E) than conventional foams with the same original relative density. It has also been further proven that re-entrant foams indeed densify under indentation due to increase in shear stiffness (Smith, et al, 1999).

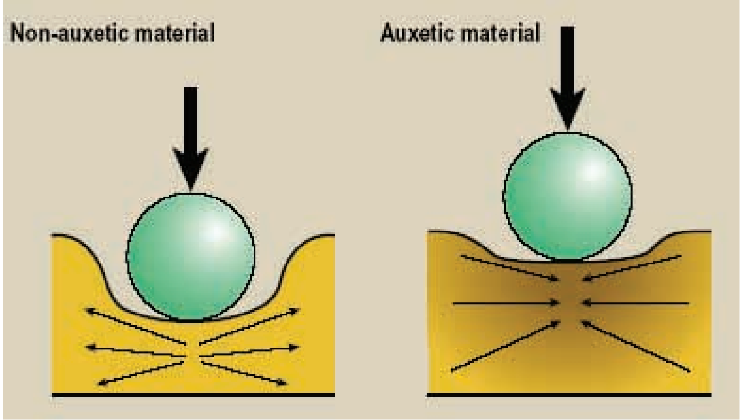


Figure 11 Schematic of deformation behaviours when both non-auxetic and auxetic materials are subject to impact compressive loading (after Alderson, 1999; Evans & Alderson, 2000).

Based on the classic elasticity theory (Timoshenko & Goodier, 1970), the indentation resistance or hardness of an isotropic material is inversely proportional to $(1-\nu^2)$, that is:

$$H \propto \left[\frac{E}{(1-\nu^2)}\right]^{\gamma} \qquad (5)$$

Where $\gamma = 1$ stands for uniform pressure distribution and $\gamma = 2/3$ is Hertzian indentation.

For a given value of E, the indentation resistance increases with negative Poisson's ratio (ν). If the ν value approaches -1, the hardness becomes infinite. Hardness has been investigated for many of the synthetic auxetic materials produced to date and enhancements have been found across the board in materials as diverse as polymeric and metallic foams (Chan & Evens, 1998; Lakes & Elms, 1993), carbon fibre composite laminates (Coenen, et al, 2001b) and microporous polymers (Alderson, et al, 2000). For example, the hardness of the auxetic microporous ultra high molecular weight polyethylene (UHMWPE) was improved by up to a factor of 2 over conventional UHMWPE (Alderson, et al, 1994 & 2000). In addition, at lower loading (e.g., 10 ~ 100N), the indentation test showed that it was more difficult to indent and the hardness was increased by up to a factor of 8 if the Poisson's ratio was changed from approximately 0 to -0.8 (Alderson, 1994; Yang, et al, 2004).

3.3 Deformation Behaviour

Very recent investigations into low velocity impact of auxetic carbon fibre laminates have also shown enhancements in energy absorption of up to a third for the first failure point (Coenen, et al, 2001a). Cold work in a re-entrant foam material has some effects due to the triaxial compression during manufacturing.

However, the annealing has an obvious effect on Young's modulus. Figure 12 shows the strain-stress relationships for conventional and re-entrant foam materials. The annealing normally reduces Young's modulus at a given volumetric compression ratio (refer to Figure 10). In other words, the material becomes less stiff. So that re-entrant copper foam is less stiff than the conventional foam from which it was derived. For the conventional copper foams the properties in tension and compression are similar. However, the re-entrant foams show dissimilar behaviours in tension and compression. In addition, in both tension and compression, the conventional and re-entrant foams exhibit a rather long plateau above the proportional limit. This behaviour is attributed to the plastic hinge formation of cell ribs (Choi & Lakes, 1992). From Figure 12, it can also be seen that the conventional foam has some strain-hardening tendency, but the re-entrant foam does not. Therefore, this material can be reasonably assumed as an elastic-perfectly plastic material in modelling.

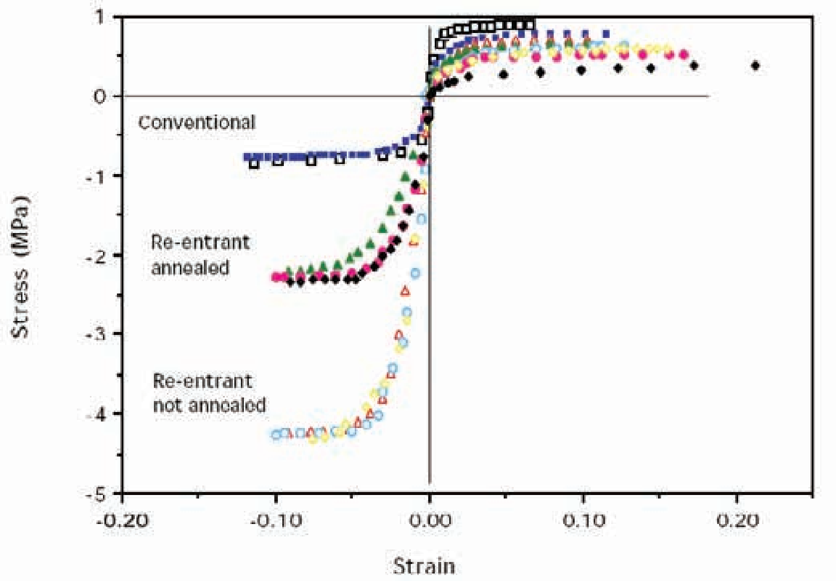


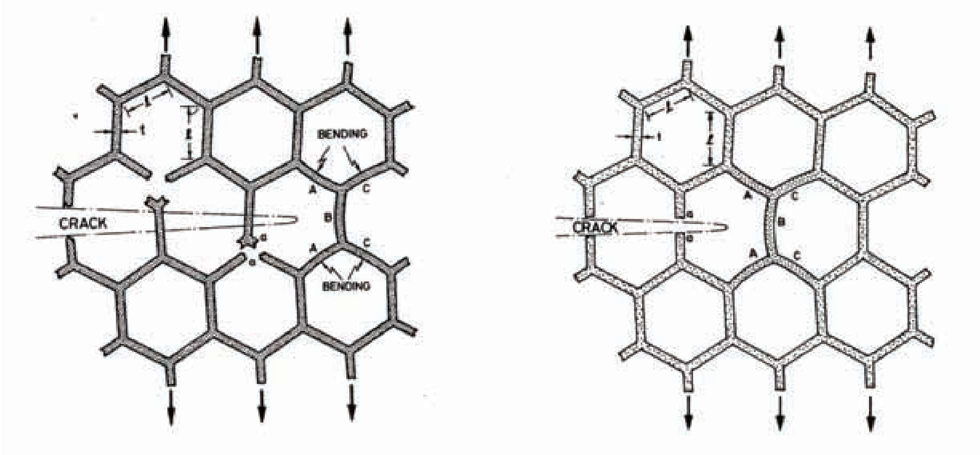
Figure 12 Stress- strain relationships for conventional and re-entrant foams. Initial relative density: 0.08. ■ Solid symbols: annealed. Open symbols: not annealed. □ Squares: conventional foam, volumetric compression 1. Δ Triangles: re-entrant foam, volumetric compression 2.0. O Circles: re-entrant foam, volumetric compression 2.5. ◊Diamonds: re-entrant foam, volumetric compression 3.0 (after Choi & lakes, 1992).

3.4 Fracture Toughness

3.4.1 Fracture Behaviour

Fracture behaviour of both conventional and re-entrant foam in tension is brittle-like. The failure occurs abruptly without necking (Gibson & Ashby, 1988; Choi & Lakes, 1992). On the scale of the dimension of the cells, a crack extends in a discrete way; each step advances the crack by one cell width (Maiti, et al, 1984). When the stress at a crack tip is high enough in the cell edge or wall, a local fracture occurs and the crack advances.

However, the crack extension can take place in two different ways (Ashby, 1983):
(1) Through the bending failure of the non-vertical cell wall or edges (Figure 13 (a)); or
(2) By the fracture of the vertical elements under a combined tension and bending moment (Figure 13 (b)).



(a) (b)

Figure 13 Schematic of crack extension manners in a cellular solid. (a) Through the bending failure mode of the non-vertical cell elements and (b) Through the tensile fracture of the vertical cell elements (after Maiti, et al, 1984).

Since the cells in conventional foams have a non-zero size, cracks in the material can not be perfectly sharp (Figure 14). The non-singular stress field at distance r (for $r > r_{tip}/2$) for a crack of 2*a* with crack tip radius, r_{tip}, is given (Ewards & Wanhill, 1986):

$$\sigma = \frac{K_I}{\sqrt{2\pi r}} + \frac{K_I}{\sqrt{2\pi r}}\left(\frac{r_{tip}}{2r}\right) \qquad (6)$$

where K_I is the stress intensity factor. The force acting on the cell rib can be obtained when the integral is over the thickness of a rib, that is,

$$F = \int_{r_{tip}/2}^{r_{tip}/2+t} \left[\frac{K_I}{\sqrt{2\pi r}} + \frac{K_I}{\sqrt{2\pi r}} \left(\frac{r_{tip}}{2r} \right) \right] r_{tip}\, dr \tag{7}$$

where t is the thickness of a rib. Using a Taylor series expansion and a first order approximation, the above equation can be expressed as:

$$F = 2.38\, K_I^* \frac{\sqrt{l}}{\sqrt{\pi}} \left(\frac{t}{l} \right) \tag{8}$$

where K_I^* is the stress intensity factor of conventional foams and *l* is the rib length (refer to Figure 13 (a)).

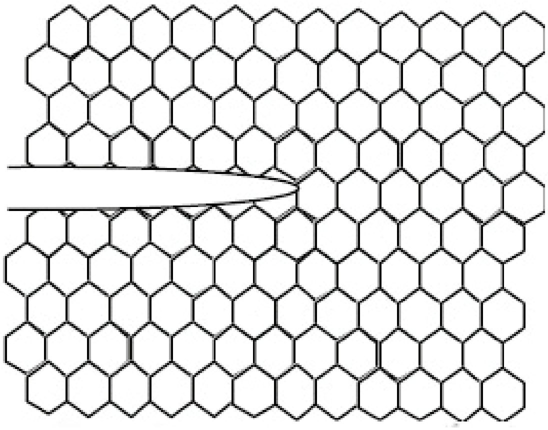


Figure 14 Structural and continuum views of a crack in a foam, suggesting the use of a non- zero crack tip radius (after Choi & Lakes, 1996).

As the tension in the cell ribs is not important in comparison to bending except for foams with very high density, the bending moment is considered as the major force applied to the cell ribs (Choi & Lakes, 1996). The stress due to the bending moment is given by

$$\sigma = 2.12 \frac{Fl}{t^3}. \tag{9}$$

Substituting Eq.(8) into the above equation, the stress is

$$\sigma = 5.05\, K_I^* \frac{1}{\sqrt{\pi}} \left(\frac{l}{t} \right)^2 . \tag{10}$$

The crack will grow if $\sigma = \sigma_f$, where σ_f is the fracture strength of the cell rib. Thus, the fracture toughness of conventional foams, K_I^*, can be calculated by

$$K_I^* = 0.20\sigma_f \sqrt{\pi l}\left(\frac{t}{l}\right)^2 . \tag{11}$$

Since $\rho^* / \rho_s \propto \alpha(t/l)^n$, therefore, the stress intensity factor of conventional foams is proportional to the normalized density, i.e.,

$$\frac{K_{IC}^*}{\sigma_f \sqrt{\pi l}} = 0.19\left(\frac{\rho^*}{\rho_s}\right) \tag{12}$$

where ρ^* is the density of a foam, ρ_s is the density of the solid from which the foam is made, α and n are constants.

For the fracture toughness of re-entrant foams, the similar formulae as equations (11) and (12) can be obtained but the special structure of this type of a material must be considered. The fracture toughness in non-conventional foams (i.e. re-entrant) can be expressed by (Choi & Lakes, 1996)

$$\frac{K_{IC}^r}{\sigma_f \sqrt{\pi l}} = 0.10\frac{\sqrt{1+\sin(\frac{\pi}{2}-\varphi)}}{1+\cos 2\varphi}\left(\frac{\rho^*}{\rho_s}\right) \tag{13}$$

where K_{IC}^* is fracture toughness of re-entrant foams and φ is rib angle related to the cell shape. The detail of the derivation of equation (12) is in the work by Choi & Lakes (1996). From Eq.(11) and Eq.(13), the ratio of the fracture toughness of re-entrant foams to that of conventional foams is given by

$$\frac{K_{IC}^r}{K_{IC}^*} = 0.53\frac{\sqrt{1+\sin(\frac{\pi}{2}-\varphi)}}{1+\cos 2\varphi} . \tag{14}$$

Since the above model is established on the simplified model, for volumetric compression ratios of 2.5 and greater, the results may be overly optimized, because re-entrant foam has a complex and irregular microstructure. Therefore, the effect of volumetric compression ratio on toughness[7] is slightly complicated, depending on the annealing state of a material (Figure 15). Compared to that of conventional foam materials, the toughness is increased by factors of 1.4, 1.5 and 1.7 with increases of volumetric compression ratio of 2.0, 2.5, 3.0, respectively (Choi & Lakes, 1992). For non-annealed materials, the toughness increases with volumetric compression ratio, but under annealed conditions, toughness increases up to volumetric compression ratio of ~2.0. Further increase in volumetric compression ratio leads to a decrease in toughness.

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[7] Toughness is here defined as the energy per unit volume to fracture (Choi & Lakes, 1992).

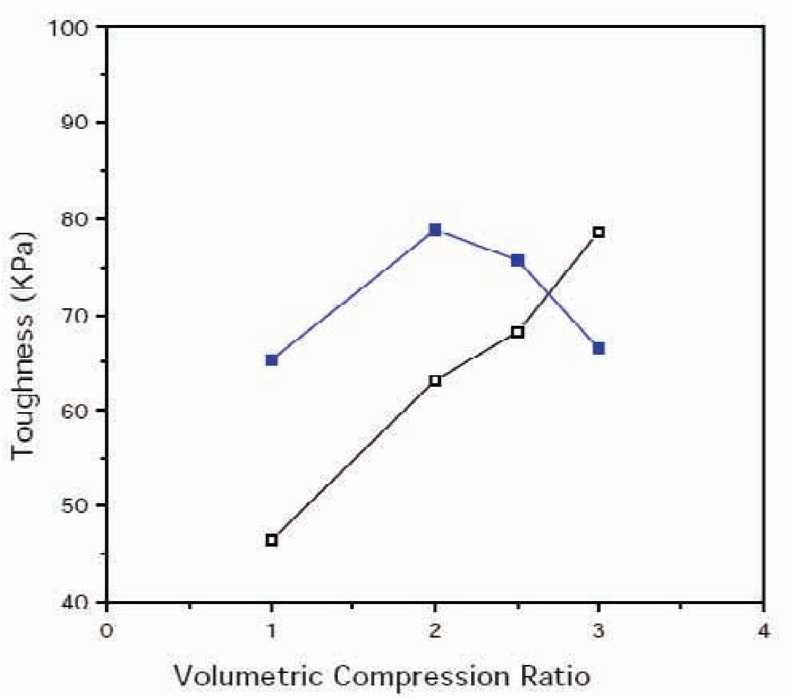


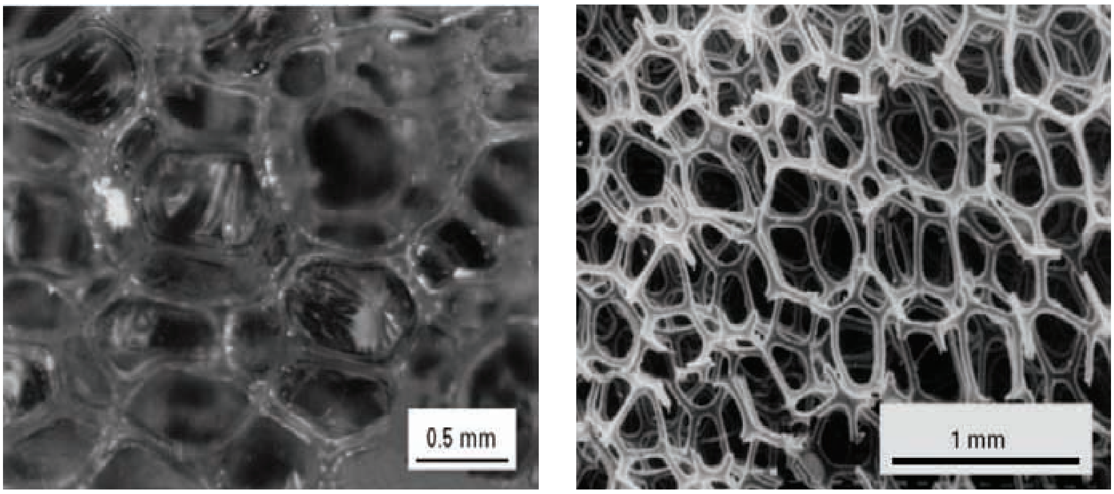
Figure 15 Toughness as a function of permanent volumetric compression of the conventional and re-entrant copper foams: open symbols, non-annealed; solid symbols, annealed (after Choi & Lakes, 1992).

3.4.2 Microstructural Morphology

The microstructure of the foam is complicated. Figure 16 shows the microstructures of the open-cell and closed-cell conventional polyester urethane foams (Chan & Evans, 1997). In the closed-cell foam, most of the cell faces are closed off by thin membranes. The porous open-cell foams allow free movement of air through-out the material when flexed. Auxetic foams have a more complex, re-entrant geometry (Figure 17 (a)). Therefore, they are much more likely to deform by hinging and flexure rather than stretching in both tension (Figure 17 (b)) and compression (Figure 17 (c)). Under tension, the cells are seen to expand transversely under a longitudinal tensile force (Chan & Evans, 1997). The reason is that auxetic foam is consisted of nodules interconnected by fibrils (Caddock & Evans, 1989). Also, conventional foams are made up of convex polyhedral cells, but auxetic foams have much more convoluted cell structures (Choi & Lakes, 1995; Chan & Evans, 1997), as shown in Figure 18. An example is the microstructure of UHMWPE is shown in Figure 19 (Alderson & Evans, 1992).

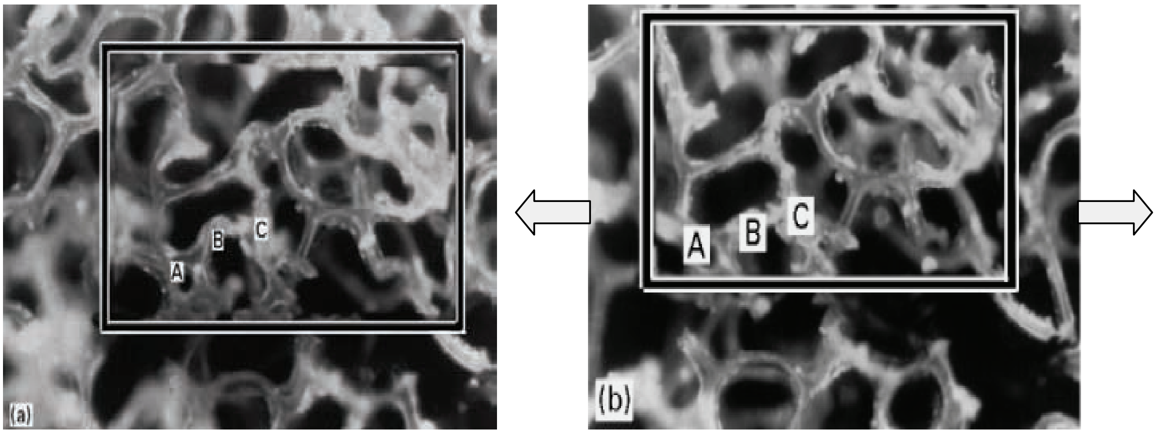
3.4.3 Crack Resistance

Compared with non-auxetic materials, auxetic materials also have other special and desirable mechanical properties. For example, if the material has a crack, when it is being pulled apart, it expands and closes up the crack. In other words, this type of material should possess more crack resistance to fracture. Also, it has high material resistance to shear strain. Shear resistance is particularly important in structural components such as sheets or beams in building, cars and aircraft.



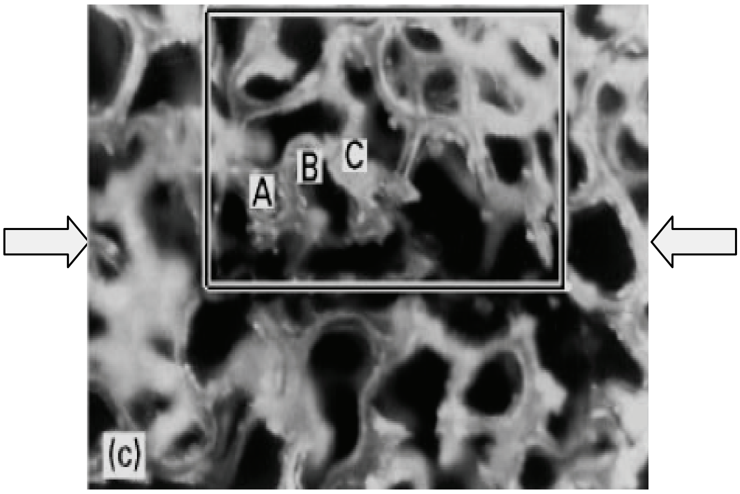
(a) *(b)*

Figure 16 Microstructures of the conventional polyester urethane foams: (a) Closed-cell (optical micrograph) and (b) Open-cell (SEM) (after Chan & Lakes, 1997).



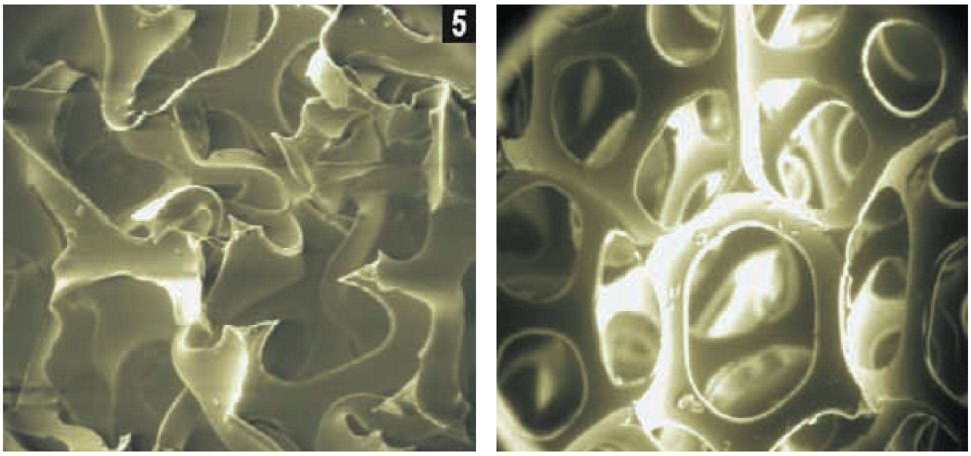
(a) *(b)*

Figure 17 (a) and (b) (after Chan & Evans, 1997)



(c)

Figure 17 Micrographs of the auxetic polyester polyurethane foams showing the elastic deformations under different type of loads. (a) Unloaded; (b) Under tension and (c) Under compression (after Chan & Evans, 1997).



(a) *(b)*

Figure 18 Open cell polymer foams: (a) non-auxetic and (b) auxetic (after Choi & Lakes, 1995; Chan & Evans, 1997).

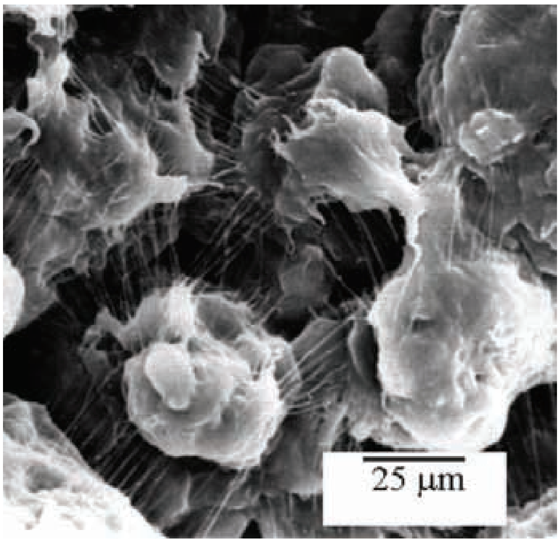


Figure 19 Micrograph of the microstructure of auxetic UHMWPE (after Alderson & Evans, 1992).

3.5 Damping and Sound Absorption

The negative Poisson's ratio foam presented shows an overall superiority regarding damping and acoustic properties compared to the original conventional foam (Scarpa, et al, 2004). Auxetic foams can have better sound absorption capacity than conventional foams at all levels of frequencies. The auxetic foams with smaller pore sizes absorb sound more efficiently than with larger pores at the frequencies above 630 Hz (Howell, et al, 1994). For example, the highest measurable ultrasonic attenuation value of auxetic microporous UHMWPE was 1.5 times the highest value of the microporous UHMWPE with positive Poisson's ratio and is more than 3 times that of conventional processed materials (Alderson, et al, 1997 and 2000). Its dynamic crushing performance is also significantly superior to normal foam, suggesting a possible use in structural integrity compliant elements.

4. Manufacturing Methods

As stated above, materials with NPRs have properties distinctive to those of conventional properties and these materials can be made from a variety of polymers or metals (Lakes, 1987; Friis, et al, 1988). There are as many different routes as there are materials. Some routes rely on transforming non-auxetic materials into auxetic foam, whereas others employ standard techniques but with novel material architecture to achieve the auxetic effect (honeycombs and fibre-reinforced composites). Still others require novel development of existing processing routes for conventional materials to produce auxetic functionality. In this literature review report, the recipe or procedure of making a material with NPR is directly taken from Lakes' and other people's published papers. This recipe can be used for educational or research purpose only. Also, the manufacture method of auxetic fibres (e.g. polypropylene-PP), which was proposed by Alderson et al (2002), is described here.

Other technical methods can also be used to manufacture materials with NPR such as re-entrant cell structure material (i.e. one of polymeric foams), but for different foam materials, the procedures or recipes are different. For example:
(1) For thermoplastic polymer foams, in the procedure a triaxial compression is applied by a factor of 1.4 to 4 in volume, followed by heating to a temperature above the softening point, then by cooling under a volumetric constraint.
(2) For metallic foams, the procedure consists of applying uniaxial compression at room temperature until the foam yields. Additional compression is then applied sequentially in each of the three-orthogonal direction until the desired volume change is achieved.

4.1 Manufacture of Auxetic Foams

4.1.1 Polymeric Foams

One way of obtaining a negative Poisson's ratio is to use a re-entrant cell structure because the properties can be controlled by processing techniques through changing the cell shape. The method used for the manufacture of auxetic samples contains four stages: (1) compression; (2) heating; (3) cooling and (4) relaxation (Lakes, 1987). To transform a conventional foam into an auxetic one using this technique requires that the foam must be simultaneously compressed in three dimensions to force the cell ribs to buckle. However, different types of polymeric foams (e.g., open or closed) require different heating time and temperatures. More details of the manufacture of the auxetic foams using this technique can be found in Chan & Evans's work (1995 & 1997). The recipe for manufacturing demonstration auxetic samples can be seen in Appendix A.

However, Lakes indicated: "Each kind of polymer foam has its own softening point and transition temperature. These instructions are for polyester and polyether polyurethane foams. For other foams the transition temperature is to be found empirically. Scott Industrial Foam with 10 to 20 pores per inch works best; it is reticulated open cell foam used for air filters. Scott foam with smaller pores also works well. Open-cell polymeric packing foams can be used; they may be more sensitive to processing temperature and humidity. Initial foam density should be low. Foam of 0.043 g/cm ^{3} [2.7 lb/ft^3] is suitable. If the initial solid volume fraction is too high, there may be insufficient space in the structure to achieve the required permanent compression. Closed-cell foam can be processed but the procedure is more difficult." A route to convert a closed-cell polymer foam to an auxetic foam has been reported (Martz, et al, 1996).

4.1.2 Metallic Foams

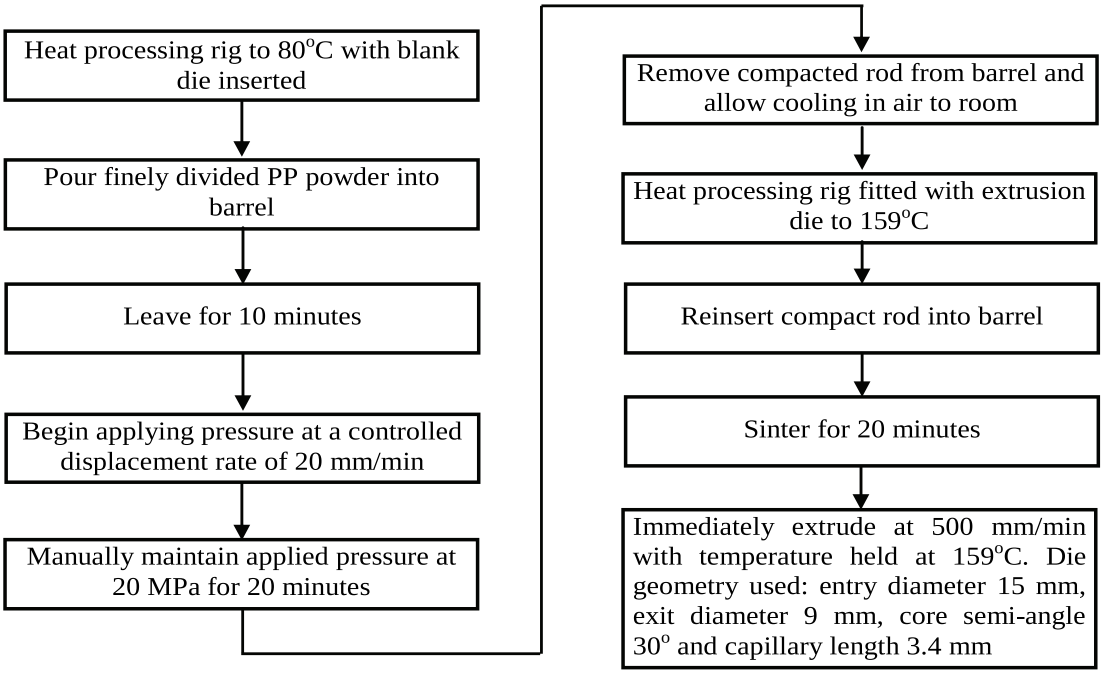
Certain types of metallic foams such as copper foam can be transformed into auxetic or re-entrant materials by successive applications of small increments of plastic deformation in three orthogonal directions. For manufacturing metallic foams with NPR, Lakes made the following comments:

"Ductile metal foams, such as those based on aluminium or copper, can be converted into NPR foams as follows. The resulting properties are given in the manuscripts referred to in the main Poisson page. Use a vice or other compression device to plastically deform the metal foam in one direction by about 5% or less. Repeat in another direction at right angles. Repeat in a third direction at right angles. Repeat the entire process until the volume of the foam is reduced by a factor between two and four. The optimum value depends on the initial density of the foam. If you have made these foams, you deserve a brass badger. This brass badger served on the battleship USS Wisconsin; it is now in the State Capitol in Madison. The nose of the badger is shiny because people like to squeeze it."

4.2 Manufacture of Auxetic Fibres and Composites

The flow chart for the process is shown in Figure 20, where the process, which was proposed by Webber et al (2000) and Alderson et al (2002 & 2005), has several stages:
(1) The first stage is to compact the polypropylene (PP) powder, which should be finely divided with an average particle size between 50 and 300 μm.
(2) In the following stage, compaction takes place within the barrel (15 mm of diameter) of the processing rig, which is fitted with a blank die, as shown in Figure 21.
(3) Then the compacted rod is reinserted into the barrel, sintered and extruded.

After these three stages, the auxetic fibres are made. This type of auxetic fibre possesses -0.22 Poisson's ratio and are less than 1 mm of the diameter, produced by a continuous process, where conventional melt spinning is used, as shown in Figure 22. The details of the process are in the paper by Alderson, et al (1995 & 2002). This is a relatively simple process to produce auxetic fibres, based on the modification of a conventional polymer processing technique. However, as Alderson indicated, the key difference is that the fibre is much thinner (only ~ 280 μm), compared with 1 mm of the conventional PP cylinders. This implies that the geometry and deformation mechanisms of the microstructure are responsible for the auxetic behaviour.



Heat processing rig to 80°C with blank die inserted

Pour finely divided PP powder into barrel

Leave for 10 minutes

Begin applying pressure at a controlled displacement rate of 20 mm/min

Manually maintain applied pressure at 20 MPa for 20 minutes

Remove compacted rod from barrel and allow cooling in air to room

Heat processing rig fitted with extrusion die to 159°C

Reinsert compact rod into barrel

Sinter for 20 minutes

Immediately extrude at 500 mm/min with temperature held at 159°C. Die geometry used: entry diameter 15 mm, exit diameter 9 mm, core semi-angle 30° and capillary length 3.4 mm

Figure 20 Flow chart of the process to produce auxetic polypropylene fibres (after Webber, et al, 2000; Alderson, et al, 2002 & 2005).

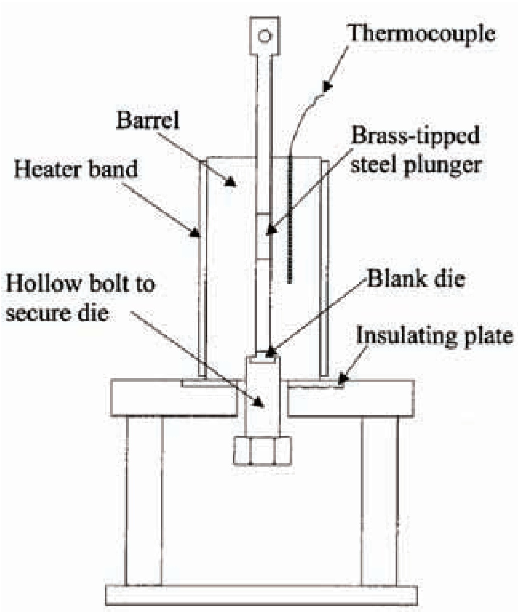


Figure 21 Schematic diagram of processing rig used to produce auxetic polypropylene fibres (Webber, et al, 2000; Alderson, et al, 2002 & 2005).

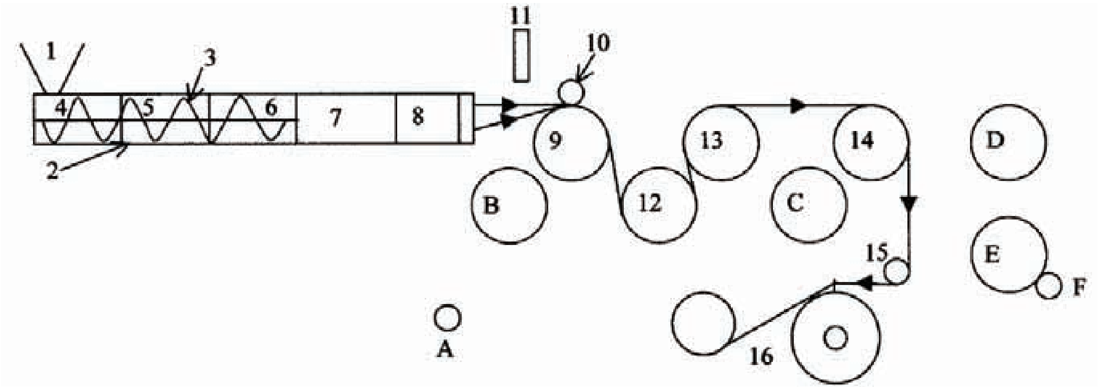


Figure 22 Schematic diagram of melt extruder used to produce auxetic polypropylene fibres (Webber, et al, 2000; Alderson, et al, 2002), where 1-polymer hopper; 2-barrel; 3-Archimedean; 4-screw feed zone; 5-screw compression zone; 6-screw metering zone; 7-cavity transfer mixing zone (adaptor zone); 8-die zone; 9-cooling roller; 10-nip roller; 11-air knife; 12, 13,14-rollers; 15-guide rail; 16-windup.

4.3 Other Methods and Examples

Auxetic microporous polymers, for example, microporous PTFE, is based on the conventional powder processing techniques of sintering (Alderson, et al, 1995) and extrusion (Neale, et al, 1995) of the polymer powder. The three steps of compaction, sintering and extrusion are necessary to achieve auxeticity because the microstructure consists of an interconnected network with nodules (particles) and fibrils, as shown in Figure 23. Feature sizes are typically at the order of 20 μm (Caddock & Evans, 1989).

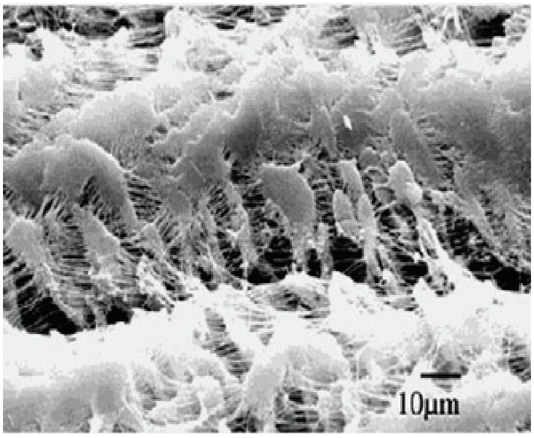


Figure 23 SEM micrograph of the auxetic expanded PTFE microstructure (after Evans, 1989; Evans & Caddock, 1989).

A novel thermal processing route, for UHMWPE used to achieve this complex microstructure, is a batch process based on conventional polymer powder processing techniques of sintering of the starting powder, which gives rise to fibrillation (Alderson & Evans, 1992). An additional initial compaction stage can be used solely to impart some degree of structural integrity to the extrudate and extrusion through a conical die, but adapted so that there is only partial melting This means the properties of the polymers can be tailored to fit the applications required and, by varying certain processing parameters, to produce everything from structural auxetic polymers, down to very auxetic, low modulus polymers (Evans & Alderson, 1992; Pickles, et al, 1996; Alderson, et al, 1997). As the UHMWPE (with a Young's modulus of ~0.2 GPa) is comparable with conventional thermoplastic polymers, therefore, this type of material is potentially suitable for use in structural applications (Evans & Alderson, 1992).

5. Potential Applications and Limitations

NPR materials offer a new direction for achieving unusual and improved mechanical performance. Studies, with support from NASA and Boeing, have demonstrated enhancements in mechanical properties for auxetic materials, including shear resistance (Choi & Lakes, 1992a & 1992b), indentation resistance (Lakes & Elms, 1993; Chan & Lakes, 1998) and fracture toughness (Choi & Lakes, 1996). The investigation of dynamic effect, partially founded by the US Office of Naval Research, has also demonstrated that sound and vibration absorption have been enhanced (Chen & lakes, 1993 & 1996). With continuous progress in the fabrication and synthesis of a wider range of such exciting materials there is huge potential for application in industrial and defence sectors.

Generally, applications of materials with NPR are mainly based on:
(i) Unusual Poisson's ratio;
(ii) Superior toughness, resilience, and shear resistance, which has been observed in these materials, and
(iii) Acoustic properties associated with the vibration of ribs in the material.

5.1 General Applications

The Poisson's ratio influences deformation kinematics in many ways, which may be useful, and it influences the distribution of stresses. For example, stress concentration factors are reduced in some situations and increased in others, when Poisson's ratio is negative. Materials with NPR can enhance the performance of piezoelectric transducers. Auxetic materials are also likely to find uses in applications such as fasteners, car bumpers, sound proofing and shin pads.

5.1.1 Sensors

Materials with NPR can advantageously be used in the design of hydrophones and other sensors (Avellanads & Swart, 1998), because the low bulk modulus makes them more sensitive to hydrostatic pressure. For example, the sensitivity is increased by almost one order of magnitude with NPR of -1, compared to a material with a ordinary Poisson’s ratio of 0.3 (refer to Eq.(5)).

5.1.2 Biomedicine

Artificial blood vessel is a typical example for the medical application. If the blood vessel is made of conventional material, it tends to undergo a decrease in wall thickness as the vessel opens up in response to a pulse of blood flowing through it (Figure 24 (a)). This could lead to rupture of the vessel with potentially catastrophic results. However, if an auxetic blood vessel is used, the wall thickness increases when a pulse of blood flows through it (Figure 24 (b)). In addition, a dilator for opening the cavity of an artery or similar vessel has been described for use in heart surgery (angioplasty) and related procedures (see Figure 25). The coronary artery is opened up by the lateral expansion of a flexible auxetic PTFE hollow rod or sheath under tension. More potential applications include surgical implants (Friis, 1992), and suture anchors or muscle/ligament anchors, where the additional benefit of a porous structure should promote bone growth (Evans & Alderson, 2000).

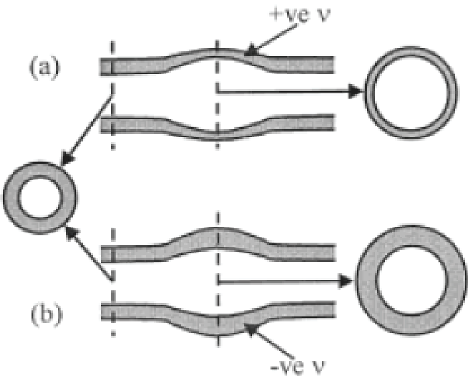


Figure 24 Schematic diagram of deformation behaviour of artificial blood vessels: (a) Conventional material and (b) Auxetic blood vessel (after Evans & Alderson, 2000).

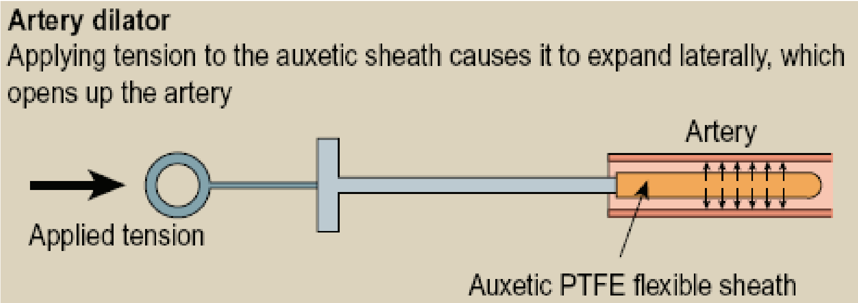
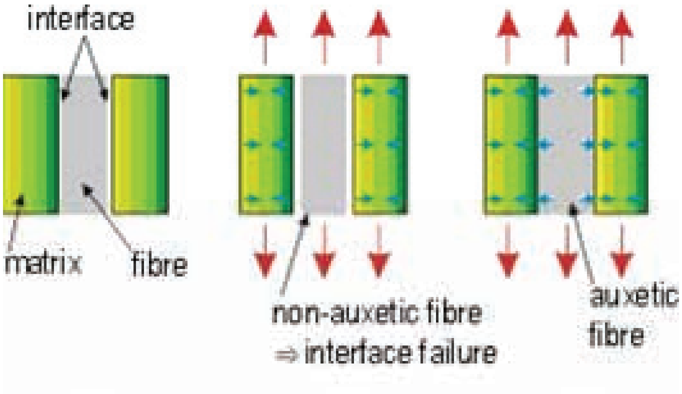


Figure 25 Dilator employing an auxetic end sheath. Insertion of finger and thumb apparatus causes the auxetic sheath to extend and expand laterally, thus opening up the surrounding vessel (after Moyers, 1992; Alderson, 1999).

5.1.3 Auxetic Fibre Reinforced Composites

It is expected that auxetic reinforcing fibres should enhance fracture resistance of composites. It is well known that the interface between matrix and fibres is the weakest part of a composite material (Figure 26 (a)). Fibre pull-out is a major failure mechanism in fibre reinforced composites. For example, a unidirectional composite loaded in tension will undergo lateral contraction of both the matrix and fibres in conventional composite materials, leading to failure at the fibre/matrix interface as shown in Figure 26 (b). However, replacing of conventional fibre by auxetic fibres could delay the pull-out of fibres, potentially helping to resist crack growth, because the possibility of maintaining the interface by careful matching of the Poisson's ratios of the matrix and fibre leading to fibre expansion during pull-out, as shown in Figure 26 (c) (Evans, 1990; Stott, et al, 2000).



(a) (b) (c)

Figure 26 Fibre pull-out in composites (after Stott, et al, 2000; Alderson, et al, 2005).

5.1.4 Structures

The counterintuitive property of auxetic materials, namely, lateral expansion (compression) under longitudinal tensile (compression) loads, is essential from the point of view of modern technology. Many applications for auxetic materials have been designed in various fields of human activity, from vascular implants, strain sensors, shock and sound absorbers, "press-fit" fasteners, gaskets and air filters, to fillings for highway joints. Materials containing inclusions of negative stiffness constitute another class of systems with unusual mechanical properties. The recent interest in such systems has its origin in their very high damping properties.

The mechanical properties of auxetic honeycombs are highly sensitive to the microstructure unit cell geometric parameters. This is a feature that could be used to design optimised sandwich structures for various applications. As an example, regular hexagonal honeycombs do not excel in sound absorption applications. Selected combinations of microstructure properties of auxetic honeycombs have been proven to increase the transmission loss factors inside cylindrical shells. Wave dispersion properties can also be custom tuned by varying the auxetic microstructure layout.

5.2 Potential Applications in Aerospace and Defence

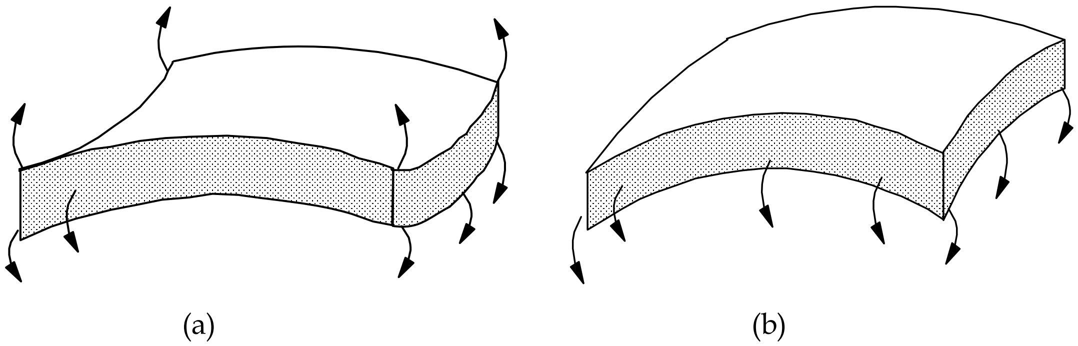
Some materials with such anomalous (i.e. NPR) properties have been used in real applications such as pyrolytic graphite with NPR of -0.21 for thermal protection in aerospace (Garber, 1963), large single crystals of Ni_3Al with a minimum Poisson's ratio of –0.18 in vanes for aircraft gas turbine engines (Baughman, et al, 1998; Nakamura, 1995), and so on. Also, the new auxetic materials and processing routes have been continually developed in recent years. Patent applications have been also reported from organisations such as Toyota, Yamaha, Mitsubishi, AlliedSignal Inc, BNFL and the US Office of Naval Research. All of these applications are related to the emerging potential of these materials.

Auxetic fibres can be employed as reinforcement, leading to enhanced impact and indentation resistance and superior energy absorption in a textile. Therefore, because of their unique properties, auxetic materials are potentially attractive for applications in protective clothing and others for military and homeland security, such as superior performance outfits, combat jackets and body armour (e.g., bullet-proof helmets, bullet-proof vests etc).

5.2.1 Smart or "Intelligent" Textiles

Defence protective clothing could also benefit from these materials, leading to higher-performance garments right across the range from thermal underwear to combat jackets and body armour.

Currently, protective materials normally need to be up to a centimetre thick, and so are very stiff, heavy and inflexible. However, body armour made from auxetic materials could give the similar protection for military personnel in the battlefield, but it would be thinner and lighter. Auxetic materials have another special property in their behaviour when bent. For example, if a sheet of any material is bent downwards, the top surface is inevitably slightly stretched. A normal material responds to this by attempting to shrink in the perpendicular direction, so the edges tend to curl upwards, leading to formation of a saddle shaped surface (anticlastic curvature), as shown in Figure 27 (a). But in auxetic materials the response is to cause the edges to curve downwards, that is convex shape (dome-like shape), which is the same direction as the bending force (Figure 27 (b). This peculiar function of auxetic materials is useful to manufacture better body armours, because auxetic body armour could give the same safeguard but thinner, lighter, and conform better to the synclastic double curvatures of the human body (Burke, 1997; McMullan, 2004). Also, the convex shapes are more appropriate than saddle shapes for sandwich panels for aircraft or automobiles (Lakes, 1987 & 1993b).



(a) (b)

Figure 27 Bending behaviours of (a) Curvature behaviours in non-auxetic and (b) auxetic (double curvature-convex shape) (after Lakes, 1987; Evans, 1990; Cherfas, 1990).

5.2.2 Bullet-Proof Helmets and Vests

Another promising application area is using auxetic polymers to make bullet-proof helmets or vests more resilient to knocks and shrapnel. When an auxetic helmet suffers an impact from one direction, material should flow in from other directions to compensate for the impact. Therefore, head injuries may be prevented or be less severe. The Defence Clothing and Textile Agency (DCTA) in Colchester, which is responsible for research into high-tech clothing for the military, has been looking into the use of auxetic textiles for military purposes. But, there is still a lot to be learnt and it is not clear what would happen under a high-speed impact such as a bullet (Burke, 1997). However, if the research work on this issue were successful, it would open up a massive market in the world. For example, the UK alone has a need for half a million helmets (Burke, 1997).

Mitsubishi has patented a 'narrow passage moving body with highly efficient movement' — in other words a bullet — in which one component is made of an auxetic material so that the overall object has a Poisson's ratio of zero (Figure 28). In this case the movement of the projectile down a barrel, for example, is helped because the sideways expansion arising from the thrusting force is reduced. Auxetic materials have also been identified as candidate materials for use in electromagnetic launcher technology to propel such projectiles. And the intended recipient of the projectile might benefit from a bullet-proof vest and other personal protective equipment formed from auxetic material because of their impact property enhancements.

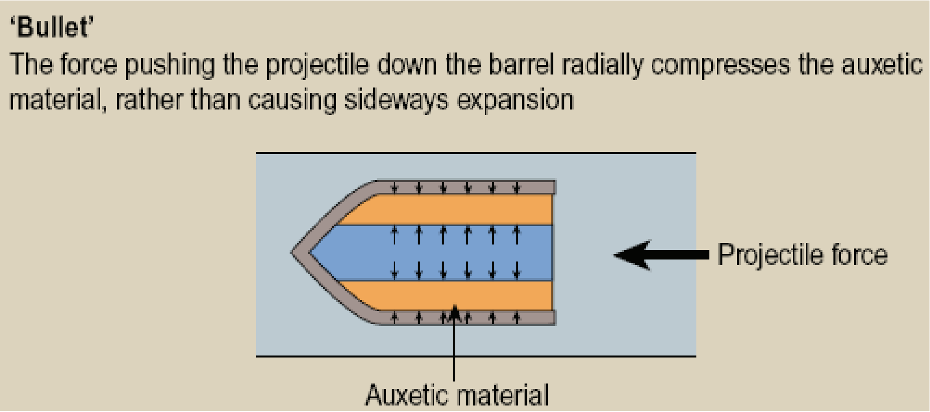


Figure 28 Schematic of the principle of auxetic material used to human protection (After Alderson, 1999).

5.2.3 Fasteners and Rivets

Because auxetic materials expand sideways when pulled, hence they would be ideal for making fasteners and rivets. Insertion of the auxetic fastener is facilitated by the lateral contraction under compression, while removal of the fastener is resisted since the fastener expands and jams itself more tightly in the hole under tension (Choi & lakes, 1991). Figure 29 shows the relationship between the load and displacement during the insertion and removal of the fastener (copper re-entrant foam). During insertion, the load-displacement curve shows an initial sharp increase in the load and then more gradual increase until the maximum displacement is reached. During the removal, the load is sharply increased and the fastener breaks at a displacement of 2.8 mm and a load of 160 N. The fracture surface was in the body of the core, away from the socket and embedded grip ends.

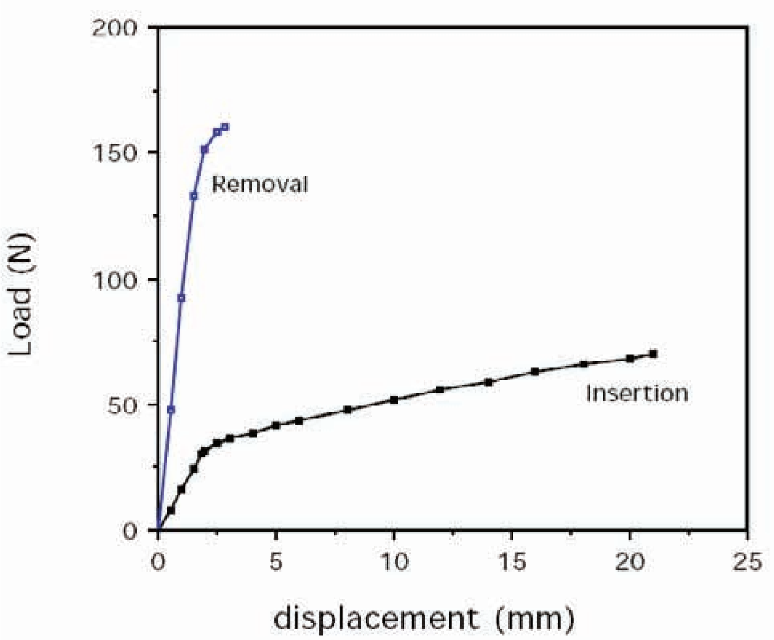


Figure 29 Load as a function of displacement for experimental insertion and removal of fastener core, which is made of copper re-entrant foam (after Choi & Lakes, 1991)

5.2.4 Energy Absorption Material for the Protection of Airborne Cargo Drops

Currently, Energy Dissipating Material (EDM) is used to cushion the impact of all airborne supplies in order to ensure that they arrive on the ground safely and are fully functional. The EDM is a paper product comprising a Kraft paper honeycomb core 75 mm thick, faced on both sides with Kraft paper. The idea is that on contact, the EDM crushes to at least 70% of its original thickness, dissipating some of the impact, and releasing trapped air to avert a massive deceleration or bounce that could damage the cargo (Connections, 2005).

Conventional polymeric foams (e.g. polyethylene) are available in a range of densities for packing and cushioning applications and for sports equipments. But materials with NPR (e.g. auxetics) possess much better impact resistance, indentation resistance and energy absorption properties. Therefore, a material with NPR might be potentially applied to aircraft equipment protection such as cargo drop to prevent the damage due to high energy absorption (Athiniotis & Cannon, 2006). However, the biggest question for the application is whether such a material is commercially available and its strength satisfies the requirements as a structural material in this particular application.

5.2.5 Other Applications

Apart for the above applications, materials with NPR should have more applications in aerospace industry. For example, from the mechanical point of view, the Poisson's ratio does not depend on scale, so auxetic materials should not be difficult to be extended to structures built from conventional components that would "open up" when stretched. These "expandable" structures can be particularly useful for the manufacture of space structures such as large antennas and sun shields that could be launched into space in a closed compact form and then "open up" at a later stage in space (Grima, et al, 2005).

As mentioned in Sec.3, auxetic materials have higher resistance against shearing (tearing force) and twisting than conventional materials. These properties are particularly important for structural components, which may fail under shear strain such as beams in buildings, sheets used in aircraft or cars etc).

Smith from the US Office of Naval Research showed that the sensitivity of a sonar receiver was increased by an order of magnitude by replacing a non-auxetic matrix with an isotropic auxetic matrix (Smith, 1991). A further advantage of using auxetic materials is their behaviour when bent. As mentioned in Sec.5.2.1, the double curvature is one of the important deformation mechanisms in auxetic materials. This feature can be used in moulding and shaping sandwich panels for aircraft components such as nose cones or car body parts.

5.3 Limitations

As stated above, auxetic materials potentially have many applications, because of their wonderful properties compared to conventional (i.e. non-auxetic) materials. However, they also have their own limitations like other materials.

The special microstructural features for auxetic materials need space to allow the "hinges" to flex, or the "nodules" to spread out. The materials often need substantial porosity. Therefore, materials with negative Poisson's ratio are substantially less stiff than the solids from which they are made and this causes limitations on the structural applications of the materials with negative Poisson's ratio (Jones, 2001). For example, they are normally not stiff enough or not dense enough for load-bearing applications.

6. Conclusions and Recommendations

Materials with NPR show unique properties, compared to ordinary materials such as enhancement of shear modulus, indentation resistance or plane strain fracture toughness, although they have less stiffness. Therefore, they have many potential applications to Defence such as personal protective equipment (e.g., protective clothing, body armour, bullet-proof vest, etc) and others (e.g., "smart" sensors, sonar, panels etc). Also, these materials could potentially be used to build completely new structures with special functions. However, more research work needs to be done for further understanding of these materials and applications to real components.

For future work, experimental tests need to be carried out to further understand the behaviours of these types of materials. Also, for future work it is necessary to collaborate with researchers from textile, chemical & biological areas to explore the potential applications for protecting military personnel from injury, or chemical & biological attacks from enemy or terrorists.

7. Acknowledgements

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Appendix A: Recipe for Polymeric Foams

Note: The following procedure is adapted from Lakes' published paper (1987a).

The mould : We have used aluminium square tube, 1" square, for a mould. If too large a mould is used, heat transfer will be poor, and only the outer portion of the foam will be transformed.

(1) Preheat furnace to about 160-170 deg C.
(2) Either measure or mark foam for later determination of strains. Mark foam in all 3 orthogonal directions, i.e., two adjacent corners and down one side.
(3) [optional: this is not necessary if sufficient care is taken in removing wrinkles] Lubricate sides of square aluminium tube with vegetable oil. Spray cooking oil (PAM) can also be used, but does not seem to work better. DO NOT use a petroleum distillate base lubricant; it will smell terrible when heated.
(4) Stuff the foam in the tube. It works well to start the foam slightly by hand and then work it up gently with a tongue depressor to remove wrinkles.
(5) Pull the foam a little on both ends to get rid of creases created by stuffing the material. This procedure will result in a pre stretched sample in the tube. The actual original length of the sample must be used when determining the amount of pre compression to apply.
(6) Place the compression device and end plates on the stuffed tube.
(7) If the desired specimen length is less than the square tube size, select the correct length of cut tubing [pipe] within the mould to compress the foam longitudinally by the same amount as transversely. Alternatively, cut the foam proportionally longer than the square tube length and do not use pipe.
(8) Push the pipe down on the loose end plate such that the foam is compressed evenly at the end. Try not to push too fast; this may contribute to the uneven distribution of compression along the length of the specimen.
(9) Gently tighten down the side screws to hold the cut pipe in place.
(10) Place assembly in centre of furnace or oven. A kitchen oven is sufficient.
(11) Leave the foam in the oven for a predetermined amount of time. The gray polyester foams transform better at a slightly lower temperature for a longer amount of time, about 20 minutes maximum. The white/cream coloured polyether foam seems to be more sensitive with respect to melting together; 17-18 min. is appropriate.
(12) Remove and cool the specimen completely. Taking the specimen out of the mould before complete cooling may result in premature release of the pre compression. It may be helpful to release foam ribs which have stuck together: stretch the specimen gently in each of three directions. Congratulations! You have made negative Poisson's ratio foam (also called anti-rubber, dilational material, or auxetic material).
(13) Measure the amount of permanent compression retained by the specimen by either measuring the new distance between the marks or by measuring the size of the transformed sample.
(14) Other kinds of moulds are possible and have been used successfully by others.

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Qianchu Liu

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19. ABSTRACT

An auxetic material exhibits exceptional features, which are different from a conventional material. That is, the auxetic material gets fatter when it is stretched, or becomes smaller when it is compressed, because it has a negative Poisson’s ratio. This report briefly reviews the latest advances in research work in auxetic materials, structural mechanisms, properties and applications, particularly in aerospace and defence.