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ADVANCED AUXETIC FIBROUS STRUCTURES AND COMPOSITES FOR INDUSTRIAL APPLICATIONS

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ABSTRACT

This paper reports an overview of advanced auxetic fibrous structures and composites for various industrial applications. Most recent developments in the area of auxetic fibres, yarns, textile structures and composites are reviewed. Innovations in terms of materials, design and structures, processing technologies and innovative applications have been critically reviewed.

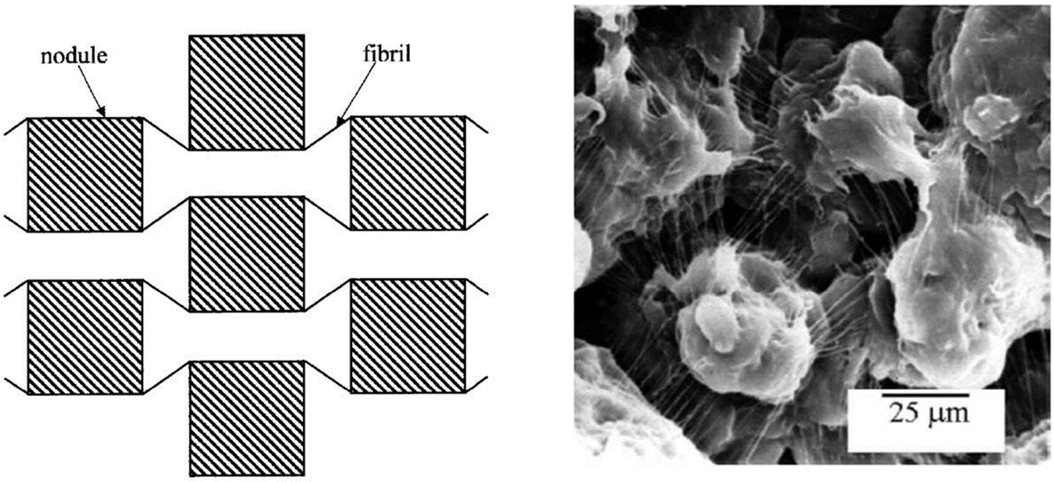
Keywords: auxetic structures, fibres, yarns, composites, Poison's ratio, applications.

INTRODUCTION

Auxetic materials are a special class of materials having negative Poisson´s ratio (NPR), i.e. stretching of these materials in longitudinal direction results in widening in the transverse direction. Auxetic materials are becoming very attractive to the scientific community due to their interesting properties such as enhanced strength, better acoustic behavior, improved fracture toughness, superior energy absorption, damping improvement, and indentation resistance (Rana, 2016). Till now, different types of auxetic materials and structures have been discovered and manufactured both at micro and macro scales and owing to their advantageous features they are recommended for wide range of applications including apparel textiles (auxetic fibers, threads, functional fabrics, etc.), technical textiles (air filter, gasket, fishnet, fastener, shock absorber, sound absorber, etc.), aerospace industry (curved body parts, wing panel, and aircraft nose-cones), materials for protection (crash helmet, projectile-resistant materials, shin pad, glove, protective clothing, car bumpers, etc.), bio-medical industry (bandage, wound pressure pad, dental floss, artificial blood vessel, drug release devices, etc.), in sensors and actuators (hydrophone, piezoelectric devices, miniaturized sensors), etc. (Rana, 2016).

AUXETIC POLYMERS AND FIBRES

Inspired by the natural auxetic materials, various polymers with auxetic characteristics such as liquid crystalline polymers, polytetrafluoroethylene (PTFE), ultrahigh molecular weight polyethylene (UHMWPE), etc. have been developed (Hong, 2016). Auxetic polymers such as UHMWPE exhibit nodule-fibril morphology in their microstructure, in which the extension of the fibrils in axial direction pushes the nodules in transverse direction, resulting in auxetic behaviour (Fig. 1). This kind of morphology has been imitated in fibre forming polymers such as polypropylene, polyamide and polyester, etc. through the use of special melt-extrusion process with optimized extrusion parameters.



(a) (b)

Fig. 1 - (a) Nodule-fibril model and (b) microstructure of auxetic UHMWPE

AUXETIC YARNS

Auxetic yarns found diverse applications in various fields such as healthcare, body armour, blast curtains and filtration. (Hook, 2007). The type of auxetic yarn which has attracted tremendous attention recently is the helical auxetic yarn (HAY). This novel yarn structure has been produced using two components: an elastic core and a stiff wrap in the form of helically wound structure, as shown schematically in Fig. 2. When a tensile force is applied, the stiff wrap fibre gets straightened displacing the elastic core fibres. Consequently, the core fibres change their position and become wrapped around the wrap fibres (Fig. 3), resulting in a lateral expansion of the yarn dimension. Consequently, an auxetic effect is observed.

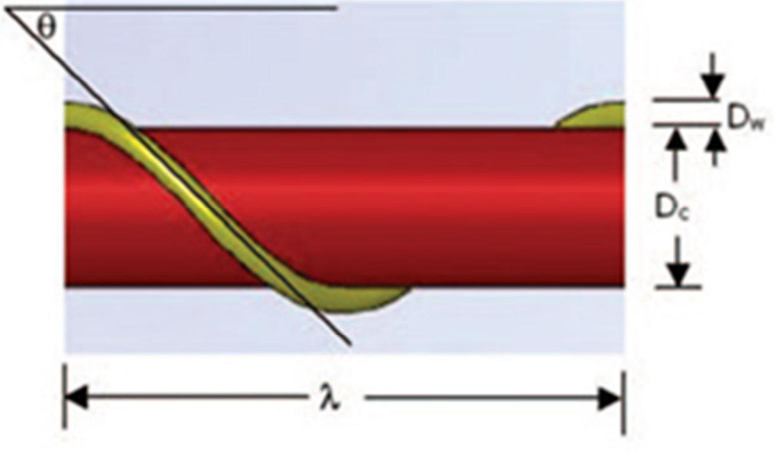


Fig. 2 - Geometry of HAY

A similar type of yarn, called “double helix yarn” (DHY) was produced by Miller et al. by blending two fibre: a high modulus UHMWPE wrap fibre and a flexible low modulus polyurethane core fibre (Fig. 3). Under tensile force, DHY exhibited expansion of width and negative Poisson’s ratio of -2.1. (Miller, 2009)

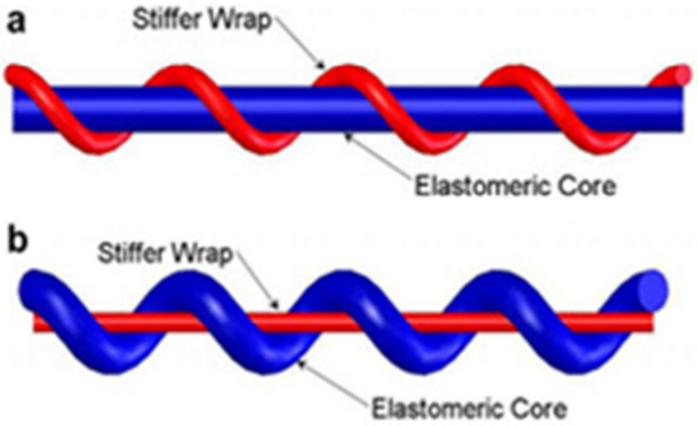


Fig. 3 - Structure of DHY (a: Free State, b: stretched state)

HAYs have also been produced using a plying technique. In this process, two stiff and two soft yarns were plied together using a process shown in Fig. 4. The stiff and soft yarns are taken from bobbins arranged alternatively on a circular disc, which rotates and twists the fibres together to form the yarn structure. Once HAYs are formed, they are taken out from the production zone and wound on to a bobbin (Ge, 2016).

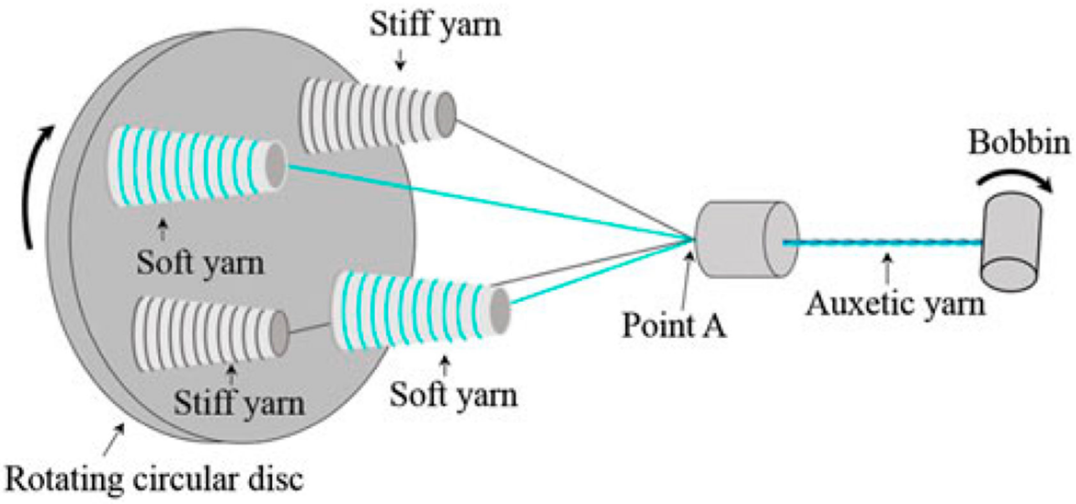


Fig. 4 - Manufacturing process of plied auxetic yarn

The extent of auxetic effect exhibited by HAYs and resulting properties of auxetic yarn strongly depends on fibres diameters, elastic modulus, initial geometry and the applied strain (Zhang, 2016). It was observed that a higher difference in component moduli, a higher core/warp diameter ratio and a lower initial wrap angle resulted in an earlier and better auxetic behaviour. A larger core/wrap diameter ratio also resulted in higher dynamic storage modulus. However, a smaller core/wrap diameter ratio could lead to higher tensile strength and ability to absorb more energy. Energy absorption was also found to be higher in case of a higher initial wrap angle. Therefore, optimization of these parameters is highly essential to achieve required auxetic, tensile and energy absorption bcharacteristics

FABRIC STRUCTURES

A textile structure is highly demanding for wide range of industrial applications due to a number of advantages, i.e. tailorable mechanical and other properties, easy handling, high flexibility, drapability, energy absorption property, and so on. Current high end industrial sectors such as aerospace, defence, construction, etc. are demanding for materials with high impact and fracture resistance and energy absorption characteristics, along with excellent strength and stiffness. Composite materials developed using auxetic textile fabrics can be a suitable class of materials for these applications. Presently, different textile technologies have been used to produce auxetic fabrics, namely knitting, weaving and non-woven technology, among which knitting has been the most widely used technique for this purpose due to its huge flexibility.

Weft-knitted auxetic textiles have been developed using different types of auxetic designs such as foldable structures, re-entrant hexagon structures, rotating rectangles, etc. Folded auxetic textiles have been produced through development of a three-dimensional structure formed using parallelogram planes of same shape and size that are connected together side to side in a zigzag fashion, as can be observed in Fig. 5 (Liu, 2010). While subjected to tension in vertical or horizontal directions, the inclination of each parallelogram changes with respect to the surface plane of the structure. This results in an opening of the whole structure leading to increased dimensions in both horizontal and vertical directions and NPR effect. Besides foldable structures, re-entrant hexagon and roating rectangles are other types of weft-knitted auxetic textiles already developed by researchers, as presented in Fig. 6 (Hong, 2011).

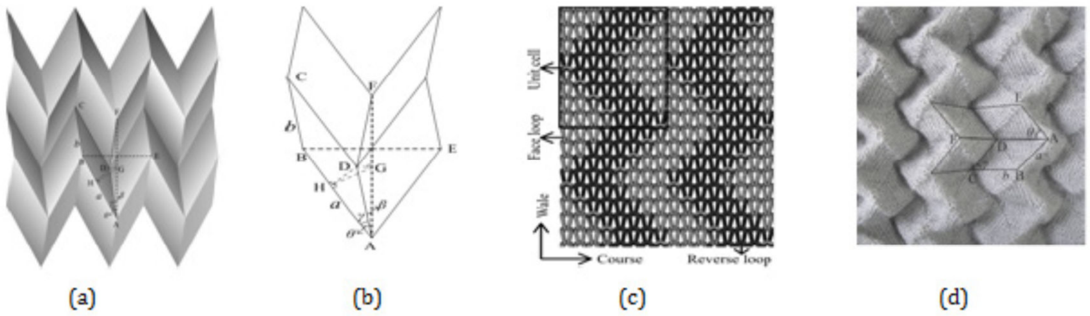


Fig. 5 - Foldable auxtic knitted textiles: (a) three-dimensional structure; (b) unit cell (c) knit pattern (d) state of the fabric under tension

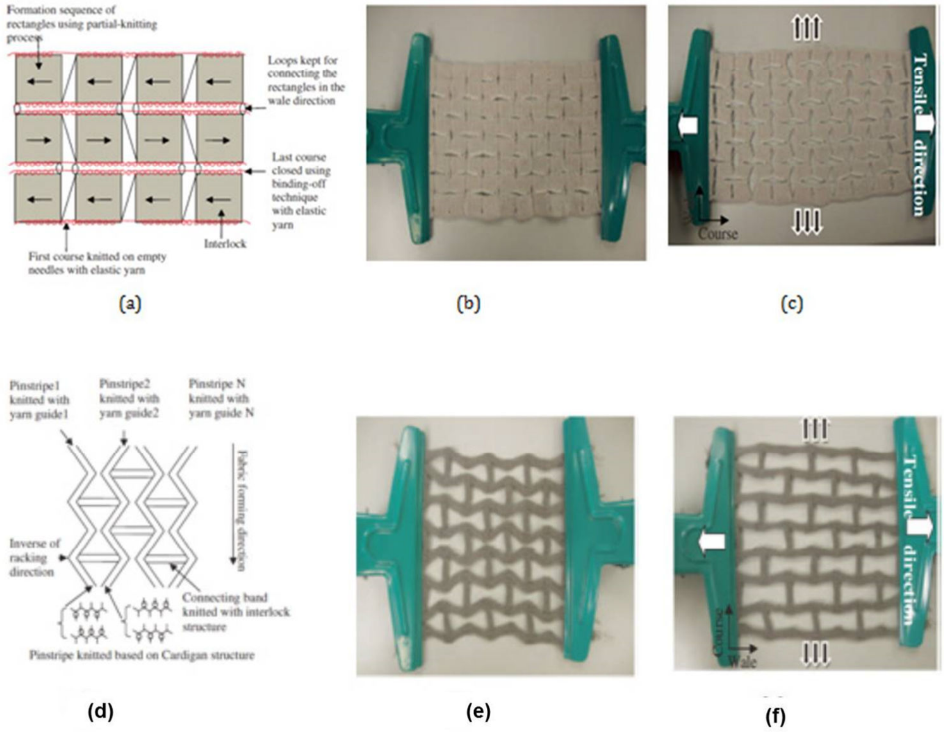


Fig. 6 - Auxetic textiles based on rotating squares (a,b,c) and re-entrant-hexagon design (d, e, f): schematic of knitting process (a, d), fabrics at free state (b, e) and fabrics under tension (c, f)

AUXETIC COMPOSITES

Different methods to fabricate auxetic composites include (a) using the angle ply method, in which the plies of laminated composites were organized in a certain sequence resulting in negative Poisson's ratio in though-thickness direction (Jiang, 2015), (b) composites developed using impregnating DHY yarns with polymeric resin (Miller, 2012) (c) auxetic fabrics impregnated with polymeric resin (Stiffens, 2016) and (d) auxetic nanocomposites (Zhang, 2013).

Angle ply auxetic composite laminates have been produced through ply stacking of unidirectional prepreg sheets of epoxy resin impregnated continuous carbon fibers. Fabricated composite panels were poised, symmetrical laminates with the ply sequence of ±θ with respect to the reference direction (Fig. 7), where θ = 0, 10, 15, 20, 25, 30 and 40°. 24 fibre layers were used to produce these composites. The composite laminates exhibited NPR for θ values in the range between 15 and 30°, according to the theoretical prediction.

Another approach for producing auxetic composites is to produce textile fabrics using DHYs and subsequently, to impregnate the produced fabrics with a polymeric resin (as shown in Fig. 8). In a recent study, DHY was produced using UHMWPE wrap yarns (diameter of 0.32 mm, Young's modulus of 6 GPa and Poisson's ratio of 0.5) and polyurethane core material (diameter of 0.64 mm, Young's modulus of 53 MPa and Poisson's ratio of 0.48) using an approximate wrap angle of 70º. Next, woven fabrics were produced using DHY weft yarns and meta-aramid warp yarns (approximately 475 dtex linear density). Auxetic composites were fabricated through impregnation of developed fabrics using silicone rubber gel. It was observed that a minimum of two layers of fabrics are required to generate the auxetic effect (Miller, 2009).

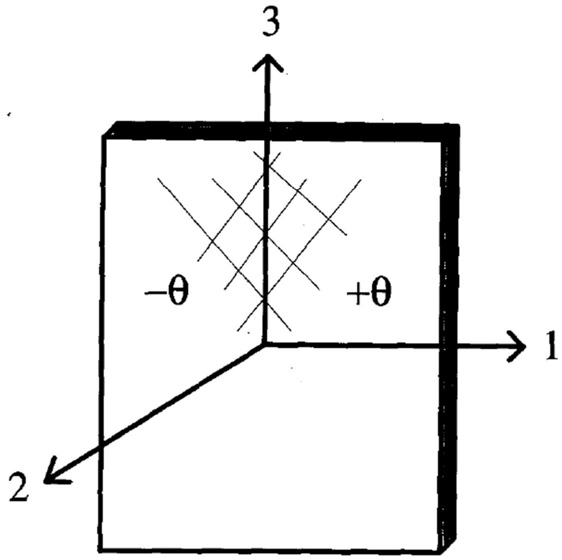
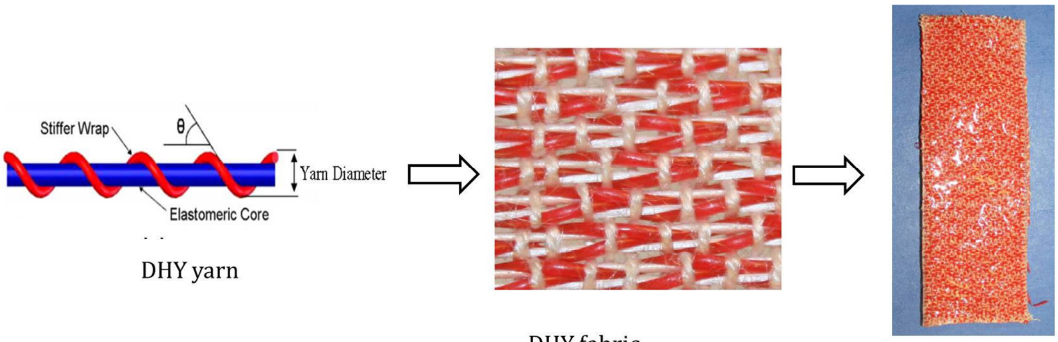


Fig. 7 - Ply stacking sequence in angle ply auxetic laminates

Auxetic composites have also been produced by impregnating DHY fabrics with polyester resin. For this purpose, DHYs were produced with nylon monofilament core (0.7 mm diameter) and low tow count carbon fiber wrap (0.2 mm diameter) using different wrap angles (10º, 20º and 30º). It was noticed that the composites with higher NPR and stiffness could be produced using a smaller wrap angle (Miller, 2012).



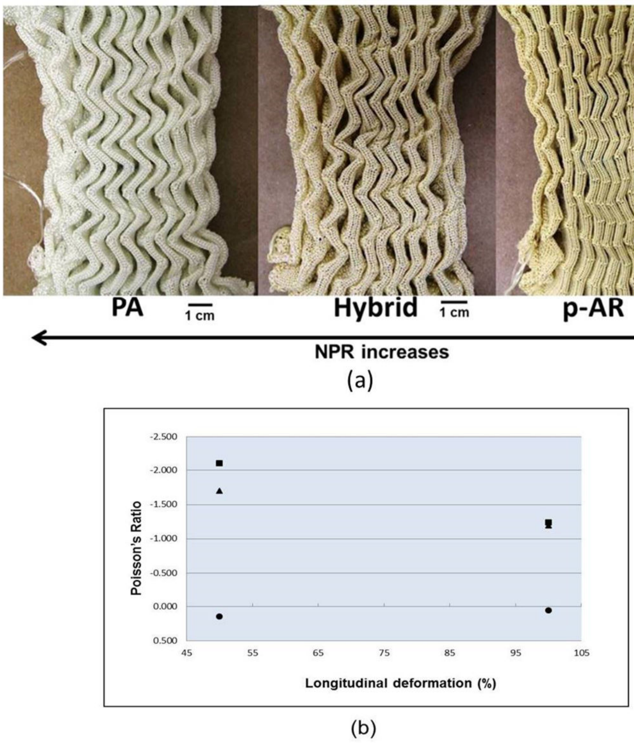
DHY yarn

DHY fabric

Composite containing single layer DHY fabric

Fig. 8 - Production of auxetic composites from DHY

However, the most recent and promising approach of producing auxetic composites is through impregnation of knitted auxetic textiles with polymeric resins. Very recently, composites were fabricated using weft knitted fabrics made from high performance yarns such as para-aramid and ultra-high-molecular-weight polyethylene (Spectra) (Fig. 9). These auxetic fabrics were impregnated with epoxy and unsaturated polyester resins based on iso-phthalic acid. The produced composites with para-aramid fibres exhibited excellent impact strength and energy absorption characteristics and considered to be highly suitable for advanced technical applications (Steffens, 2016).



(a)

(b)

Fig. 9 - (a) auxetic fabrics produced using polyamide (PA), para aramid (p-AR) and hybrid yarns and (b) Poisson’s ratio of developed fabrics

CONCLUSIONS

Auxetic fibres, textiles and composites are still in the development stage. Although a few auxetic fibres and DHYs are commercially available, they are still expensive. On the other hand, auxetic textiles and composites are not currently being marketed by any company. In fact, still scientific investigations are going on for proper designing, production, optimizing and understanding these materials. It is believed that in the coming years these materials will be an important material of choice for many advanced technical applications.

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