Materials and Design 106 (2016) 81–89

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Development of novel auxetic textile structures using high performance fibres

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ARTICLE INFO

Article history:
Received 14 January 2016
Received in revised form 30 March 2016
Accepted 18 May 2016
Available online 18 May 2016

Keywords:
Auxetic structures
High performance fibres
Knitted fabric
Negative Poisson's ratio
Mechanical performance

ABSTRACT

The present work reports the first attempt of developing auxetic structures using high performance fibres through knitting technology. Polyamide (PA) and para-aramid (p-AR) fibres and their combination were knitted in to purl structures using flatbed knitting machine, varying different structural (such as loop length, cover factor and yarn density) and machine parameters (such as take-down load). The influence of different parameters on negative Poisson's ratio (NPR) was thoroughly investigated. It was observed that NPR improved strongly with the increase in loop length of knitted structures. NPR also increased with the decrease in cover factor and increase in course density of knitted fabrics. An increase in take-down load also improved NPR for tightly knitted samples, but led to initial decrease and subsequent increase in NPR for medium and higher loop lengths; except for p-AR fabrics, which showed a decrease in NPR with take-down load for higher loop lengths. Tensile properties of the developed auxetic structures were also found to depend strongly on fibre type and loop length, and the highest tensile performance was achieved with lower loop lengths and p-AR yarns. The p-AR fabrics produced using lower loop length and lower take-down load resulted in the highest NPR of −0.713. Therefore, the developed knitted structures produced using high performance yarns and showing strong auxetic effects can have huge potential for industrial applications, especially in personal protection materials, such as cut resistance fabrics, bullet proof vest, helmets, and so on.

1. Introduction

Auxetic materials were discovered over 100 years ago [1] [2]. However, these materials only started to gain research relevance over the last two decades [3]. The comparison between auxetic and conventional materials has also begun to be intensely explored recently [4]. The auxetic effect confers improvements in the material's mechanical properties, such as enhancement in fracture toughness, shear moduli, indentation resistance, and allows porosity and permeability variation (under pressure) [5] [6] and dome shape [7] [8]. Due to this wide range of characteristics, auxetic materials can be used in various areas, including medicine, architecture, civil engineering, sport clothing, high-performance equipment, protection against explosives, insulation, filters, among others [9] [7] [10] [11] [12] [13] [14] [6] [15] [16] [17] [18].

Fibrous and textile structures are extensively used in technical applications due to their tailor-able physical, mechanical and chemical properties [19]. Recently, various advanced fibrous architectures produced using weaving, knitting and braiding technologies are finding wide spread applications, either in the flexible forms or in the form of rigid composite materials. Medical, electronics, aerospace, transportation, civil engineering, sports, etc. are different application areas of advanced fibrous structures and composites. Looking at the several benefits of auxetic materials and structures, development of fibrous structures with auxetic effect appears to be a great opportunity to solve problems those were very complex or expensive in the past.

So far, only a few research studies have been published on auxetic textile structures. One such example is the helical auxetic yarn [20] [21] [16]. Some other studies explored the warp knit auxetic structures produced using a highly elastic yarn in the base of the structure [22]. Hexagonal knit auxetic structures produced utilizing elastic yarns have also been reported [23]. Different warp and weft knitted auxetic structures have also been produced using mainly wool and acrylic yarn [24] [25] [26]. Recently, three-dimensional auxetic structures have been produced combining non-woven and knitted structures and based on warp knitted spacer structures using polyamide and polyester yarns, respectively [27] [28].

In the last few years, a proliferation in the number and variety of 'high performance' technical fibers has been noticed. Composite products have been the main focus for the use of high performance fibres and their composite applications have increased tremendously [29] [30] [31] [32]. These high performance composites are particularly useful for the production of aircraft and automobile body parts for which both strength and light weight are crucial. The use of high-performance fibers in many diverse engineering applications is well documented [33].

Therefore, the utilization of high performance fibres in advanced fibrous architectures, including auxetic structures, may offer light weight,

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http://dx.doi.org/10.1016/j.matdes.2016.05.063
0264-1275/

excellent mechanical performance and several interesting characteristics that can fulfil the explicit demands imposed by several advanced technical sectors. However, auxetic textile structures (e.g. knitted structures) using high performance yarns such as high tenacity polyamide (PA) and para-aramid (p-AR) have not been studied till date, according to the author's knowledge. These yarns, due to their unique characteristics, are able to promote different degrees of auxetic effects in the produced knitted fabrics. Furthermore, it has been noticed that there exists a lack of studies that take into account the influence of dimensional parameters of knitted structures, such as loop length, material composition and take-down load on the negative Poisson's ratio (NPR). As auxetic behaviour of a textile structure strongly depends on its structural mobility and rearrangement under mechanical deformation, various structural (such as loop length, cover factor, etc.) and material parameters (such as fibre stiffness) will strongly influence the auxetic behaviour. Therefore, to design an auxetic fabric based on a knitted structure the influence of these parameters should be properly understood. To bridge this knowledge gap, the main objective of the present work is the development of novel weft knitted auxetic fabrics using high performance yarns and to study the influence of different material, structural and machine parameters on the auxetic performance of the produced fabrics.

2. Experimental

2.1. Materials

Knitted fabrics were produced from 98.6 Tex high tenacity PA yarns with 140 monofilaments and 88.5 Tex p-AR yarns with 500 monofilaments. p-AR yarn (Standard TWARON® 2000) and PA yarn were supplied by TEIJIN Group (Netherland) and RHODIA (Portugal), respectively. Table 1 shows the main properties of PA and p-AR yarns used in this study.

2.2. Development of knitted structures

The knitted fabrics were manufactured on a 10-gauge Stoll CMS 320 TC flat knitting machine using a 2-cam system with a pattern based on a purl structure through a zigzag organization (like parallelograms) of the face and reverse loops. The knitting pattern indicating the unit cell, face as well as reverse loops is presented in Fig. 1. After the knitting, the structures tend to curl and form a three dimensional geometry. This V-bed machine is controlled by a computer and has a full working width of 127 cm and 500 needles per needle bed. The programming language is Sintral, enabling the control of needle selection, cam setting, and take-down tension setting, supporting the production of simple structures, conventional and three-dimensional preforms or three-dimensional structures like sandwich [34] [29]. Table 2 lists different parameters used to produce the knitted fabrics.

2.3. Poisson's ratio evaluation

Samples were conditioned during thirty days at 20 ± 1 °C and 65% humidity before Poisson's ratio measurement. For the evaluation of NPR, an innovative testing device was developed and used for the whole set of samples (Fig. 2a). The specimens were marked at specific points in the course and wale directions, as shown in Fig. 2b. The fabrics were clamped at their two ends in the testing device and extended manually along the course direction. The knitted fabric was deformed by steps of 1 cm and the distance between the reference points along the course and wale directions at each deformation step was measured. To minimize the clamping effects, measurements were done in the middle section of the specimens. The next step was to calculate the strains in the course and wale direction using the following equations:

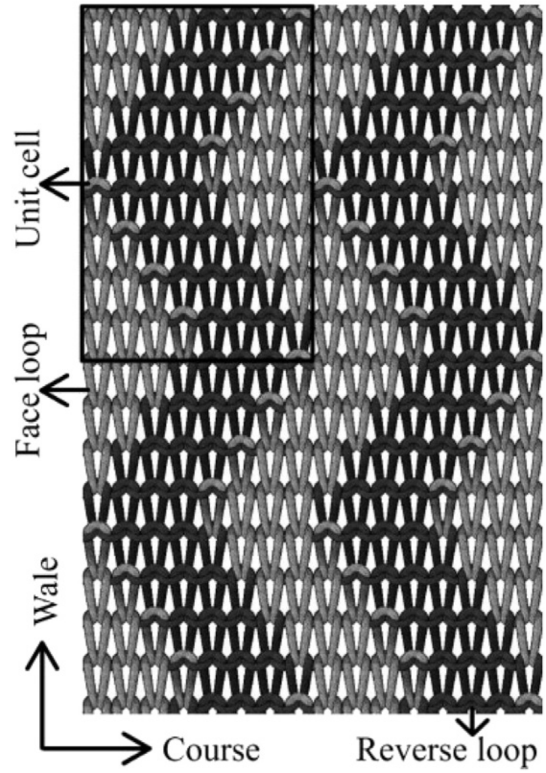

Fig. 1. Knitting pattern of produced purl structures [24].

$$\varepsilon_x = \frac{x_n - x_0}{x_0} \quad (1)$$

$$\varepsilon_y = \frac{y_n - y_0}{y_0}. \quad (2)$$

Where x_n and y_n are the distances between the points marked in the wale and course direction, respectively after a deformation step and x_0 and y_0 are the initial distance between the reference points [24]. The values of ε_x and ε_y were calculated and consequently, Poisson's ratio was calculated in each deformation step using Eq. 3 for 3 samples in each group (PA, p-AR and hybrid fabrics). The maximum

Table 1
Comparison of PA and p-AR yarns' properties.

Properties	PA	p-AR
Linear density [tex]	98.60	88.50
Number of filaments	140	500
Tensile strength [N]	76.57	172.00
Tenacity [N/tex]	0.78	1.85
Young modulus [N/tex]	1.89	44.65
Extension[%]	22.87	3.98
Loop tensile strength [N]	105.09	225.20
Loop tenacity [gf/tex]	55.54	123.46

Table 2
Parameters used to study the auxetic behaviour.

Loop length (machine unit)	Materials	Take-down load (machine unit)
10.0; 10.5; 11.0	PA	6.3; 7.7; 9.0
10.0; 10.5; 11.0	p-AR	6.3; 7.7; 9.0
10.0; 10.5; 11.0	Hybrid (50% PA/50% p-AR)	6.3; 7.7; 9.0