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Dynamic thermo-mechanical and impact properties of helical auxetic yarns

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ABSTRACT

This paper presents an experimental investigation of the dynamic thermo-mechanical and impact properties of helical auxetic yarns (HAYs). A series of thermoplastic polyurethane (TPU) core fibres fabricated using an extrusion process have been wrapped with either ultra-high-molecular-weight polyethylene (UHMWPE) wrap or stainless steel wire wrap to form helical auxetic yarns. Dynamic mechanical analysis (DMA) measurements indicated that the core/wrap diameter ratio and the initial wrap angle influenced significantly the dynamic thermo-mechanical behaviour of HAYs. The impact test results have shown that the fibre property, impact velocity and the initial wrap angle had great effect on the impact response of a HAY. Importantly, in this work it is shown that an optimal wrap angle can be found to give the best combination of stiffness, energy absorption and auxetic performance of HAYs.

1. Introduction

Materials with a negative Poisson's ratio are called auxetic materials [1]. Auxetic materials become wider in tension and narrower in compression. The helical auxetic yarn (HAY) is one type of auxetic material, first proposed by Hook et al. [2]. The HAY comprises an elastomeric core and a stiff helical wrap, see Fig. 1a. When a tensile load is applied the core fibre becomes wider as the wrap fibre straightens out, causing a lateral expansion of the core, and thereby exhibiting a large negative Poisson's ratio as shown in Fig. 1b. Combining two of these primary structures together and arranging them in pairs, an 'out of phase' movement occurs between the paired structures, causing pores to open along their length (Fig. 1c). Multiples of this two-yarn primary system can be incorporated into a textile to offer an uni-directional auxetic fabric. Therefore, such advantages of HAY structures open up a number of possible applications, including body armour [2] and blast mitigation [3] due to its high energy absorption ability. In addition, the HAY may be placed in a composite as a yarn reinforcement and the formed composite is able to exhibit auxetic, low modulus [4] and high modulus [5] behaviours depending on the stiffness of the HAY and matrix. The HAY has been investigated previously in terms of manufacture, auxeticity and static mechanical properties [6–11]. According to the previous studies, the auxetic behaviour can be tailored by selecting the core/wrap diameter ratio, component moduli, the initial wrap angle, and the applied strain.

The basic requirement for body armour and blast mitigation is a material or structure that can absorb energy locally and redistribute that energy fast and effectively at high strain rates [12]. Therefore, low density and high strength fibres may offer better energy absorption and lighter weight in protective fabrics. The ballistic behaviour of high performance fabrics has been investigated experimentally and theoretically in the last two decades [13–22]. The absorption of energy is caused by the deformation of yarns during the impact test. Yarns within fabrics are either broken or deformed as a result of energy absorption. The following parameters have been identified as major factors in influencing the ballistic performance of fabrics: material properties (tensile strength, modulus and elongation of a yarn), fabric structure, number of fabric layers, projectile geometry, impact velocity, boundary conditions (the size of the specimen and means of the fixture) and friction between the projectile and the fabric and the yarns themselves.

It has been suggested previously that the HAY can be woven into technical auxetic textiles and placed in a composite for body armour and blast mitigation applications. However, prior to any fabrics and composites manufacturing, testing and analysis, it is important to understand the dynamic thermo-mechanical

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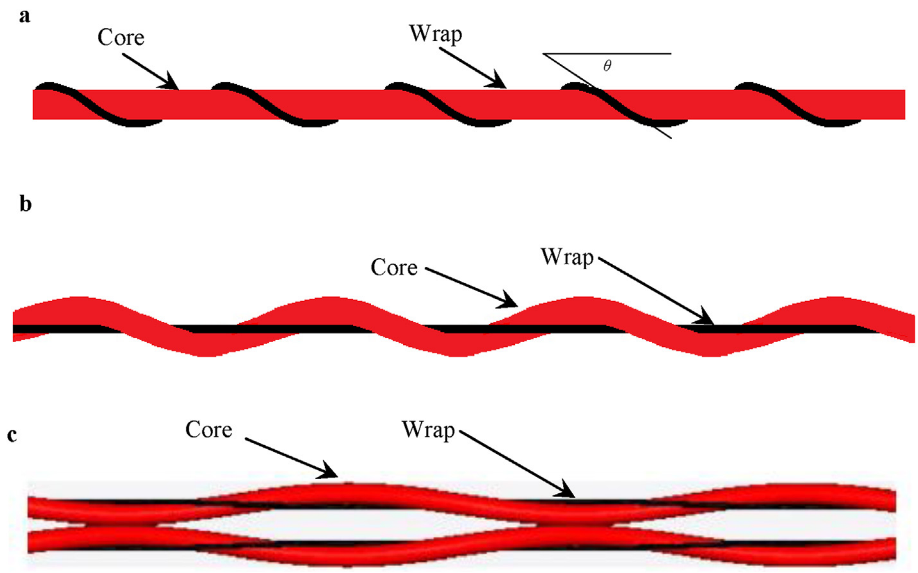

Fig. 1. Schematic of HAY structures: (a) one HAY at zero strain; (b) one HAY at maximum strain; and (c) pores open under tension in a pair of HAYs for textile application (after [11]).

properties and the energy absorption capability of the HAY itself. The energy absorption capability of the HAY is a major factor in its blast mitigation behaviour which may lead to improved safety in an explosion. This paper reports experimental investigations on the dynamic thermo-mechanical behaviour and high strain rate performance of HAYs.

2. Methods

2.1. Fibres and HAYs manufacturing

Elastomeric core fibres were fabricated by extrusion using a Rondol (www.rondol.com) 18 mm diameter bench top single screw extruder (model-Linear 18). Elastollan® TPU-CA85A granules (polyester-based TPU) were purchased from BASF for manufacturing core fibres. Multifilament UHMWPE fibre and monofilament stainless steel wire were purchased from Monofil Technik and employed here as the wrap fibres due to their high strength, high modulus, and differing energy absorbing mechanisms on failure. Accurate diameters of core and wrap fibres were obtained using optical stereo microscope. Helical auxetic yarns were manufactured using a bespoke spinner, described in a previous study [7]. The properties for component fibres and HAYs are shown in Table 1. Three types of monofilament core fibres and two types of wraps were utilised to fabricate HAYs. The Young's moduli of the component fibres (samples A to E) were obtained using the elastic region (0.05–0.25%) [23].

2.2. DMA measurements

DMA measurements for TPU fibres, UHMWPE fibres and HAYs were conducted using a dynamic mechanical analyser (DMA1, Mettler Toledo) in the tensile mode, see Fig. 2. The fibres and HAYs were tested from 25 °C to 125 °C at heating rate of 3 °C × min^{-1} and at 1 Hz frequency. The tensile amplitude of 10 μm was applied for core and wrap fibres, and a larger tensile amplitude of 250 μm was employed for HAYs in order to investigate the influence of the wrap on the thermo-mechanical property of HAYs. A pre-tension of 0.5 N was applied for all the measurements.

Table 1
Measured properties for fibres and HAYs.

Sample	Type	TPU core diameter (μm)	UHMWPE wrap diameter (μm) (±27 μm)	Stainless steel wrap diameter (μm) (±0.3 μm)	Initial wrap angle (°)	Young's modulus (MPa)
A	Core Fibre	394.5 ± 23.8	–	–	–	12.5 ± 2.2
B	Core Fibre	683.6 ± 30.5	–	–	–	14.7 ± 3.6
C	Core Fibre	1302.1 ± 23.4	–	–	–	14.8 ± 1.4
D	Multi-filament Wrap	–	370	–	–	23,000 ± 3000
E	Wire Wrap	–	–	139.8	–	43,000 ± 1700
F	Helical auxetic yarn	394.5 ± 23.8	370	–	30.3 ± 1.6	–
G	Helical auxetic yarn	683.6 ± 30.5	370	–	30.8 ± 1.9	–
H	Helical auxetic yarn	1302.1 ± 23.4	370	–	12.5 ± 1.5	–
I	Helical auxetic yarn	1302.1 ± 23.4	370	–	20.6 ± 1.2	–
J	Helical auxetic yarn	1302.1 ± 23.4	370	–	30.9 ± 1.4	–
K	Helical auxetic yarn	1302.1 ± 23.4	370	–	40.7 ± 1.9	–
L	Helical auxetic yarn	1302.1 ± 23.4	–	139.8	19.8 ± 1.1	–
M	Helical auxetic yarn	1302.1 ± 23.4	–	139.8	31.4 ± 1.5	–
N	Helical auxetic yarn	1302.1 ± 23.4	–	139.8	40.5 ± 1.3	–