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Some significant advances in woven auxetic textiles

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Abstract

The article reviews some significant research trends in auxetic textiles. Auxetic textiles have been the focus of much attention due to their great promise for advanced protective clothing, flexible energy harvest devices, and functional textiles. Herein, plain fabric, basket fabric, and a derivative weave with the warp and weft yarns arrangement in a series of zigzags were prepared by incorporating different initial wrap density helical auxetic yarns in the weft direction using a commercial semi-automatic loom. The fabrication of auxetic fabrics by using conventional yarns and machinery has gained extraordinary interest fromresearchers in recent years. However, to date this approach has only been adopted to fabricate auxetic knitted fabrics and uni-stretch auxetic woven fabrics. This paper reports a study that aimed to develop a new class of bi-stretch woven fabrics with auxeticbehavior using conventional elastic and non-elastic yarns, and available weaving machinery.

Key words: Auxetic, Woven, Negative poisons ratio, helical auxetic yarn, tensile performance,elastic deformation.

1 Introduction

Auxetic textiles have advanced rapidly in the past fewdecades due to their intuitive behavior of expandinglaterally when subjected to a tensile stress. This contradictorydeformation mode provides many benefits overconventional positive Poisson's ratio behavior; forexample, materials which have a negative Poisson'sratio value always have increased shear stiffness, synclasticcurvature (dome shaped), fracture toughness,and indentation resistance, especially for excellentenergy absorption and damping properties [1-7]. Allthese performances enhance their potential applicationsin the manufacture of advanced protective clothing(e.g. body armour, helmet, etc.), shape adaptive materials,and smart textiles [1-4].

Conventional fabrics have positive Poisson's ratio (PR)and, upon stretching in one direction, they undergocontraction in the transverse direction, which isknown as lateral shrinkage. In contrast,auxetic fabrics become wider when stretched and possessnegative Poisson's ratio (NPR) [8-10].The term auxetic is derived from the Greek word(auxetos), which means 'that which tends to increase'by K Evans. A number of fascinating properties arelinked with the auxeticbehavior of auxetic fabrics, suchas improved comfort and shape fitting at joint parts dueto lateral expansion, increased porosity under stress,synclasticbehavior for better formability, etc. [11-14] Thesecounterintuitive properties make auxetic fabrics attractivefor many applications [15-17]. Such applications mayinclude riding kit for bikers that can cast itself to differentbody shapes, a fabric for denim products thatprovides comfort and an ability to mould and moveeasily in accordance with body movements, maternitywear and stretchable chest band carriers. Sincethe deformation behavior of the auxetic fabric willbe consistent with that of the body movements, theshape fitting and comfort at joint parts will beimproved [18-20].

2 Highly elastic woven fabrics using helical auxetic yarns

As the Poisson's ratio is a physical parameter that isindependent of the material scales, auxeticbehavior canbe achieved from the molecular to macroscopic scale.A great amount of effort has been devoted to thepreparation of auxeticfibers (yarn, fabric, composite)by creating auxetic geometries including helical,rope-like, honeycomb, and porous polymer-likestructures or by combining with 3D printing,thermomechanical treatment, and chemical modificationtechnologies [21-32]. After the structure of helicalauxetic yarn (HAY) was pioneered by Hook in2003, both auxetic structures and auxeticyarn have been greatly developed [33-39]. Attracted bythe contradictory mechanical deformation behavior of HAYs, researchers began designing all kinds of textileswith a negative Poisson's ratio (NPR) including knittedfabrics, woven fabrics, and composites [40-45].Meanwhile, the key structure parameters of these auxetictextiles were investigated too [46-48]. Furthermore, focusingon the innovative ideas, Hu's group developed anothertype of bi-component auxetic yarn with a rope-likemulti-plied structure. Subsequently, these multi-pliedyarns were incorporated within the woven fabric toobtain a series of fabrics with auxeticbehavior. Bymeasuring and characterizing the auxeticbehavior ofthe yarns and fabrics, they found that the in-planeNPR behavior of a woven fabric can be inheritedfrom its constituent auxetic yarns, but with a significantreduction due to a combination of different factors.These factors include the embedding of auxetic pliedyarns during fabric fabrication, the constraint of weftyarns, and the overlapping effect of auxetic yarns uponextension. Some research results also show that theweave structure of the woven fabric has a greatimpact on the NPR of the auxetic fabric, and a fabricwith a long floating length of HAYs is beneficial to asignificant auxeticbehavior.

However, current technologies for auxetic textilesare associated with challenges that other tradition textilesdo not face, such as the labor-consuming and timeconsumingmanufacturing process of the fabric as wellas how to insert HAYs in every kind of textile effectively.Therefore, it is both urgent and challenging toconstruct fabrics with NPR behavior through continuouslyimproving their geometric structure, controllability,and stability to push forward their promisingapplication in flexible wearable energy harvest and conversiondevices, such as triboelectric generators, andfunctional textiles, such as ''intelligent particle filters,''in terms of their outstanding superiority in energy harvest,synclastic curvature, variable permeability, elasticity,and durability.

In this work, a series of highly elastic, multi-scaleauxetic fabrics, which had different structure designs,were fabricated by incorporating HAYs in the weftdirection. Of particular note, a derivative weave withthe warp and weft yarns arranged in a series of zigzagwas prepared [49]. The HAYs were used in the preparation offabrics with negative Poisson's ratio (NPR), which haddifferent initial wrap densities. As proof of auxeticbehavior,a real-time recording of the woven fabrics structuredat different elongation levels was characterized using ahigh-resolution camera. Among all the as-preparedwoven fabrics, fabrics showed a maximum NPR valueof about _0.585 and total elastic deformation of 8.4% ata strain of 20% when the maximum NPR value of HAYsin the weft direction was _2.5. Meanwhile, the key geometricparameters used to tailor auxeticbehavior havebeen identified and systematically discussed, and it isproved that the fabric structure can make an obviousdifference to the auxeticbehavior. In addition, theHAY initial wrap density is another parameter that canbe utilized to optimize the NPR performance. Our workprovides a reform of mainstream convention textiles andcreates considerable potential for more practical applicationsof auxetic textiles.

In summary, we have achieved the fabrication of HAYsinto woven fabric by selecting different HAYs anddesigning different structures which may make a differenceto the NPR effect. Plain fabric, basket fabric, andderivative fabric with HAYs used as the weft yarn werefabricated to demonstrate the auxeticbehavior. Aftercomparison of various fabrics, the maximum NPRvalue of the derivative fabric with the warp and weftyarns arranged in a series of zigzags reached _0.585,which is much higher than the value of plain fabric anda basket fabric limited by intersections. In addition, thetensile behavior and elasticity of the textiles are extremelyimportant for daily use; thus, the complete loaddisplacementcurve and elastic deformation at a strainof 20 and 40% of hybrid fabrics were systematicallyinvestigated. We found that the deformation mechanismof all fabric follows the same rules and can be discussedin three regions. Importantly, the ultimatedisplacement as well as the breaking load of the derivativefabric mentioned above were superior when contrastedwith those of plain and basket fabrics. Theultimate displacement of fabric increased by about10% with the initial wrap density of the HAYs increasingfrom 150 to 300m_1. At the same time, a maximumtotal elastic deformation of 8.4%, which is composed ofinstantaneous elastic deformation (7.6%) and slowelastic deformation (0.8%), at a strain of 20% couldbe observed in the same fabric, which demonstratesthe practicability and superiority of the as-designedderivative fabric for a wide range of applications.

Furthermore, the weave structure and initial wrapdensity of the HAYs are proved to be an effective strategyin optimizing the auxeticbehavior and improvingthe maximum NPR value without replacing the rawmaterial and compromising the intrinsic properties ofthe components. More specifically, a small initial wrapdensity of the HAYs (large migration intensity of thecomponents in HAYs), long floats, and few intersectionpoints are desirable for generating excellent NPReffects and a higher NPR value. At the same time, thearchitecture design of the auxetic textiles can provideinspiration for their development in sensors or smartwearable devices. Our research not only promotes thediversification of auxetic textiles used in flexible wearabledevices and functional textiles but also providesconsiderable guidance to continuously improve theirstructure, controllability, and stability to push forwardtheir application in more fields.

3 Bi stretch auxetic woven fabrics

Auxetic fabrics can be produced by twoapproaches [50,51]. The first one is to fabricate auxeticfabrics by using auxetic fibres or yarns, and thesecond one is to fabricate auxetic fabrics from conventionalyarns by using special geometrical arrangements,as the auxeticbehavior is purely linked to the geometricalarrangements of structural units. The auxetic fabricsthat have been produced and investigated to dateinclude woven fabrics, weft knitted fabrics, warp knitted fabrics, textile structures for compositereinforcementsand non-woven fabrics [52-67].Knitted fabrics, both warp and weft knitted, aremostly produced by adopting the second technique.Auxetic weft knitted fabrics based on foldable geometriesand double arrowhead auxetic geometryhave been developed by various researchers. Auxeticwarp knitted fabrics have also been developed basedon spacer structure, rotational hexagonal loops,double arrowhead geometry and re-entrant hexagonalknit structures. Nevertheless, most of the developedauxetic knitted fabrics have certain limitations,such as high thickness, low structural stability andlow elastic recovery, which restrict their use in tightgarments. Furthermore, due to complicated geometricalstructures, most of the auxetic knitted fabricscould not be produced on a larger scale.

Auxetic woven fabrics can be fabricated by bothapproaches. To date, most auxetic woven fabrics havebeen produced based on regular interlacement patternsby directly using helix auxetic yarn (HAY), either in thewarp direction (WD) or in the weft direction(FD). Two types of auxetic woven fabrics producedby using HAYs in FD have been produced.

The first one yielded an out-of-plane NPR and an inplaneNPR up to _0.1 only when the fabric was testedunder thickness constraints. In the second type, threeweave patterns, namely, plain, 2/2 twill and 3/5(3) satin,were employed [68,69]. The auxeticbehavior of the woven fabricswith these constructions was tested by image analysis.The analysis showed that while both the plain andtwill fabrics exhibited the most auxeticity, the satinwoven fabric was significantly less auxetic.6 Auxeticwoven fabric made of HAYs in the WD was a twoplyplain woven narrow fabric. The fabric exhibitedan in-plane NPR in a strain range of 15–40%, reachinga maximum NPR value of 0.1 at 32% strain.

Recently, the use of non-auxetic yarns to produce auxeticwoven fabrics based on special geometrical arrangementshas also been reported. The reported fabricswere uni-stretch auxetic woven fabrics based on foldablegeometries, produced by using conventional elasticand non-elastic yarns in FD. The maximum NPR valueof -0.1 was achieved for these fabrics when stretchedalong FD. However, auxetic woven fabrics developedto date also have some major limitations. For example,in the case of auxetic woven fabrics made of HAYs, theauxeticbehavior of HAYs cannot be exploited fully dueto woven structural restrictions, and the auxeticbehaviour achieved is smaller and in one direction only. On theother hand, auxetic woven fabrics made of non-auxeticyarns have extensibility and a smaller NPR of 0.1only along the FD. Such limitations restrict their applicationin clothing. Auxetic woven fabrics made of conventionalyarns, having high extensibility and NPR inboth the FD and WD, reduced thickness, and betterformability that can easily be shaped into garmentsare yet to be developed. Such innovative fabrics mayhave great potential for clothing applications.

This paper reports a study that aimed to developsuch a type of fabric by using readily available inexpensiveconventional elastic and non-elastic yarns, andavailable weaving machinery. The phenomenon of differentialshrinkage is created to realize foldable geometryinto the woven architecture, and to produceauxetic fabrics with high extensibility and a largerNPR in both the WD and FD. As the fabrics havehigh extensibility in both the WD and FD, they arenamed 'bi-stretch' fabrics.

This study reports the development of a novel class ofbi-stretch auxetic woven fabrics by using conventionalelastic and non-elastic yarns and available weavingmachinery [70]. The phenomenon of differential shrinkageis created to realize parallel in-phase zig-zag doubledirectionalfoldable geometry running along the FDinto woven architecture. The developed fabrics exhibitedan NPR effect over a larger strain range whenstretched along the WD or FD. From this study, thefollowing conclusions can be drawn.

1. The parallel in-phase zig-zag double-directionalfoldable geometry can be realized into bi-stretchauxetic woven fabrics by creating differential shrinkagephenomena within the fabric structural unit celldue to combinations of loose and tight weaves, andthe use of non-auxetic elastic and non-elastic yarnsalong both the WD and FD.
2. The creation of the folded effect depends upon thenumber of completed yarn floats within the looseweave area. The greater the number of completedyarn floats within the loose weave area, the moreregular the resulting folded effect.
3. The shrinkage in the WD and FD is different. Highershrinkage is obtained in the FD.
4. By using the (L) weft yarn arrangement, the shrinkagein the FD is increased but the shrinkage in theWD is decreased.
5. The NPR effect in the WD and FD is different. Ahigher NPR effect is obtained when stretched alongthe WD.
6. The float length of loose weave has a significanteffect on the NPR behavior of fabrics. However,the higher float length does not mean that it willproduce higher NPR. The highest NPR effect is producedby the fabric with a float length of (3).
7. The weft yarn arrangement also has a significanteffect on the NPR. The (L) weft yarn arrangement can increase the NPR effect when stretched along the WD, but reduces the NPR effect when stretchedalong the FD.
8. The effect of float length on the NPR of a fabricsignificantly depends on the weft yarn arrangementwhen the fabric is stretched along the WD.

The range of auxetic woven fabrics that can be producedis extensive but it is a matter of continuingresearch. The phenomenon of differential shrinkage/non-uniform contraction profile can further beexploited to investigate the realization of other auxeticgeometries in the woven fabric structure. For example,out of phase zig-zag geometry is another variation ofthe foldable geometry. This geometry forms foldedstrips in the diamond-like pattern instead of the zigzagpattern, and could possibly be realized in a wovenfabric structure by employing the same design technique,and by using conventional elastic yarns andweaving machinery.

4 Conclusion

The derivative weave using HAYswith a 150m_1 initial wrap density as the weft yarn not only possesses superior auxeticbehavior but also has goodperformance in strength and elasticity—essential properties useful for textile daily application. This fabric exhibits a high auxetic effect, low elastic deformation (total deformation of 8.4% at 20% strain), excellent flexibility, andhigh break load. Moreover, by taking account of the key geometric parameters, a systematic discussion of the fabrics hasbeen completed to evaluate the effect on the auxeticbehavior; this clarified that changing the fabric structure and initialwrap density of a HAY is an effective strategy to tailor auxeticbehavior without compromising the intrinsic properties ofcomponents. On the basis of our research, auxetic textiles can be considered a promising candidate for next-generationsmart textiles and advanced functional textiles.

Bi-stretchauxetic woven fabrics were firstly designed based on a foldable geometry possessing negative Poisson's ratio by considerationof different design parameters, including the yarn float length, the placement of tight and loose weaves, and thearrangement of elastic and non-elastic yarns in the weft direction, and then fabricated on a dobby weaving machineequipped with multiple weft supplies and a separately controlled second beam assembly attachment. The fabricatedfabrics were finally tested on a tensile machine to assess their auxeticbehavior in both the warp and weft directions. Theresults showed that the bi-stretch woven fabrics developed exhibit negative Poisson's ratio up to 0.36 and 0.27 whenstretched along the warp and weft directions, respectively, and could be applied for clothing applications that requireenhanced shape fit and comfort.

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