Manufacture and Evaluation of Auxetic Yarns and Woven Fabrics

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Auxetic materials are a type of novel materials exhibiting negative Poisson’s ratio (NPR) with potentials for special applications. Herein, the aim is to optimize the auxetic yarn and fabric manufacturing processes, establish the understanding of the influence of yarn and fabric parameters on the auxeticity of the engineered materials and explore the potential applications of auxetic textile materials. The auxetic yarns are manufactured based on a conversional helical structure composing initially a super elastic polyurethane core and a high modulus Nylon 6.6 binder. A hollow spindle machine is used to produce the auxetic yarn with optimized twisting and delivery speeds. Stable helical yarns with auxetic properties are manufactured using the optimized parameters, and woven fabrics are produced from the selected auxetic yarns in both warp and weft directions. Experiments show that the maximum NPR of helical auxetic yarns reaches a remarkable level of $-5.6$, and the auxetic fabrics display notable geometric changes compared with the nonauxetic fabrics with the same structural parameters. The auxeticity demonstrated in the fabrics implies applications in areas such as filtration and impact protection.

1. Introduction

Auxetic materials expand in the transverse direction under tensile loading in the longitudinal direction, or contract when compressed, in contrast to the conventional materials. Negative Poisson’s ratio (NPR) was reported in natural materials by Viogt in the late 19th century. Evans et al. advised that NPR structures and materials could be renamed as “auxetics” for convenience from the Greek word “auxetos.” The auxetic characteristics have been reported on fundamental theory in 1989 and different structures including re-entrant structure, folded structure, honeycomb structure. Also, many auxetic materials have been discovered up to date. Iron pyrites were found auxetic with the Poisson’s ratio of $-0.14$, polyurethane foams were reported for a NPR value of $-0.7$, and warp-knitted and weft-knitted fabrics were found to demonstrate NPR effect too. Alderson and Evans experimented on microporous ultrahigh molecular-weight polyethylene (UHMWPE) and found the Poisson’s ratio ranged between 0 and $-1.24$.

There are two general approaches for making auxetic textiles. The first one is using the conventional yarns with specially designed fabric structures, such as the re-entrant structures and rotating structures made for knitted fabrics and bistretch auxetic woven fabrics with re-entrant hexagonal geometry. The other approach is to use auxetic yarns directly to make fabrics. Some researchers produced auxetic woven fabrics using double helix yarns, and their studies showed that such fabrics demonstrated some level of auxeticity and increased porosity. An out-of-register double helical yarns were used to produce double-pick woven fabrics by Miller et al. which showed that the two-layer fabric assembly had the auxetic effect with the Poisson’s ratio to be $-0.1$. In addition, Hu and coworkers created an auxetic yarn with a four-ply structure with the Poisson’s ratio of about $-2.0$, and it was used to make woven auxetic fabrics which demonstrated much smaller auxeticity. It has to be said that despite the progress in making fabrics from auxetic yarns, the responses of the fabrics under tensile loading need further clarification.

High modulus fibers together with an elastic core element are the most commonly used materials for manufacturing auxetic yarns. Helical auxetic yarns (HAYs) are one type of the most promising yarns for exploitation according to Hook. HAYs have been made of two or more plies of component yarns with different diameters and with extremely different elastic moduli. These plies were twisted together, with the thinner and stiffer yarn wrapping over the thicker and more elastic core ply. When stretched, the two types of plies would swap their roles, leading to a situation where the thinner and stiffer ply became the straight core and the thicker and more elastic ply turned into the binder, as shown in Figure 1. However, it remains to be a challenge to produce stable helical yarns, with matched lengths of the two yarn plies, that influences yarn auxeticity in a great
extent. Recently, to overcome the yarn slippage problem causing mismatched ply lengths, Liu et al. worked on the heat treatment for their two-ply auxetic yarns with a thermal melting component, to improve the structural stability. Another method is using circular braiding technology for making auxetic yarns, where the stiffer ply was directly braided onto the core helically. Researchers worked on yarns with more plies, and these yarns exhibited auxetic effect as well. However, the engineering design of the helical yarns for auxeticity and the setting of machine parameters call for further investigation.

Accordingly, this article aims to study the relationship between auxetic yarn structure and the machine parameters to create stable HAYs, and to create and evaluate woven fabrics made from the HAYs with optimal structural parameters. The concentration for this research is placed on the dimensional change between adjacent yarns within the fabrics and the dimensional change of the overall fabric. Uniaxial tensile test and low velocity impact test are conducted to evaluate the yarn and fabric mechanical properties.

2. Auxetic Yarns

2.1. Design of Auxetic Yarns

In this study, HAYs were manufactured by wrapping the a conventional polyamide multifilament ply of 16.5 tex over the highly elastic polyurethane multifilament ply of 241.1 tex. A hollow spindle fancy-yarn machine was used for making the auxetic yarn, where two or three plies of filaments can be twisted together with different wrapping relations among them. Different yarn manufacturing parameters, as shown in Table 1, were experimented on for producing auxetic yarns.

2.2. Physical Appearance of the Yarns

Seven yarn samples, Yarns 1–7 shown in Figure 2, were made using seven different twisting speeds in the range of 2000–5000 rpm with a fixed delivery speed of 12.5 m min\(^{-1}\). It is shown in Figure 2 that the yarn structure became more stable with higher twisting speed, and the wrapping was too loose when the twisting speed was set low as in the cases of Yarns 6 and 7. A stable structure features close wrapping of the binding filament around the core ply. The wrapping angle, as shown in Figure 1, is determined by the combination of the machine twisting speed, the yarn delivery speed, and the linear density of the core ply. The twist angle can be theoretically expressed as follows

\[
\alpha = \arctan \left( 4.44 \times 10^{-5} \frac{\pi \sigma}{V} \sqrt{\frac{T}{\rho}} \right) \tag{1}
\]

where \(\alpha\) is the wrapping angle (°), \(T\) is the core ply linear density (tex), \(\rho\) is the volume density of the core ply (g \(\text{cm}^{-3}\)), \(\sigma\) is the twisting speed (rpm), and \(V\) is the yarn delivery speed (m \(\text{min}^{-1}\)).

It was noted that Yarn 4 demonstrated a stable structure with an average helical angle of 34°. To find the boundary that the stable yarn with lowest helical angle, Yarn 8 was designed by adopting the twisting speed of 2000 rpm and the delivery speed of 7.5 m \(\text{min}^{-1}\), corresponding to the helical angle between that of Yarns 4 and 5. As shown in Figure 2b, Yarn 8 shows a more stable structure than Yarn 5, i.e., the gaps between the two plies in Yarn 8 is smaller. This exercise proved that the lowest helical angle to guarantee in a stable structure under this set up is about 34° which was used for making Yarn 4.

2.3. NPR Evaluation

Considering both yarn stability and auxetic behavior, the eight types of auxetic yarns were tested according to Standard ASTM D 3822 on an Instron testing machine together with the Instron Bluehill software. A microfocus camera (Jiusion 1000 \(\times\) USB Digital Microscope) was used during the tensile test to capture and record the yarn deformation. Upon achieving the yarn strains in the axial and transverse directions using ImageJ software, the Poisson’s ratio \(v\) was calculated using Equation (2).

\[
v = \frac{\varepsilon_{\text{trans}}}{\varepsilon_{\text{axial}}} \tag{2}
\]

where \(\varepsilon_{\text{trans}}\) is the transverse strain and \(\varepsilon_{\text{axial}}\) is the axial strain.

The deformation of an auxetic yarn under tensile loading can be described in four stages. Before loading, the wrapping filament ply stays on the core yarn helically without tension. At the initial loading stage, the outer contour of the auxetic yarn starts to contract because of the straightening of wrapping filament ply. In the second stage, the helical radius of the wrapping filament decreases, and the core elastic filament ply is forced to become helical too as tension in the whole yarn increases. When

Table 1. Manufacturing parameters and wrapping angles of auxetic yarns.

| Yarn   | Twisting speed [rpm]\(^a\) | Delivery speed [m min\(^{-1}\)] | Avg. helical angle [°] | Linear density [tex]\(^b\) |
|--------|-----------------|-----------------|-----------------|-----------------|
| Yarn 1 | 5000            | 12.5            | 38.96           | 269.2           |
| Yarn 2 | 4500            | 12.5            | 37.84           | 267.5           |
| Yarn 3 | 4000            | 12.5            | 36.38           | 265.4           |
| Yarn 4 | 3500            | 12.5            | 34.03           | 264.4           |
| Yarn 5 | 3000            | 12.5            | 29.87           | 263.8           |
| Yarn 6 | 2500            | 12.5            | 26.73           | 263             |
| Yarn 7 | 2000            | 12.5            | 25.22           | 261.8           |
| Yarn 8 | 2000            | 7.5             | 31.98           | 264             |
| Yarn 9 | N/A             | N/A             | 0               | 257.6           |

\(^a\)rpm: rounds min\(^{-1}\);
\(^b\)tex: a unit of weight for yarn, 1 tex equals to 1 g per 1000 m.

Figure 1. A HAY: a) the initial state and b) the loaded state.
the auxetic yarn is fully loaded, the wrapping and core filaments swap positions, that is, the former core filament turns to be the wrapper and the original wrapping ply becomes the new core. As a result, the outer contour of the auxetic yarn is expanded. If the yarn is further loaded, the new core is further extended until break. During this process, the profile size of the auxetic yarn becomes smaller. Figure 3 shows the Poisson’s ratios of Yarns 4, 5, and 8, respectively, where the Poisson’s ratios of the sample yarns increased at first due to the interaction between the wrap and the core. Then, the Poisson’s ratios decreased from the maximum values to the minimum, as the core filament ply started to deform and became helical around the stiff wrap filament ply. Finally, after the soft core had become helical, the Poisson’s ratios approached to the value of 0 as the axial yarn strain was further increased. Each type of yarn was tested 10 times, and the median value among all samples of Yarns 5 and 8 is shown in Figure 3. Figure 4 shows the appearances of the three different yarns, and some loops were observed in both Yarns 5 and 8. Comparison among the three yarns revealed that Yarn 5, with a maximum NPR of $-2.3$ on average, had a better auxetic behavior than Yarn 8 whose NPR is $-1.61$ on average; and that between Yarns 4 and 5, the volatility of Yarn 4 was lower than that of Yarn 5 although Yarn 4 has a lower NPR of $-1.5$, and it displays a more stable structure in Figure 4a which is an important factor for fabric production.

2.4. Analysis on Yarn Auxeticity

In the meantime, a yarn (Yarn 9) made from parallel polyamide and polyurethane filament plys, of nonauxetic nature, was tested for tensile behavior too for comparison purpose. The tensile behavior of HAY and that of the nonauxetic yarn are shown in Figure 5. The curve for the auxetic yarn demonstrated low initial tensile modulus because of the helical structural feature of the yarn, where the elastic polyurethane ply were extended easily, and the wrapping polyamide ply did not constrain the extension as it straightened when the whole yarn was loaded. The modulus of the yarn became higher gradually after the strain reached 20%. Further loading to the yarn made the polyamide ply more straightened and the polyurethane more helical until the two completely swapped positions. The auxetic yarn broke when the straightened polyamide ply failed. In the case of the nonauxetic yarn where the two plies were parallel, the tensile behavior shown in Figure 5 mainly came from the polyamide ply because it offers higher tensile rigidity. It is noted that the peak shapes for the two yarns are almost identical. Hence, with
the same components of the yarn, helical structure displayed a higher axial strain compared with parallel structure, and these two structures showed no significant difference in the value of breaking stress.

Figure 6 shows the maximum NPR of auxetic yarns produced with different helical angles. The Poisson’s ratio gradually reduced as helical angles decreased, corresponding to the principle that a lower helical angle leads to a higher auxetic behavior.[28] The maximum NPR achieved was −5.6 with the helical angle of ≈25°. During the experiments, it was found that even if the HAYs had been produced, some of them with a higher auxetic behavior were not suitable for fabric production due to the poor stability of these yarns.

3. Woven Fabrics Made from Auxetic Yarns

3.1. Selection of Yarns

Among the produced samples from Yarns 1 to 8, Yarn 4 with the helical angle of 34° manifested itself as the most appropriate yarn for weaving, because when the yarn helical angle was lower than 34°, the yarn structure became unstable. Therefore, Yarn 4 with acceptable auxetic effect was selected for producing a fabric because the stability of the yarn had to be the first consideration for the fabric stage.

3.2. Fabric Parameters

The woven fabric was produced on the ARM AG CH-3507 BIGLEN semiautomatic weaving machine, as shown in Figure 7. Yarn 4 of 264.4 tex, which is helically auxetic, was selected as warp and weft yarns for weaving the plain woven fabric, denoted as AF, with the warp and weft densities being 11 × 9 threads cm⁻¹, having the areal density of 526.2 g m⁻². For comparison purposes, another woven fabric, coded NF indicating nonauxetic fabric, was made from Yarn 9, a yarn with the same filaments but with a parallel yarn structure instead of helical. The warp and weft densities of fabric NF was also 11 × 9 threads cm⁻¹ but the areal density is 502.3 g m⁻².
The photographs of the two fabrics are shown in Figure 8. During the weaving process, the warp yarn sheet was given a 5% prestretch to meet the requirement for weaving. A constant basic warp tension level was maintained during the production process by controlling the let-off and take-up. The reed with 7.7 dents cm\(^{-1}\) was used, and 1 warp end was drawn into one dent to avoid yarn entanglement during weaving. The fabric density increased when the fabric was taken off loom, which is due to the property of the elastic materials and the tension applied in warp and weft yarn during weaving.

### 3.3. Characteristic of Fabrics Made from Auxetic Yarns

Fabric AF and NF were subjected to tests for tensile properties, fabric porosity, and impact properties, respectively. Three specimens were tested for each sample, and each test was carried out in both warp and weft directions.

#### 3.3.1. Tensile Properties and Porosity

Tensile tests were conducted on INSTRON 2519-107 with a crosshead speed of 100 mm min\(^{-1}\) and a gauge length of 100 mm. Three specimens for each AF and NF fabrics were tested three times in both warp and weft directions, and the results are shown in Figure 9. The number in the bracket presents the sample number of AF and NF. As shown, the variation in load-extension curves of NF (4)–(6) is larger than that of NF (1)–(3), because the tension and the density of the fabric in warp direction were controlled by the machine during weaving, while these parameters in weft direction were controlled

![Figure 7. ARM AG CH-3507 BIGLEN semiautomatic hand weaving machine.](image)

![Figure 8. Fabrics made from yarns of different structures. a) AF; and b) NF.](image)

![Figure 9. Tensile properties of AF and NF: a) warp direction and b) weft direction.](image)
Figure 9 shows that AF exhibited a low initial modulus and a big extension (≈70%). After the helical nylon yarn plies were straightened, they took the load applied to the fabric specimen. The nylon of AF started to break when the fabric were extended to around 70 mm, whereas the specimens of NF started to break at ≈35 mm elongation. NF undertook notably higher load than the AF, as the two components of the parallel yarn used in NF took on the load from the beginning of the test. Comparing the difference between the warp and weft directions, as shown in Figure 9, the AF (4)–(6) could bear more loads (around 400 N) than AF (1)–(3). The difference in load bearing of AF between the warp and weft directions may be associated with the fact that the warp yarns were repeatedly loaded during weaving by beat-up, whereas the weft yarns were hardly loaded in hand weaving. The pretension of the warp yarns could also influence the result.

To measure the porosity and the auxetic behavior of the fabrics, a microfocus USB video class (UVC) camera was set up on the top crosshead of the tensile machine in front of the fabric sample, as shown in Figure 10. Timed shots of the fabric sample were captured every 4 s during the tensile loading, which corresponded to a 6.67% strain interval shots. Images, containing 640 × 480 pixels, were exported and measured by ImageJ software. Equation (3) is used to calculate the fabric porosity based on the ImageJ measurements.

\[ \varphi = \frac{P_o}{P_t} \times 100 \]  

where \( \varphi \) is the porosity of the fabric, \( P_o \) is the total number of pixels of all pores, and \( P_t \) is the total number of pixels of whole image.

Figure 11 shows the changes of porosity of AF and NF in both warp and weft directions as the fabric specimens were tensile loaded. It is noted that AF had a higher porosity than that of NF at all levels of strains, and the difference increases as the strain became higher. This is believed to be associated with the mechanical properties of the yarns used for AF and NF fabrics. Figure 12 shows the different configurations of the yarns in fabrics under loading tension. When stretched in a warp direction, the yarns were deformed to either synclastic form or symmetrical form, and it is apparent that the pores were larger formed among auxetic yarns compared with that among parallel yarns. The initial porosity of AF was slightly higher than that of NF due to the fact that the HAYs ended up with larger thread spacing. In addition, the porosity of AF was demonstrated ≈3 times as large as that of NF just when the fabrics started to fail.

The Poisson’s ratio was calculated from the data obtained from the tensile testing. The dimension changes of the fabric were measured at every timed interval by ImageJ software and the maximum NPR of AF was –0.052 in weft direction and –0.025 in warp direction, respectively. The auxetic behavior of the woven fabric was much smaller than that of the auxetic yarns. This could be explained by the crimp interchange. When the woven fabric was loaded in the warp (say) direction, the crimp in warp yarn was reduced and that forced the crimp in the weft yarn to increase, resulting in narrowing down of the fabric in the weft direction. When the fabric density was high, the auxetic yarns would be pushed with each other, but the expansion of the fabric may still be minimal because of yarn deformation in the transverse direction and the crimp interchange as described earlier. If the fabric density was low, the deformed...
auxetic yarn would not influence the fabric dimension because increase in the outer contour diameter of the yarn was still smaller than the gap between two adjacent yarns. Because of all these, it could be deduced that the auxetic behavior of woven fabrics could not be expected purely based on dimensional changes.

Associated to the porosity analysis earlier, air permeability of AF and NF fabrics were conducted using the ADL ATLAS Tester with a test area of 20 cm², which is shown in Figure 13. AF and NF fabric samples together with a pure polyurethane fabric sample PUF, which was made for comparison purposes only, were tested for their air permeability. Each sample was test three times at different levels of pressure. Figure 14 shows the average data of air permeability with applied pressures ranging from 200 to 300 Pa. For different levels of pressure, the air permeability of PUF fabric was the highest, followed by that of the AF and NF. Compared with AF and PUF fabric, NF displays the lowest air permeability because the deformation of the pore areas under pressure was restricted by the nylon filament in the parallel structure of the yarn. In contrast, PUF was fully elastic, and when pressure was applied it would be pushed open without external restriction, and therefore demonstrated the highest air permeability. Due to the helical structure of the auxetic yarns, AF fabric deformed relatively easily until the moment when the stiffer ply became straightened. Considering both air permeability and porosity of AF, it is seen that the air permeability of AF fabric could be made different with control, and therefore would have potentials for filtration. Based on the results of HAYs, it could be seen that the porosity of the AF fabric may be changed by adjusting the helical angles in the yarn.

3.3.2. Impact Property

Impact testing was conducted on Dynatup Model 8200 Instrument with 4 kg of drop mass. Single layer fabrics were used as test samples. Figure 15 shows the energy and the load of AF and NF against the fabric deflection, with the impact speed being 1.5 m s⁻¹. The result showed that NF received an 18% higher resistant load than AF during the impact test and AF displays a 20% larger deflection than NF. Experiments also led to the finding that during an impact event, AF absorbed more energy than NF because of its higher extensibility, as shown in Figure 15.

Figure 16 shows the load and the energy of AF with the impact speed of 1, 1.5 and 2 m s⁻¹, respectively. It was found that the maximum load of AF is ≈0.3 kN. As for the speed of 1 m s⁻¹, the tested fabric is not broken and the highest load is less than 0.2 kN, meaning that the fabric could withstand more loads and energy. The surface of the fabric after impact is shown in Figure 17a. It is obvious that nylon is a little loose and located below the polyurethane due to its low elasticity. At the speed of 1.5 m s⁻¹, the nylon, which is the wrap filament of the auxetic yarn, is broken. The appearance of the fabric surface is shown in Figure 17b. The deflection of AF is slightly higher than the first one. At the impact speed of 2 m s⁻¹, the fabric is totally broken, and this situation is shown in Figure 17c. It is noted from Figure 16 that after the failure of the nylon ply, the polyurethane ply became load bearing and the second peaks in load and energy appeared. In Figure 16a, the load of AF with the speed of 2 m s⁻¹ declines sharply at the deflection of 30 mm. Then, it rises slowly...
and arrives to another peak of the load which is $0.1 \, \text{kN}$. Unlike the tensile properties of auxetic fabrics, the nylon bears the force at first from the deflection of $0$–$30 \, \text{mm}$ until it is broken, and the polyurethane bears the force from the deflection of $30$–$120 \, \text{mm}$. In Figure 16b, the total energy absorption is higher with the increasing speed of impact. This could provide a good reference for the impact applications.

4. Conclusions

HAYs with different parameters were manufactured for the optimization of auxeticity and the structural stability, and woven fabrics with helical and parallel yarn structures were created for characterization. Parameters of the yarns and fabrics have been analyzed on properties including helical angles of the yarns, tensile properties, Poisson’s ratios, porosity, impact property, as well as air permeability. According to the experimental results, the following conclusions are drawn. 1) A lower helical angle leads to a higher auxetic behavior theoretically, however, some of the yarns with a low helical angle could not be used for making fabrics due to the poor structural stability hence the quality of the yarn. Based on the combination of the elastic yarn and stiffer yarn, the maximum NPR of HAY was achieved at $-5.6$. 2) Auxetic yarn with a helical structure has a higher axial strain compared with the yarn which has a parallel structure and these two structures have no significant effect on the value of stress. 3) Auxetic woven fabric made of HAYs in both weft and warp directions has been manufactured and evaluated, the auxetic behavior of which is found not significantly obvious with maximum NPRs of AF being $-0.052$ in weft direction and $-0.025$ in warp direction, much smaller than that of the auxetic yarn. Thus, the woven fabrics such made should not be expected to be auxetic in dimensional changes but in other aspects which will be reported in subsequent papers of ours. 4) Increased fabric porosity was observed in AF because of the behavior of the auxetic yarns, and the permeability can be controlled by adopting different helical angles of the yarn. This indicates special applications for fluid filtration. 5) Impact tests revealed that one layer of AF has higher energy absorption than that of NF under the same impact conditions. This calls for further investigation for special applications.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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