Tensile and Forming Properties of Auxetic Warp-knitted Spacer Fabrics

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Abstract: Poisson's ratio is defined as the negative ratio between the lateral strain and the longitudinal strain of a material under tensile or compressive loading condition. Auxetic fabrics are those having negative Poisson's ratio (PR), which means that when their longitudinal strain is positive, their lateral strain is also positive, and vice versa. In this work, tensile and forming properties of auxetic warp-knitted spacer fabrics were investigated and compared with those of the conventional warp-knitted spacer fabrics. Both uniaxial tensile tests and hemi-spherical compression experiments were conducted, and the relationships of the tensile and forming properties with auxetic effect were discussed in terms of different fabric structural parameters. The results show that the auxetic warp-knitted spacer fabrics have a prolonged low stress stage in the wale direction, indicating that they are more prone to undergo deformation along wale direction, and the fabric with longer low stress stage has better auxetic effect. The results also show that the formability of auxetic warp-knitted spacer fabrics is much better than that of conventional warp-knitted spacer fabrics due to much low forming energies required under hemi-spherical compression, and can be affected by many factors such as auxetic effect, fabric thickness and stiffness, yarn materials and the structure of spacer layer. When all other parameters are similar, auxetic fabric with better auxetic effect will have better formability. The study has provided useful information for the design and application of this type of nonconventional spacer fabrics.

Keywords: Tensile behavior, auxetic fabric, knitting, spacer fabric, formability

1. Introduction

Poisson's ratio is defined as the negative ratio between the lateral strain and the longitudinal strain of a material under tensile or compressive condition. Auxetic fabrics are those having negative Poisson's ratio (PR) [1], which means that when their longitudinal strain is positive, their lateral strain is also positive, and vice versa. Auxetic fabrics laterally expand when stretched or laterally shrink when compressed. Compared to conventional fabrics with positive Poisson's ratio, auxetic fabrics exhibit a number of unusual properties, including excellent formability, enhanced air permeability and reduced clothing pressure. Such properties are very useful in making of functional garments for sportswear and medical care applications [1].

To date, a number of auxetic fabrics have been developed and manufactured by different technologies such as weaving [2], knitting [3], non-woven [4] or others [5]. Weaving technology was first employed to produce auxetic fabrics from the helical auxetic yarn by Miller et al [2]. However, due to the constraints imposed by woven structures, the auxetic effect of the woven fabrics is not as good as that of the auxetic yarn. In comparison with weaving, knitting is more suitable for producing auxetic fabrics due to its flexibility in structure design and fabrication process. Hu et al. [3] and Liu et al. [6] first used weft knitting technology to produce auxetic fabrics. Based on different auxetic geometries including re-entrant hexagons, rotating units and folded structures, various weft-knitted auxetic fabrics were knitted with electronic flat knitting machines. Glazzard et al. [7] also explored auxetic weft-knitted fabrics from a design perspective. Inspired by double arrowhead geometry, they produced a special type of auxetic fabrics made of purl rib structure to achieve chevron shape, and suggested that auxetic fabrics would be more interesting and useful by collaborating knitting technology and design together. Compared with weft knitting, warp knitting is more suitable for making open structures which are essential for many auxetics.

Ugbolue et al. [8, 9] developed a group of warp-knitted auxetic fabrics based on the re-entrant hexagonal structure. Highly elastic yarns were employed to realize the auxetic effect and the PR could reach -0.86. Alderson et al. [10] developed another type of warp-knitted fabrics based on double arrowhead geometry using three types of yarns. While two types of yarns were used to form the auxetic component, another type of yarn was used to form the stabilizing component in the warp-knitted structure. However, the developed fabrics only demonstrated auxeticity in the diagonal directions. Non-woven technology was also adopted for producing auxetic fabrics. Verma et al. [4] developed a type of non-woven auxetic fabrics by post-processing method and the non-woven fabrics obtained showed an auxetic effect in the thickness direction. Apart from single technology, Ge et al. [5, 11, 12] combined non-woven and stitching together to manufacture 3D auxetic textile structure for composite reinforcement. In this type of structure, the auxetic effect was realized when compressed in the thickness direction.

Spacer fabrics are a type of 3D textile structures formed by connecting two fabric layers with a layer of spacer yarn, and have been applied in different areas, such as automotive [13], impact protection [14-16], sound absorption [17], medical care [18, 19], etc. In our previous studies [20-22], auxetic fabrics with in-plane negative PRs up to -2.6 [20] were successfully developed based on conventional warp-knitted spacer fabric structures by modifying their outer layer geometry through a compression and heat-setting process. The deformation behaviors [21] of the developed fabrics were studied based on the experimental observations of the fabric unit cells and two semi-empirical models were built for predicting their PR values. A finite element model was also developed to simulate the deformation behaviors of these auxetic fabrics, and the simulated fabrics were very close to the real ones [22]. However, the previous studies are still limited and they do not account for the auxetic behaviors of this type of auxetic fabrics. In addition, until today the studies on mechanical behaviour of auxetic fabrics are not sufficient to deal with this type of auxetic fabrics [9, 23]. Therefore, it is of great significance to fill up this gap of research.

Since the auxetic effect of these auxetic warp-knitted spacer fabrics is realized in the state of tension, the tensile property is very interesting and has a relationship with the auxetic behaviors. Formability is another interesting property of auxetic fabrics, which is very important for both garment and industrial uses. Fabrics with good formability are easier to fit the human body and exert less pressure to the wearer, bringing garments with a more comfortable feel and elegant appearance. It is well known that knitted fabrics have better formability than woven fabrics due to their extensible knitted loops [24]. Compared to conventional knitted fabrics, auxetic knitted fabrics fit even more better on a curved surface because of the formation of synclastic curvature when bent [20], which gives auxetic knitted fabrics much better formability. This paper presents a further study on the tensile behavior and formability of auxetic warp-knitted spacer fabrics.

2. Experimental

2.1 Preparation of auxetic spacer fabrics

Auxetic spacer fabrics were made from existing conventional warp-knitted spacer fabrics as base fabrics by a compression and heat-setting process [20]. As shown in Fig. 1, the base fabrics were made of polyester multifilament yarn as outer layers and polyester monofilament yarn as spacer layer. The base fabrics were first compressed along their wale direction (Fig. 2) to transform their outer layer geometry from conventional hexagons (Fig. 1a) to diagonal hexagons (Fig. 1k). Then the compressed fabrics were subjected to a heat-setting process to keep this geometrical configuration to obtain the final auxetic fabrics (Fig. 1e). The heat-setting process was carried out in an oven, and the condition was set at 200 degree Celsius for 25 minutes. Three types of base spacer fabrics (Base fabric A, Base fabric B and Base fabric C) were used. Their details are listed in Table 1. All the base fabrics have the same outer layer hexagonal geometry. They are different in the spacer yarn connecting method and hexagon size. Base fabrics A and B have the same size of hexagonal geometry, but the spacer yarns of Base fabric A cross through the hexagons (Fig. 1b), and those of Base fabric B do not (Fig. 1c). Base fabric B and Base fabric C have the same method for spacer yarn connecting, but Base fabric C has the smaller size of hexagons and less thickness (Fig. 1d). All the three base fabrics were compressed to a compression strain of 50% to produce auxetic fabrics. In order to make the comparison, another two compression strains (40% and 45%) were also used for Base fabric B as it was the fabric easiest to be transformed to auxetic fabrics with better geometry regularity as compared to Base fabric A and C, because the crossed yarns hindered the compression of Base fabric A, and the ribs of Base fabric C were thinnest, which caused more irregular units after transformation. Therefore, five auxetic fabrics, namely Auxetic fabric A (Fig. 1f), Auxetic fabric BS (Fig. 1g), Auxetic fabric BM (Fig. 1h), Auxetic fabric BL (Fig. 1i) and Auxetic fabric C (Fig. 1j) were produced. As shown in Fig.1k, four geometrical parameters, long rib length L_0, short rib length l_0, angles α_0 and β_0, are enough to determine the geometry of the auxetic spacer fabrics. The values of these geometrical parameters and thickness for each auxetic spacer fabric are provided in Table 2.

Table 1 Details of base spacer fabrics

	Base fabric A	Base fabric B	Base fabric C
Outer layer yarn	400D/96F Polyester DTY	400D/96F Polyester DTY	150D/48F Polyester DTY
Spacer layer yarn	0.15mm Polyester monofilament	0.12mm Polyester monofilament	0.10mm Polyester monofilament
Chain notation of Base fabric A	GB1: (1-0-0-0/1-2-2-2)*3/(2-3-3-3/2-1-1-1)*3// GB2: (2-3-3-3/2-1-1-1)*3/(1-0-0-0/1-2-2-2)*3// GB3: 4-5-4-3/4-5-2-1/2-3-2-1/4-5-4-3/4-5-4-3/4-5-3-2/3-4-3-2/3-4-1-0/1-2-1-0/3-4-3-2/3-4-3-2/4-5-4-3// GB4: 1-0-1-2/1-0-3-4/3-2-3-4/1-0-1-2/1-0-1-2/1-0-2-3/2-1-2-3/2-1-4-5/4-3-4-5/2-1-2-3/2-1-2-3/1-0-1-2// GB5: (2-3-3-3/2-1-1-1)*3/(1-0-0-0/1-2-2-2)*3// GB6: (1-0-0-0/1-2-2-2)*3/(2-3-3-3/2-1-1-1)*3//		
Chain notation of Base fabric B and Base fabric C	GB1, GB2,GB5 & GB6 are the same as Fabric A GB3: 4-5-4-3/4-5-4-3/4-5-4-3/4-5-4-3/4-5-4-3/4-5-3-2/3-4-3-2/3-4-3-2/3-4-3-2/3-4-3-2/3-4-3-2/4-5-4-3// GB4: 1-0-1-2/1-0-1-2/1-0-1-2/1-0-1-2/1-0-1-2/1-0-2-3/2-1-2-3/2-1-2-3/2-1-2-3/2-1-2-3/2-1-2-3/1-0-1-2//		

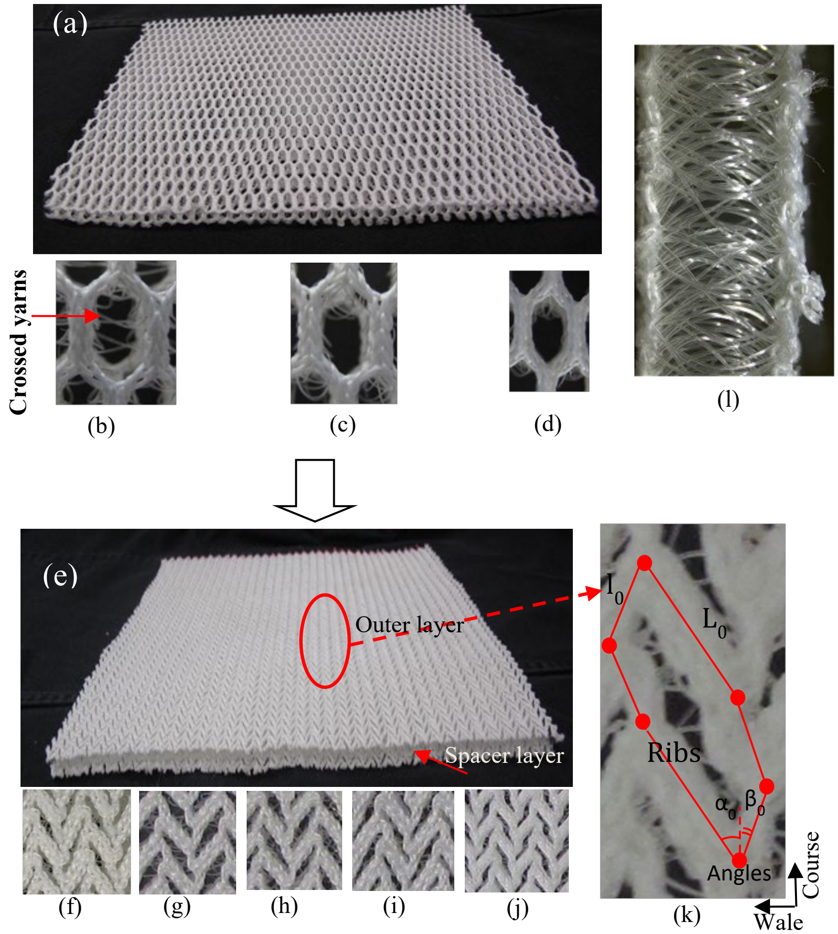


Fig.1 Photos of spacer fabrics: (a) 3D view of a conventional spacer fabric; (b)/(c)/(d) Amplified hexagon unit of Base fabrics A/B/C; (e) 3D view of an auxetic spacer fabric; (f)/ (g)/ (h)/ (i)/ (j) Amplified outer layer of Auxetic fabrics A/BL/BM/BS/C; and (k) Amplified hexagon unit of auxetic fabric (l) Side view of a conventional spacer fabric

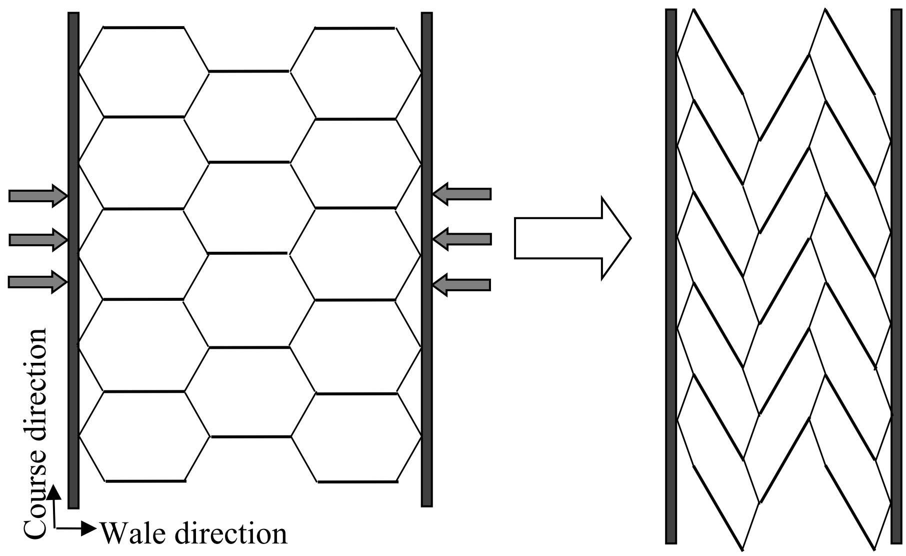


Fig.2 Schematic of compression process

Table 2 Geometrical parameters of auxetic spacer fabrics produced

Fabric name	Base fabric	Compression strain (%)	Thickness (mm)	L_0 (cm)	l_0 (cm)	α_0 (degree)	β_0 (degree)
Auxetic fabric A	A	50	7.4	0.44	0.221	32	24
Auxetic fabric BS	B	50	7.9	0.44	0.220	32	23
Auxetic fabric BM	B	45	7.8	0.44	0.222	36	30
Auxetic fabric BL	B	40	7.6	0.44	0.224	40	32
Auxetic fabric C	C	50	5.9	0.32	0.160	31	24

2.2 Tensile tests

The tensile tests of the produced auxetic warp-knitted spacer fabrics were conducted on an Instron 5566 tensile device equipped with a 10kN load cell. The test followed ISO Standard 13934-1:2013 with modification of the gauge length from 200mm to 150mm. Due to the anisotropic behaviors of the warp-knitted spacer fabrics, each type of fabric was tested along the course direction and the wale direction, respectively (Fig.3). The sample size was 200mm x 50mm and the tensile speed was 50mm/min. In order to get the information of fabric sample size changes during the test for calculating PR, nine dots were marked on each sample as shown in Fig.4. A camera with a timer shot function was used to take a photo of the tested sample in every 6 seconds, which corresponded to a tensile strain of 3.33%. From the photos obtained, the values of the original length (X_0) and width (Y_0) as well as their variations X and Y during the test for each fabric sample were obtained for calculating the tensile strain ε_a and transverse strain ε_t using Eq.1 and Eq.2, respectively.

$$\varepsilon_a = \frac{X - X_0}{X_0} \tag{1}$$

$$\varepsilon_t = \frac{Y - Y_0}{Y_0} \tag{2}$$

After the tensile strain ε_a and transverse strain ε_t were known, Poisson's ratio υ was calculated from Eq.3.

$$\upsilon = -\frac{\varepsilon_t}{\varepsilon_a} \qquad (\varepsilon_a \neq 0) \tag{3}$$

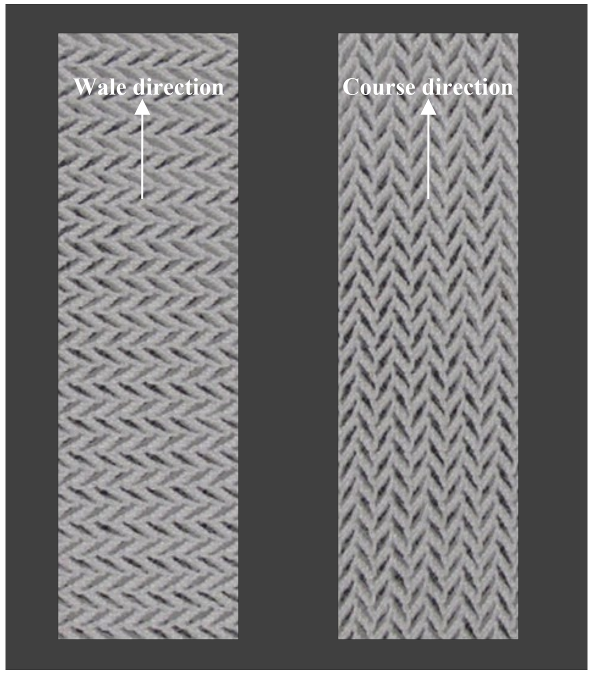


Fig. 3 Fabric samples in different directions

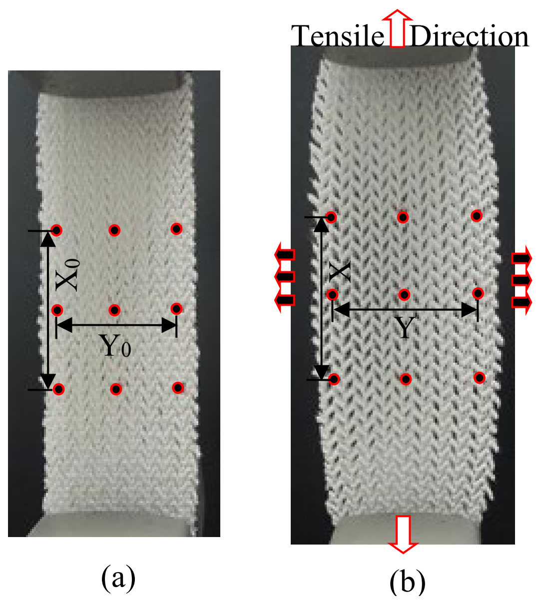
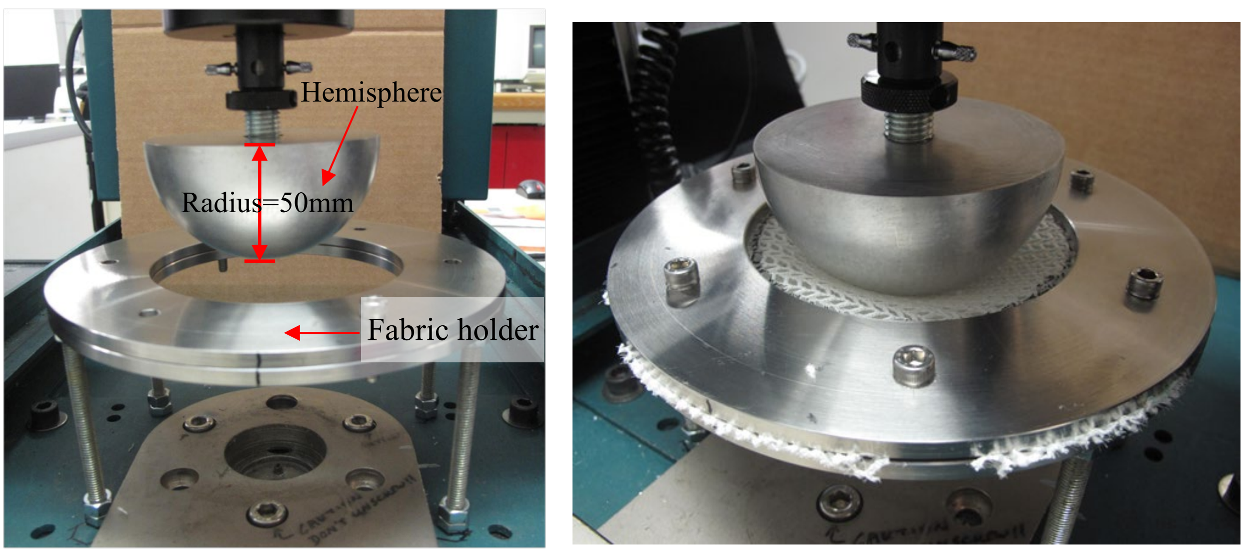


Fig.4 Points marked on auxetic fabric: (a) Initial state; (b) Extended

2.3 Formability tests

The formability is the capacity of a fabric to shape into a specific geometry. A fabric with good formability will require lower forming energy, has fewer or no formation of wrinkles, and does not breaks easily in the forming process. In this study, a self-made hemispherical compression device was used to evaluate the formability of the auxetic spacer fabrics. As shown in Fig.5a, the hemispherical compression device consists of two separated parts, a hemispherical plunger (made of aluminum), and a fabric holder (made of stainless steel). The hemispherical plunger was attached to the load frame of an Instron 5566 machine by a connector. It was used for compressing the fabric along the vertical direction. The diameter of plunger used was 100mm. The fabric holder was used to tightly hold the fabric sample during test as shown Fig.5b.



(a) (b)

Fig.5 Hemispherical compression test: (a) Testing device; (b) Fabric under test

The compression process was conducted with a compression speed of 50mm/min. It stopped when the sample was broken or the plunger reached to the maximum displacement which was 50mm when the plunger totally penetrated to the fabric holder. The testing data, including the compression forces and the displacements of the hemispherical plunger, were recorded by the testing machine automatically at every 0.1 seconds. From these recorded data, the total forming energy accumulated from the initial compression to the maximum displacement or breaking of the sample could be approximately calculated from Eq. 4:

$$W = \sum_{i=1}^{max} F_i \Delta x \quad (4)$$

Where W is the total forming energy (Unit: Joule), i is the number of recording point, F_i is the force recorded at each recording point (Unit: Newton), and Δx is the increment of displacement of the plunger (Unit: Meter).

3. Results and discussion

3.1 Tensile properties

3.1.1 Comparison between conventional base fabric and auxetic fabric

Base fabric B and Auxetic fabric BS were selected as examples to compare the tensile properties of conventional and auxetic warp-knitted spacer fabrics, since Auxetic fabric BS was found to have the best auxetic effect among the auxetic fabrics produced. The stress-strain and PR-strain curves of both fabrics are shown in Fig.6a and Fig.6b, respectively. It can be found from Fig.6a that in the course direction, the strain range of the two fabrics are not very different, but the peak stress of Auxetic fabric BS is higher than that of Base fabric B. The peak stress of Auxetic fabric BS is 2.3Mpa, which is about twice of the peak stress value of Base fabric B. The reason is that Auxetic fabric BS is made of Base fabric B by a 50% compression strain in the wale direction, which results in a double density of Auxetic fabric in the course direction. While for the wale direction, the difference of their peak stresses is relatively smaller, but the strain range of Auxetic fabric BS is much higher than that of Base fabric B. While Base fabric B could be only extended to 50% strain, Auxetic fabric BS could be extended to 225% strain. The same reason as above mentioned could be used to explain this phenomenon. As Auxetic fabric B is obtained by compressing Base fabric B in the wale direction during the fabrication process, a decompression process takes place in the beginning stage of the extension. In this stage, only small tensile force can cause a large deformation of the auxetic fabric. Therefore, a prolonged low stress stage (defined as lower than 1% of the peak stress) appears in the wale direction of Auxetic fabric BS. The compression process of the base fabric to obtain the auxetic effect also causes a reduction in the peak stress of auxetic fabric due to a small damage of regularity of fabric geometry.

Regarding the PR, it can be seen from Fig. 6b that Auxetic fabric BS has very obvious auxetic effect with a highest negative PR of -2.6 when stretched in the course direction. Since PR is defined as the negative ratio of the transverse strain to the tensile strain, the PR is affected by the values of these strains. When stretched in the course direction, the course direction contributes to the tensile strain and the wale direction contributes to the transverse strain. As mentioned above, the tensile stress of Auxetic fabric BS is very low in the wale direction in the initial stage. Therefore, the wale direction, as the transverse direction, is very easy to be deformed when stretched in the course direction and a high transverse strain is yielded. As a result, the high auxetic effect is obtained when stretched in the course direction. However, when stretched in the wale direction, the course direction as the transverse direction is not easy to open up, which yields low transverse strain. That is why the auxetic effect in the wale direction is not so evident.

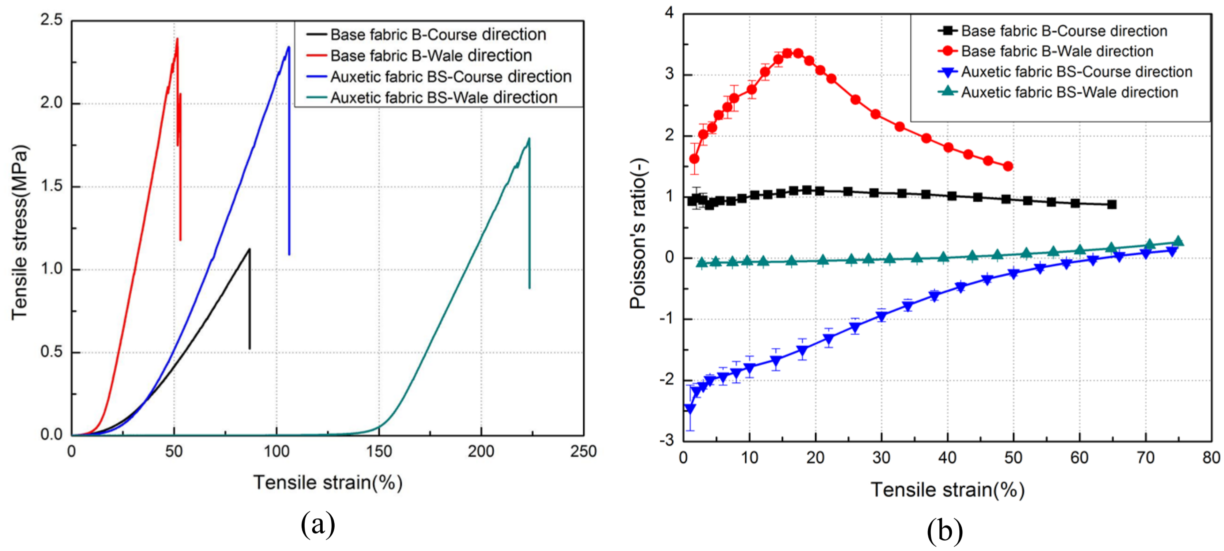


Fig.6 Comparison between conventional base fabric and auxetic fabric: (a) tensile stress-strain curves; (b) PR-strain curves

3.1.2 Effects of compression strain and structural parameters

Effects of the compression strain or α_0 and β_0 on tensile properties and auxetic effect of auxetic fabrics are shown in Fig. 7. Auxetic fabrics BS, BM, and BL were made of the same Base fabric B, but with different compression strains. Although rib lengths L_0 and l_0 in their outer layer unit geometry are maintained the same, angles α_0 and β_0 are different. The higher the compression strain, the smaller α_0 and β_0 are obtained, and vice versa. The smallest α_0 and β_0 could be obtained when the fabric is fully compressed. As shown in Table 2, Auxetic fabric BS has the smallest α_0 and β_0 and Auxetic fabric BL has the largest α_0 and β_0.

From Fig. 7a, it can be found that the auxetic fabric with smaller α_0 and β_0 has higher peak stress in the course direction. The peak stress for Auxetic fabric BS, BM and BL is 2.3MPa, 1.9MPa, and 1.7MPa, respectively. The reason is that the auxetic fabric with smaller α_0 and β_0 has higher density in the wale direction, resulting in higher peak stress in the course direction. From Fig.7b, it can be found that all the three fabrics have prolonged low stress stage (defined as lower than 1% of the peak stress) in the wale direction, and the smaller α_0 and β_0 are, the longer low stress stage is obtained. The low stress stages could reach tensile strains of 140%, 130% and 110% for Auxetic fabric BS, BM, and BL, respectively, indicating that all these auxetic fabrics are very easy to be deformed in the wale direction.

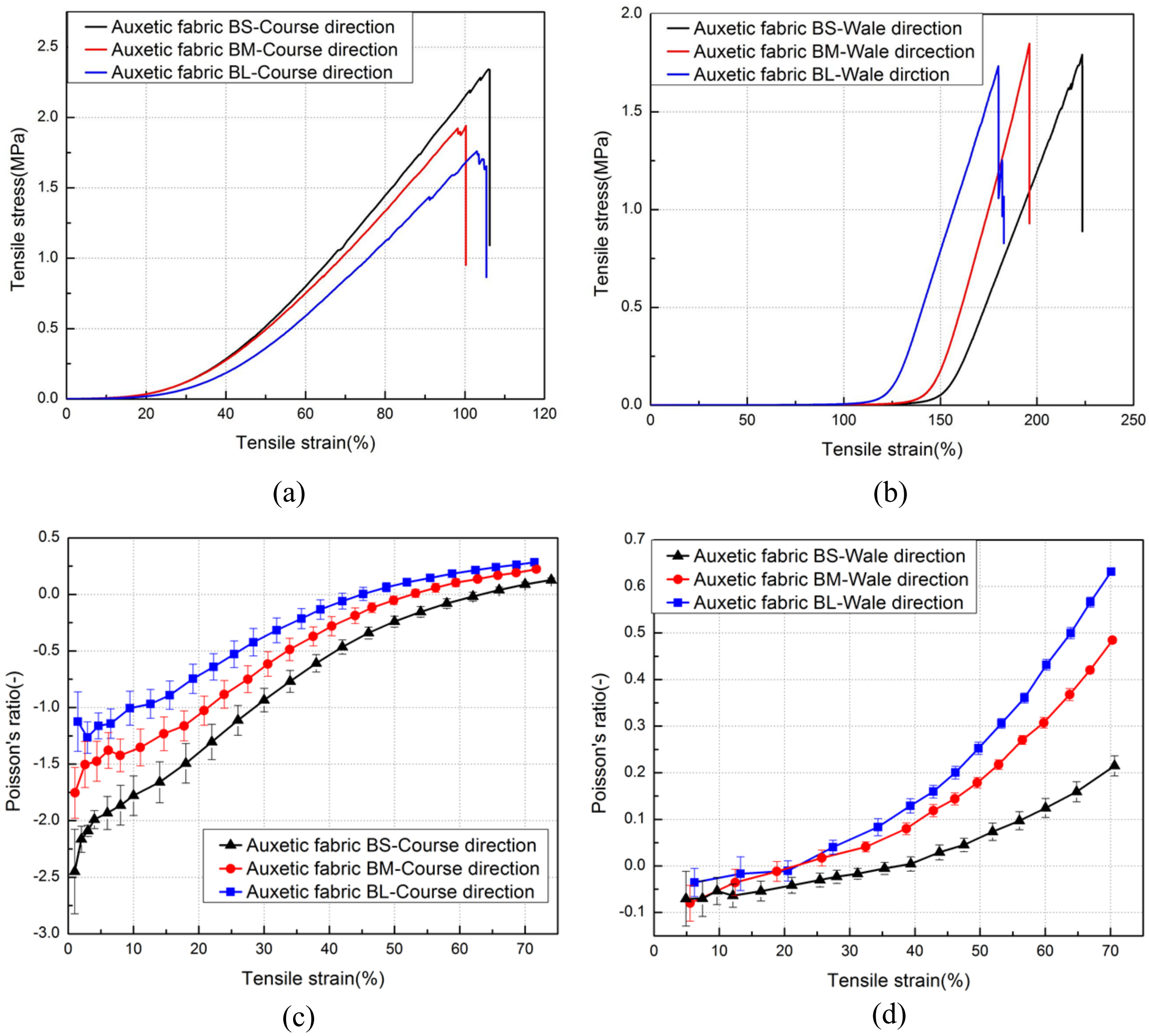


Fig. 7 Effects of α_0 and β_0 on tensile properties and auxetic effect of auxetic fabrics: (a)/(b) Tensile stress-strain curves; (c)/(d) PR-strain curves

Regarding the PR, it can be seen from Fig.7c and 6d that the effect of α_0 and β_0 are similar in both course and wale directions. When stretched in the course direction, the auxetic effect of three fabrics increases with the decrease of α_0 and β_0. The same effect can be found when stretched in the wale direction, the auxetic effect of three fabrics also increases with the decrease of α_0 and β_0. The results confirm again that the auxetic effect is much better when stretched in the course direction than when stretched in the wale direction. As aforementioned, the wale direction is the transverse direction when stretched in the course direction. The auxetic fabric with smaller α_0 and β_0 has longer low stress stage in the wale direction, which means that the auxetic fabric with smaller α_0 and β_0 is easier to be deformed in the transverse direction and yields more transverse strain. Therefore, Auxetic fabric BS with the smallest α_0 and β_0 has higher negative PR and keeps negative to a higher strain when stretched in the course direction.

Corresponding to the deformation of the auxetic fabric unit cell when stretched in the course direction, as shown in Fig.8a, it can be found that the original state of the short ribs along the tensile direction are relaxed and curved. In the first 20% tensile strain, the ribs become tensioned and straight to the tensile direction as shown in Fig. 8b. In this stage, the main deformation is the rotation and straightening of the ribs, so the required tension force is very low, which reflected on the stress-strain curves as the initial low stress stage as shown in Fig.7a. Another phenomenon can be found from the unit cell is that the fabric opens up a lot in the transverse direction during the first 20% strain. That is why the fabrics have very good auxetic effect in the first 20% tensile strain. When angles α_0 and β_0 get smaller, the fabric is more compact and opens up more, giving better auxetic effect. After the ribs become straight, the extension of the fabric mainly comes from the extension of the ribs. Therefore, the required tension forces are higher, and a higher stress stage is reached.

When stretched in the wale direction, as shown in Fig.9, there is an obvious decompression stage of the fabric at the beginning of the tension. The diagonal hexagonal units gradually are recovered to the conventional hexagonal units, and then the ribs continue to rotate to the tensile direction until they are totally aligned with it as shown in Fig.9d. During this process, only a low load is needed for the rotating and straightening of the ribs, and the extension of the fabric is very large. This is why a prolonged low stress stage appears on the stress-strain curves when stretched in the wale direction as shown in Fig.7b. In the first 20% strain, from Fig. 9a and Fig.9b, there are not too much changes can be found in the width of the fabric unit, but one of the short rib (as pointed by arrow in the Fig. 9a) in the unit is curved in the original state, and it becomes straighter during tension as shown in Fig.9b, that may be the reason that the fabric has very small auxetic effect in the first 20% strain in this direction.

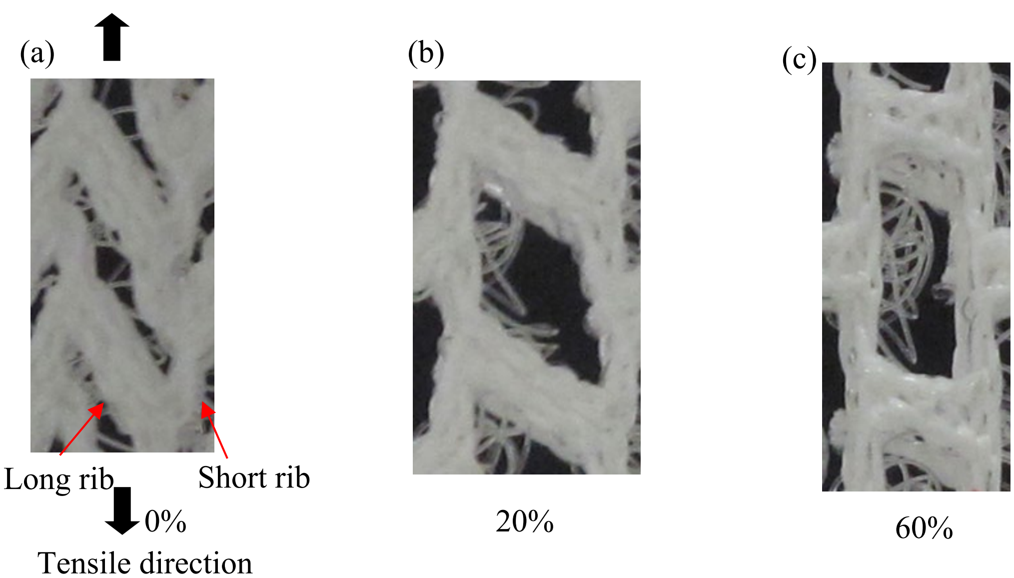


Fig. 8 Deformations of an auxetic fabric unit at different strains when stretched in the course direction

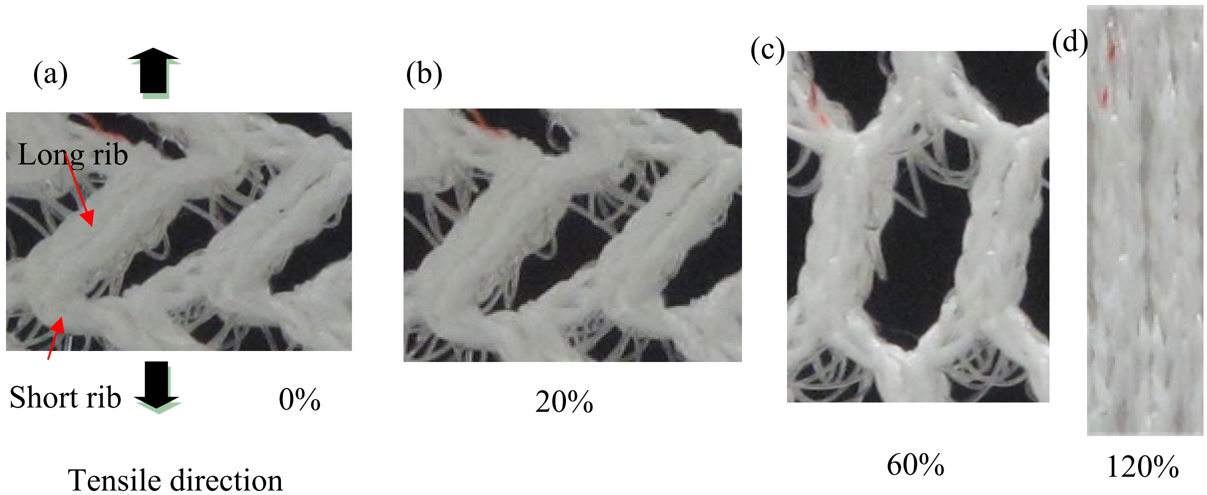


Fig. 9 Deformations of an auxetic fabric unit at different strains when stretched in the wale direction

Effects of rib length and spacer layer structure on tensile properties and auxetic effect of auxetic fabrics are shown in Fig. 10. Auxetic fabric BS and C have the same knitted structure and the same geometry angles α_0 and β_0, but they have different rib length as shown in Table 2. From Fig.10a and 10b, it can be found that the peak stresses of Auxetic fabric C in the course direction and wale direction are about 3.1MPa and 2.5 Mpa, respectively. Both are higher than those of Auxetic fabric BS. The reason could be that Auxetic fabric C has the smaller size of hexagon units, making it have more units in the same sample size, which gives the sample higher strength. Another phenomenon can be found from Fig10b is that the Auxetic fabric BS has longer low stress stage than that of Auxetic fabric C in the wale direction. Regarding the PR, it can be seen from Fig. 10c and 10d that the auxetic effect of Auxetic fabric BS is better than that of Auxetic fabric C when stretched in the course direction, which obeys the same rule as the above-mentioned, i.e. when an auxetic fabric has longer low stress stage and easier to be deformed in the transverse direction, it will have better auxetic effect in the tensile direction.

The main difference between Auxetic fabric A and BS is that they have the different spacer layer structure. Auxetic fabric A is made of the spacer yarns that cross through the hexagons as shown in Fig.1b. From Fig.10a and 10b, it can be found that their peak stresses are similar, but again, the Auxetic fabric BS have longer low stress stage in the wale direction. And again, the auxetic effect of Auxetic fabric A is not as good as Auxetic fabric BS. The reason could be the crossing yarns in the spacer layer of Auxetic fabric A hinders the deformation of the fabric, and lowers the auxetic effect of Auxetic fabric A, especially at the initial stage of the tension, the interaction of the crossing yarn hinders the open up of the fabric, causing the lower PRs of Auxetic fabric A at the initial stage.

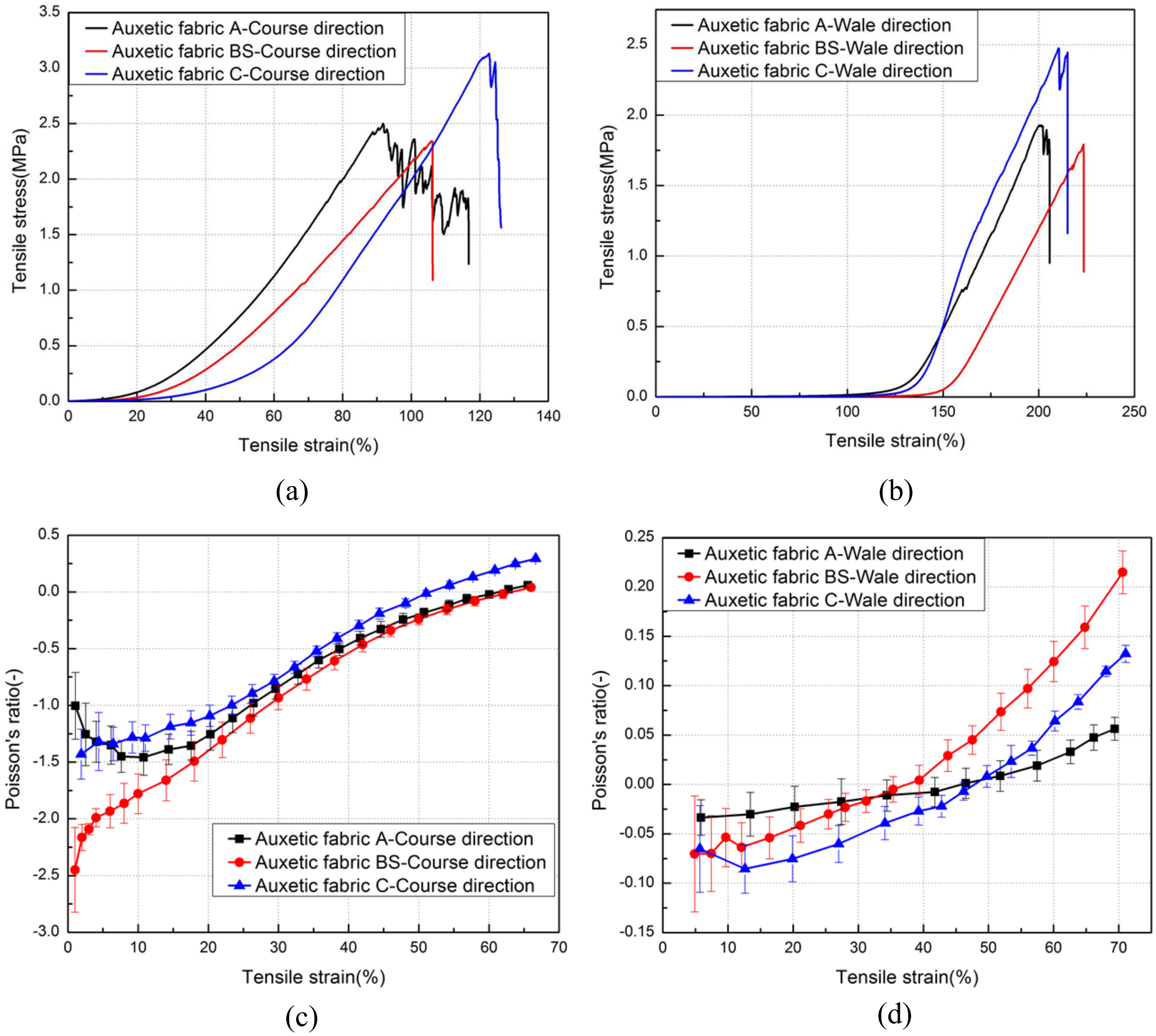


Fig.10 Effects of rib length and spacer layer structure on tensile properties and auxetic effect of auxetic fabrics: (a)/(b) Tensile stress-strain curves; (c)/(d) PR-strain curves

3.1.3 Comparison of stiffness among auxetic fabrics

From the tensile curves of the auxetic fabrics, it can be found that their stiffness is very different in the course and wale direction. Therefore, their stiffness was calculated and listed in Table 3. Auxetic fabric A has the highest stiffness in both course and wale direction with values of 440.79 N/m and 25.96 N/m, respectively. For the Auxetic fabric BS, BM and BL, their stiffness has a reverse order in course and wale direction. Auxetic fabric BS has the highest stiffness at 235.58 N/m in the course direction among the three fabrics, but has the lowest value at 8.15 N/m in the wale direction. Since the stiffness of all five the auxetic fabrics is very different in the course and wale direction and the orders are irregular, their stiffness ratios of the course direction to the wale direction were calculated and also listed in Table 3. From Table 3, it can be found that the descendent order of the stiffness ratios of the five auxetic fabrics is BS>A>BM>C>BL. Auxetic fabric BS has the highest stiffness ratio. Its auxetic effect is also the best among all the auxetic fabrics as shown in Fig.11. Auxetic fabric BL has the lowest stiffness ratio, and its auxetic effect is also the lowest among the auxetic fabrics. Therefore, higher stiffness ratio between the course and wale direction of fabric may be helpful for the design of auxetic fabric with higher auxetic effect.

Table. 3 Stiffness of the auxetic fabrics in course and wale direction

Auxetic Fabric / Direction	A	BS	BM	BL	C
Course (N/m)	440.79	235.58	149.77	97.433	110.13
Wale (N/m)	25.96	8.15	9.43	12.36	10.55
Course/wale (-)	16.98	28.91	15.88	7.88	10.44

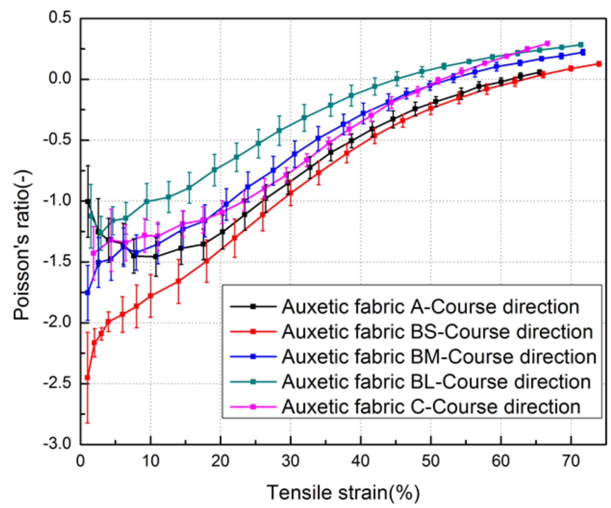


Fig.11 PR-strain curves of all the auxetic fabrics

3.2 Formability

3.2.1 Comparison between conventional base fabrics and auxetic fabrics

The hemisphere compression load-displacement curves of the base and auxetic spacer fabrics are shown in Fig.12a. It can be found that the trends of the curves for the base fabrics and the auxetic fabrics are similar, but loads of the base fabrics are much higher than those of auxetic fabrics. The compression peak loads of base fabrics are all exceed 2000N while the peak loads of auxetic fabrics are between 100N and 450N. This means that the auxetic fabrics are easier to be deformed. Base fabric A, which is the stiffest one, has the highest load at 2500N, and it is the only one fabric which was broken during test at a displacement of 44mm. As shown in Fig.13, Base fabric A was broken in the central part of the sample during test. The reason is that the Base fabric A has spacer yarns passing through the hexagonal units, causing the poor flexibility of the fabric. Other fabrics all reached the maximum displacement without rupture. And during the test, wrinkles were found in none of the fabrics.

The forming energies of the base fabrics and auxetic fabrics were calculated using Eq. 4 and the results are shown in Fig.12b. It can be found that all the auxetic fabrics require less forming energies than those of the base fabrics. Since Base fabric A was broken, the forming energy of Base fabric A was calculated until 44mm displacement, but its forming energy is still 10 times of that of Auxetic fabric A. Three Auxetic fabrics B (BS, BM, and BL) and Auxetic fabric C require about one-thirtieth of the forming energy of their base fabrics, i.e., Base fabric B and Base fabric C, indicating auxetic warp-knitted spacer fabrics have much better formability than those of the conventional warp-knitted spacer fabrics.

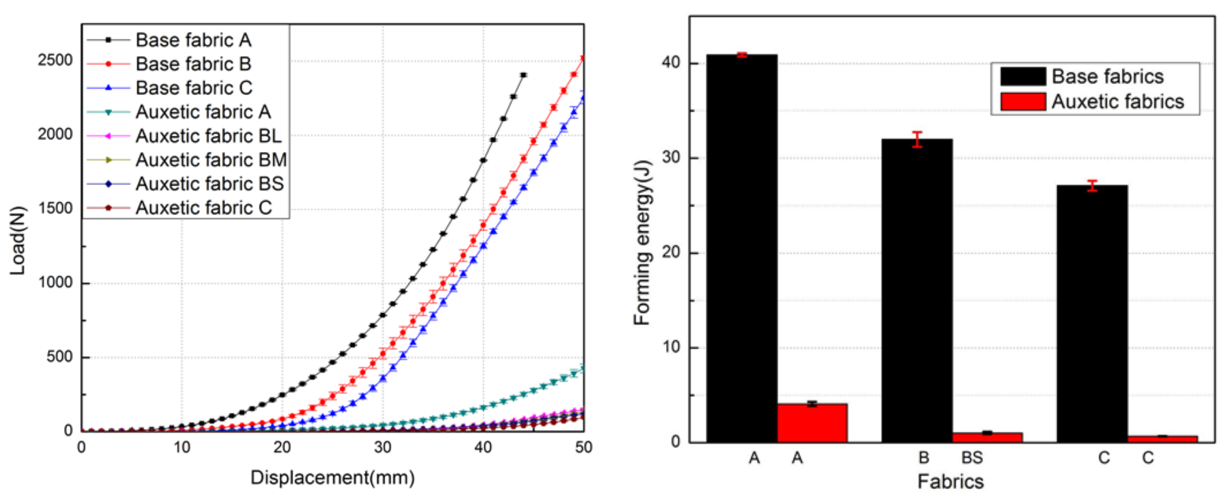


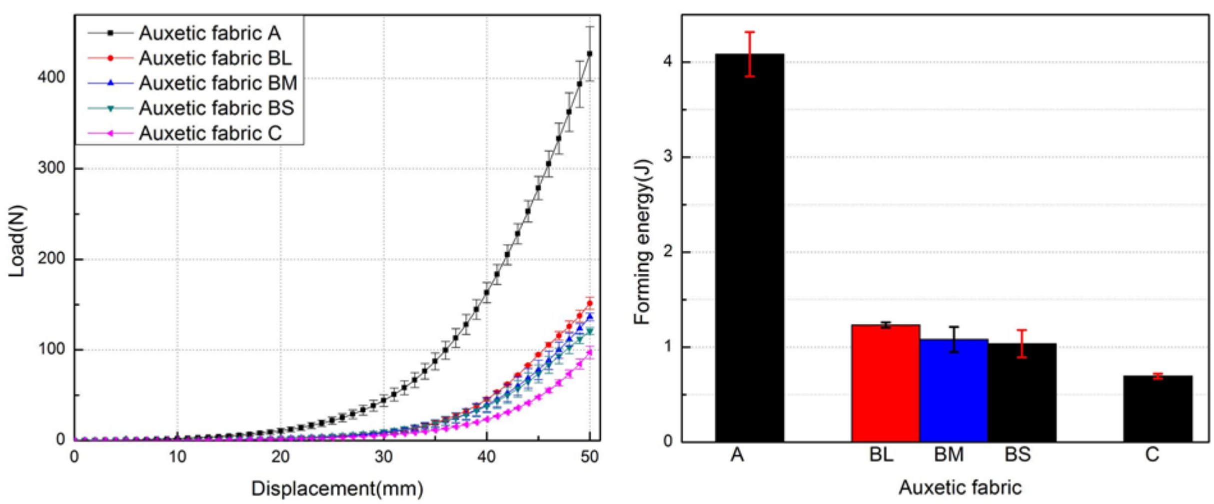
Fig.12 Comparison between the base and auxetic fabrics: (a) Load-displacement curves; (b) Forming energies

(a) (b)

Fig.13 Fabric samples after forming test; (a) Base fabric A; (b) Auxetic fabric

3.2.2 Comparison of different auxetic fabrics

Fig.14a shows the load-displacement curves of all the auxetic fabrics. It can be found that the trend of the load-displacement curves of the auxetic fabrics inherits the trend of the base fabrics. The peak load of Auxetic fabric A is about 420N, which is the highest one among the auxetic fabrics. The peak load of Auxetic fabric BL, BM and BS is 150N, 140N, and 120N, respectively. And Auxetic fabric C has the lowest peak load of 100N. Fig.14b compares the forming energies of the Auxetic fabrics. The forming energy of Auxetic fabric A is the highest (about 4.1J), while that of Auxetic fabric C is the lowest (about 0.7J), and Auxetic fabric BL, BM and BS require forming energies between those of Auxetic fabric A and C. Auxetic fabric A has the highest stiffness (Table 3) in both course and wale direction, and its thickness is similar to Auxetic fabric B but higher than Auxetic fabric C, that is why Auxetic fabric A has the highest forming energy. From Fig.10c, it can be found that Auxetic fabric BS has better auxetic effect than that of Auxetic fabric C, but its forming energy is higher than that of Auxetic fabric C as shown in Fig.14b. The reason is that the Auxetic fabric C is made of thinner yarns, and its thickness is less, which increases its formability. For Auxetic fabrics BS, BM, and BL, they are all made of Base fabric B. They have the same material, thickness and similar structure, but have different stiffness and auxetic effect. As aforementioned, Auxetic fabric BS has the highest stiffness in the course direction, but has the lowest stiffness in the wale direction among Auxetic fabrics BS, BM, and BL. Therefore, their forming energies could not be simply compared in term of stiffness in one direction, but could be compared in term of auxetic effect. As shown in Fig.7c, the descending order of auxetic effect of these auxetic fabrics is Auxetic fabric BS>BM>BL, which is just opposite to the descending order of forming energies of these fabrics as shown in Fig. 14b. Therefore, auxetic fabric with better auxetic effect needs less forming energy and has better formability. The results show that the formability of auxetic warp-knitted spacer fabrics is affected by many factors including the auxetic effect, fabric thickness, stiffness, yarn materials and the structure of spacer layer. When other parameters are similar, auxetic fabric with better auxetic effect will have better formability.



(a) (b)

Fig.14 Comparison among auxetic fabrics: (a) Load-displacement curves; (b) Forming energies

4. Conclusions

From the results obtained, the following conclusions could be drawn.

1) The auxetic warp-knitted spacer fabrics have very different tensile behaviors compared to their base spacer fabrics. They have higher peak stress in the course direction and a prolonged low stress stage in the wale direction.
2) Auxetic fabric with longer low stress stage in the wale direction has better auxetic effect when stretched in the course direction.
3) Auxetic warp-knitted spacer fabrics have much lower forming energies than conventional warp-knitted spacer fabrics, therefore, have much better formability than the conventional warp-knitted spacer fabrics.
4) The fabric stiffness ratio between the course direction and the wale direction has a positive effect on the auxetic behavior of auxetic fabrics. Higher stiffness ratio between these directions can lead to higher auxetic effect.
5) Structural parameters including rib length, angles between the ribs, structure of the spacer layer and fabric thickness have obvious effects on tensile behavior and auxetic effect as well as on formability of auxetic fabrics. When other parameters are similar, the auxetic fabric with better auxetic effect will have better formability.

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