UGBOLUE S.C.O. [1], KIM Y.K.[2]
[1] Edwin Clark University, Kiagbodo, Delta State, Nigeria
[2]University of Massachusetts, Dartmouth, MA, USA

ADVANCES IN AUXETIC WARP KNITTED PERSONAL PROTECTIVE STRUCTURES

Purpose. *To present current Advances in Auxetic Personal Protective Structures*

Methodology. *Details of design concept adopted for the Auxetic structures and fabrication methods are given.*

Results. *Both quantitative and qualitative methods of assessment of auxetic property of fabric were developed and used to compare the Non-auxetic Control Fabric versus Auxetic Fabric. The novel Auxetic fabrics also offer improved shear stiffness, enhanced dimensional stability, increased plane strain fracture toughness and increased indentation resistance).*

Scientific novelty. *Proposed Multi-Threat Protective Auxetic Fabric for First Responder's Base Uniform is conceptualized.*

Practical value. *Double Needle Bar (DNB) Auxetic Kevlar fabrics can provide superior 3-D curved surface conformity*

Keywords: Auxetic structure, Poisson`s ratio, Personal Protection.

Introduction. Engineered fabrics are especially desired for military protective clothing applications. Such fabrics, exhibiting ***high tactile comfort***, can be ***ergonometrically*** designed. However, through the use of an extensive database that contains hand feel, mechanical, construction, and tactile comfort data for fabrics, desired comfort can be predicted by measuring a limited number of properties (i.e., Kawabata Index). Thus, output systems can be optimized to exhibit the highest level of comfort by engineering a fabric with specific properties.

Using the Ballistic and blast protection, as an example, we can summarize the essentials of Personal Protective Wears (PPW) as follows:

– Every piece of armor that soldiers wear, with the exception of eye protection, contains a ***textile component***.

– Advanced textiles play an important role in ***blast protection***, but the Army is still looking for a ***lighter weight, modular, scalable and tailorable suite*** of equipment that will provide required levels of protection without hindering ***mobility or mission effectiveness***.

– Blast protection systems that provide the most protection currently are ***bulky, hinder movement and cause soldier fatigue***.

– The Army has set the near-term goal (one to five years) of a ***10 percent reduction in armor weight*** for current threats and ***improved ergonomic design*** concepts. Its mid-term (six to 10 years) and long-term (11 to 15 years) goals are to continue to improve weight reduction and ergonomic design.

Typically, it is important to formulate constructive objectives to accomplish the PPW fabrication strategy, namely:

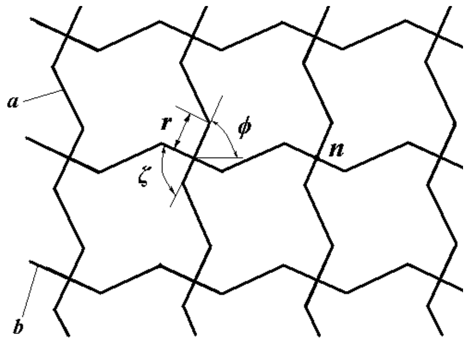
(a) to develop and characterize a novel specialized material that is ***lightweight, comfortable, and efficient***.

(b) to integrate barrier properties in such garments which would incorporate suitable ***antimicrobial*** and other suitable chemicals to provide protection against a range of microorganisms.

This informed the development of Auxetic warp knitted structures and fabrics that have negative Poisson's ratio wherein lateral direction is expanded when the structure is stretched in the machine direction resulting in novel properties and performances.

1. *Auxetic Fabrics Design Concept.*

The model depicted in Smith et al [1] has been shown to be successful for explaining the auxetic behavior of some engineering foams. Many models of deformation within network materials proposed by Gaspar et al [2] make use of the assumption that there is a single mode of deformation that dominates over other modes. Some of these network models [3] have been put forward to resemble materials that may exhibit a negative Poisson's ratio but have yet to be manufactured. The broken-rib model by Smith et al [1] is one such model. The results by Gaspar et al [2] showed that a material with this microstructure does produce a negative Poisson's ratio. The principal assumptions for the deformation are: the angles between ribs deform elastically; no change of length of the individual ribs is allowed; the translational symmetry of the net is kept throughout deformation. The engineering strain of such a model is shown in Figure 1.



$$\varepsilon_y = 4r\left(\frac{\sin\phi_n}{\sin\phi_0} - 1\right) \quad \varepsilon_x = 4r\left(\frac{\cos\left(\zeta_0 - \phi_0 + \Delta\phi\left(k-1\right)\right)}{\cos\left(\zeta_0 - \phi_0\right)} - 1\right)$$

$$\nu_{yx} = -\frac{\left(\cos\left(\zeta_0 - \phi_0 + \Delta\phi\left(k-1\right)\right) - \cos\left(\zeta_0 - \phi_0\right)\right)\sin\phi_0}{\left(\sin\phi_n - \sin\phi_0\right)\cos\left(\zeta_0 - \phi_0\right)}$$

Fig. 1. **Schematic of geometrical model for the structure**

2. *University of Massachusetts Dartmouth Auxetic Fabric Design*

Research efforts [3-13] in the area of auxetic structures have shown mechanical improvements over traditional fabrics. These efforts have mainly focused on the initial production of auxetic fibers and filaments, which are then woven into fabrics to achieve the macroscopic auxetic properties. Whereas promising properties have been measured, this approach is limited due to the time consuming and expensive production of individual auxetic fibers. In contrast, our team at UMD, Ugbolue, et al [14-22], pioneered the fabrication of Auxetic warp knit fabrics using inexpensive, commercially available non-auxetic yarns. Thus, our team at UMD, Ugbolue, et al [14-22] translated the concepts in the applicable model [1.2] into practically engineered structures in order to produce functional textile structures.

The UMD technique provides a faster means of producing auxetic fabrics using non-auxetic yarns by exploiting knowledge of fabric geometry, design, and structural mechanics. The main advantages of our approach over competitive auxetic fabrics are: improved productivity, fabric versatility, performance, and speed of warp knitting production resulting in a more cost effective and efficient manner than by weaving especially when conventional weaving looms are being used. Luna Innovations Roanoke, VA 24016, recently teamed with University of Massachusetts, Dartmouth (UMD) to develop auxetic materials that have significant advantages compared with currently used materials for pelvic personal protective equipment.

The auxetic textiles produced have demonstrated significant improvements in mechanical properties over conventional fabrics and are anticipated to translate to improved blast/ballistic protection. It is noted that the fabric thickens and strengthens as it is impacted by shrapnel and improvised explosive devices.

Indeed, the enhanced blast / ballistic protection provided by auxetics allows thinner, lightweight, breathable protective textiles that will reduce thermal burden. It must be emphasised that a major problem with conventional materials (i.e. materials having positive Poisson's ratio) is that they can hardly be curved into a doubly curved or domed shape, instead the core forms a saddle shape on bending. In the case of auxetic fabrics (i.e., fabrics with negative Poisson's ratio), double curvature can be easily achieved.

2.1.The Ultimate Auxetic Textiles

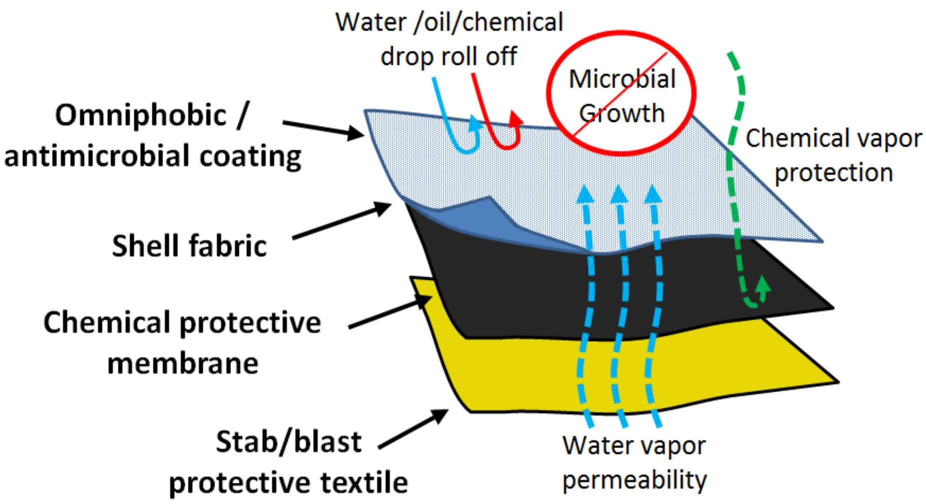


Fig. 2. **Proposed Multi-Threat Protective Fabric for First Responder's Base Uniform made from Auxetic Textiles**

2.2.Fabrication of Auxetic Structures

In fabricating Auxetic Knit structures from non-auxetic yarns, various types of warp knit fabrics and in-lay warp knit fabrics were designed and produced on various warp knitting machines as shown in Figure 3.

Fig. 3. **Jacob Muller Warp Knitting Machine used for producing Auxetic Structures**

These fabrics were produced on a Double Needle Bar Karl Mayer 16 Gauge Raschel warp knitting machine equipped with 6 guide bars but only 4 guide bars are used in the study. The fabric design concept was guided by the available Tier 1 Pelvic Protection Effort Material Target Requirements. Two yarns were selected for use in this study, namely, *100% Kevlar of 400 denier linear density as a base yarn and 150 denier polyester filament yarn covered with 70 denier Lycra as in-laid yarn.*

To achieve the auxetic property, most designs employed a high elastic yarn, such as Lycra in the structure. This yarn is in-laid between the stitch wale in the knitting direction to ensure that the fabric structure retains the necessary configuration after relaxation. The filling yarn is in-laid between neighboring wales and wraps the junctures of the ground loops and depicted as *Inlay Type A* as shown on the right-hand diagram in **Figure 4.** Also, shown in **Figure 4** are diagrams of a typical conventional warp knitted fabric, shown on the left and a typical Auxetic warp knitted structure appropriately shown in the centre of the figure.

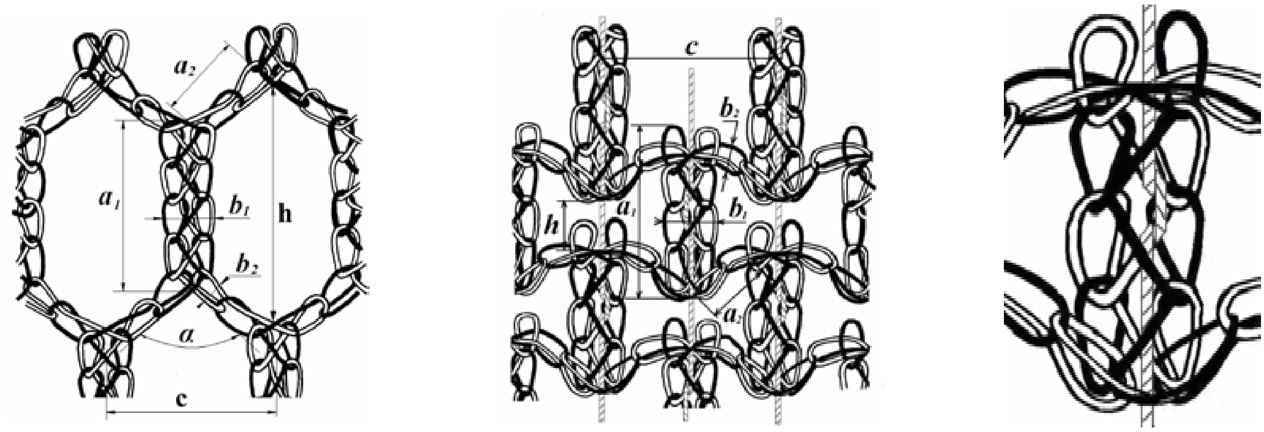


Fig. 4. **Conventional, Auxetic Structures and Inlay type A**

3. *Measurement of Some Fabric Physical Properties*

3.1. *Courses per unit length and Wales per unit length:* A course is a predominantly horizontal row of loops produced by adjacent needles during the same knitting cycle. In warp knitting each loop in a course normally is composed of a separate yarn. Courses per inch (cpi) or courses per cm are used to evaluate the loops along the axial or walewise direction.

A wale is a predominantly vertical column of needle loops produced by the same needle knitting at successive knitting cycles and thus intermeshing each new loop through the previous loop. In warp knitting a wale can be produced from the same yarn. Wales per inch (wpi) or wales per cm are used to evaluate the loops along the transverse or coursewise direction.

The number of courses and the number of wales per unit length are obtained by using a counting glass. The results are reported using SI units namely, number of courses or wales in 10 mm. The mean of ten readings is recorded for each direction of the fabric.

3.2. *Stitch Density,* S: The term loop or stitch density S is the total number of needle loops in a square area measurement. It is obtained by multiplying, for instance, the number of courses and wales, per square unit length together. The unit is loops/in^2 or loops per cm^2.

3.3. *Thickness and Basis Weight*: The thickness (with the unit of mm) of each sample is tested using a Thickness Testing Instrument according to ***ASTM D1777-64.8***. Each sample is also weighed on an electronic balance to determine its basis weight or areal density (g/m^2 or oz/yd^2 or lb/ft^2).

3.4. *Bulk density, B*: The bulk density of a knitted fabric**,** *B=[T/W]^{x}Unit conversion facto*r, where W is basis weight in oz/yd^2 and T is the thickness in inches. Thus Bulk, cm^3/g =*[T/W]* where T is in cm and W is basis weight in g/cm^2.

Table 1

Fabric Geometry and Physical Properties of 400 Denier and Other Baseline Fabrics

Fabric Designation	*Yarn Linear Density (Base Yarn Plus Inlay Yarn Denier)*	*Fabric Structure*	*Wales Per cm*	*Courses Per cm*	*Stitch Density (Loops/ cm²)*	*Thickness (mm)*	*Basis Weight. (g/m²)*	*Basis Weight. (oz/yd)*	*Bulk Density (g/cm³)*
Luna – UMD Phase ll Fabric # 1-5 (Control)	400 Kevlar Base	1x2 Tricot Base	7.0	7.0	49	1.20	512.1.	15.0	2.344
Luna-UMD Phase ll Fabric #2-6	400 den Kevlar base plus150 den polyester covered with 70 den spandex as inlay	Auxetic warp knit structure as shown in Table 2	7.0	7.0	49	1.35	595.1	17.54	2.269
Luna – UMD Phase ll Fabric #3-7	400 den Kevlar base plus150 den polyester covered with 70 den spandex as inlay	Auxetic warp knit structure as shown in Table 2	7.0	7.0	49	0.85	437.0	12.9	1.945
Luna-UMD Phase ll Fabric #4-8	400 den Kevlar base plus150 den polyester covered with 70 den spandex as inlay	Auxetic warp knit structure as shown in Table 2	7.0	7.0	49	1.05	455.7	13.4	2.303
Draper 1766-12	180 denier Kevlar	Weft knit 1X1 Rib	18	12	216	0.48	213.35	6.29	2.254
Woven Baseline Fabrics									
Fabric Designation	*Yarn Linear Density*	*Construction*	*Ends Per cm*	*Picks Per cm*	*Fabric Cover (%)*	*Thickness (mm)*	*Basis wt. (g/m²)*	*Basis W (oz/yd)*	*Bulk Density (g/cm³)*
Warwick WT 9-1386	1500 denier Kevlar	Woven Plain weave	7.1	7.1	60.9	0.36	277.95	8.19	1.295
Warwick WT 9-1094A	200 denier Kevlar	Woven Plain weave	39.4	39.4	94.3	0.2	106.25	3.13	1.087

3.5. *Measurement of Fabric Tensile Properties*. Instron 5569 Mechanical Tester and ***ASTM D5034-95(2001)*** test method were used for more detailed evaluations at UMD. To check for specimen slippage, the specimen was marked across at the front inner edge of each jaw. It is noted that the mark tends to move away from the jaw edge if slippage occurred. The result was then discarded and another sample taken if the specimen slipped in the jaws, broke at the edge of or in the jaws, or the test results fell markedly below the average for the set of specimens. Instrument control (including standard and customizable methods) and data collection and analysis were performed using the Instron software (Blue Hill).

The Kevlar warp knit fabrics were very strong and the breaking points were not easily attained. As a result, the tensile tests were mostly terminated after samples had been deformed up to 70 % strain levels in the wale-wise direction. The fabrics were much more extensible in the course-wise direction and samples were deformed up to 120 % strain levels. The plots of load versus extension % for the fabrics deformed in both directions can then be produced.

3.6. ***Measurement of Poisson's ratio*****.** The measurement of Poisson's ratio is an important fundamental tool for determining the auxetic property of materials. **If the Poisson's ratio is negative then the structure is auxetic.** The factor which influences the Poisson's ratio is identified as intrinsic unit size displacement, which depends on chain course numbers.

It is surmised that the Poisson's ratio values decrease as the number of tricot courses increase. Indeed, the auxetic properties depend on the interaction of vertical and horizontal ribs in the knitted structure**.**

To measure the Poisson's ratio of the identified fabrics, video-extensometry along with micro-tensile testing techniques are employed by using Instron 5569 Mechanical Tester *ASTM D5034-95(2001).* All samples are tested by straining the entire fabric strip evenly and each duly marked 2 cm X 2 cm square of the sample is measured to obtain the Poisson's ratio by using the equation:

$$\nu_{xy} = -\varepsilon_x / \varepsilon_y$$

where ε_x is the strain in the x-direction, or transverse strain,
and ε_y is the strain in the y-direction, or the axial strain.

Initially all samples of 10 cm long are strained at a rate of 5.08 cm/min, in the wale-wise and course-wise directions. The test process is observed with a Canon 7D SLR camera. The strain of the sample is measured using the camera to capture an image of the sample at different strain levels, totaling 16 pictures per sample. The width of each sample is measured in three locations to ensure that the measured Poisson's ratio is as accurate of measurement as possible.

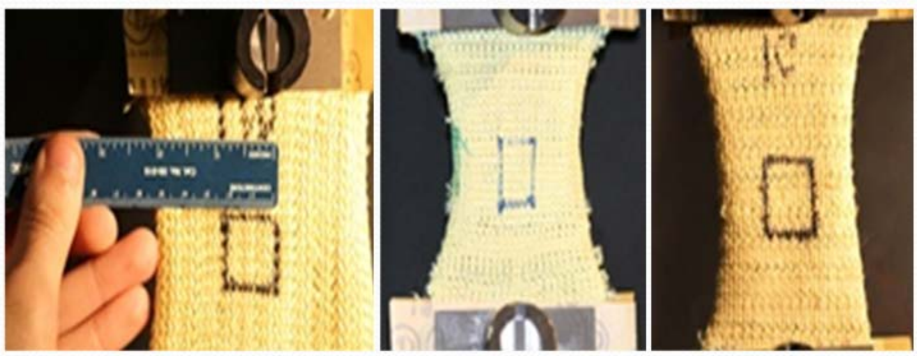
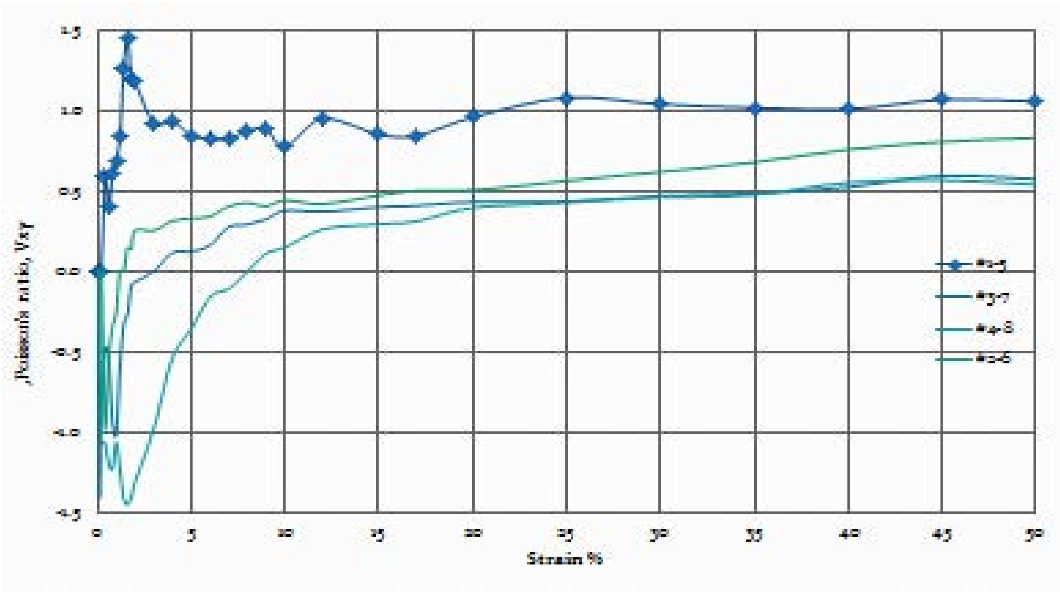
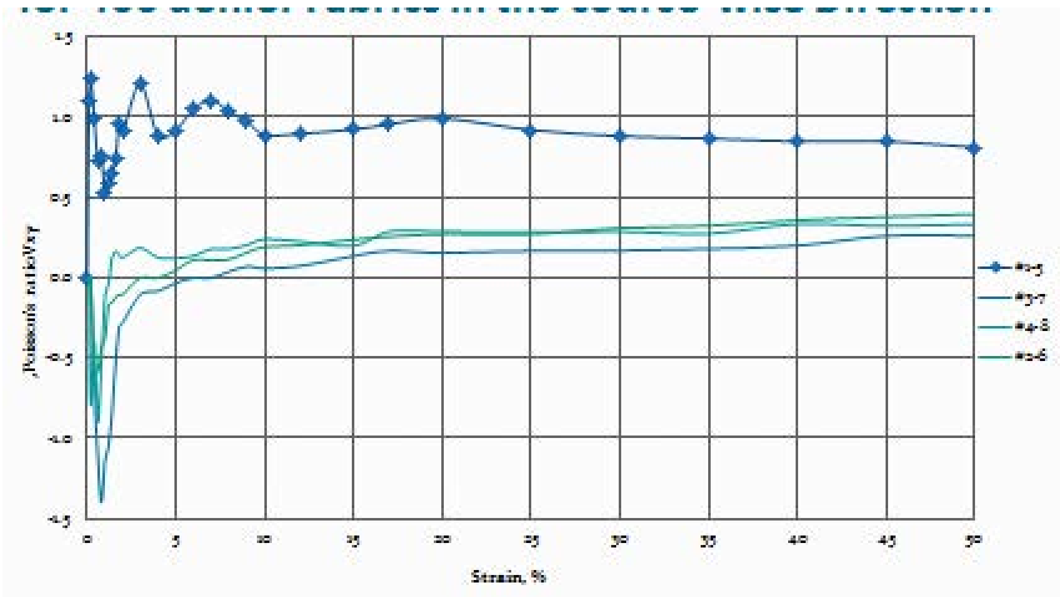


Fig. 5. **Example of Measurement of Poisson's ratio protocol**

Each fabric structure is tested three times, using different samples of the fabric structure each test. The Poisson's ratio is obtained after all samples had been photographed and strain values obtained using appropriate image analysis software. It should be noted in the photographs that the relationship of interest (for determining if auxetic) is not necessarily the relationship of the strain in the y direction to the x direction. The axial strain can still be greater than the transverse strain (as pictured), yet the auxetic nature is a reflection of the transverse strain increasing under axial load (as measured, the width of the box increased relative to the initial width).



a. in wale-wise direction



b. in course-wise direction

Fig. 6. **Plot of Poisson's ratio vs. strain % for 400 denier Fabrics**

A qualitative method of assessment of auxetic property of fabric as developed at the UMD Laboratory is shown in Figure 7 and was used to compare the Non-auxetic Control Fabric versus Auxetic Fabric.

Fig. 7. **Qualitative assessment of the auxetic properties: Woven vs. Auxetic Kevlar**

Fig. 8. **Fabric Structure and Design Profiles for Typical DNB Auxetic Fabric**

Concluding Remarks. Over the past decade researchers at the University of Massachusetts-Dartmouth (UMD) have been involved in developing several materials technologies having high relevance to creating a *light weight, superior impact resistant* advanced fiber reinforced organic polymer laminar composite (*OPLC*) material. One such novel material technology is:
Double needle bar *(DNB) Auxetic warp knitted fabrics that have the unique feature of negative Poisson's ratio*, of which lateral direction is expanded when it is stretched in machine direction.

It is believed that DNB Auxetic Kevlar fabrics can provide superior 3-D curved surface conformity as reported in our publication. It is also shown in our patent that the Auxetic technology can be used in conjunction with a range of composite materials, personal protective appliances, fibrous materials, biomedical filtration materials.

Thus. the novel Auxetic fabrics will offer improved shear stiffness, enhanced dimensional stability, increased plane strain fracture toughness and increased indentation resistance.

Acknowledgement. Our studies on Auxetic structures have been supported by the US Department of Commerce Grant 02-07400 through funds for the National Textile Center project, F06-MD09. The excellent contributions of the UMD Auxetic research team comprising Professors S.C.O. Ugbolue, Yong Kim, Steven Warner, Qinguo Fan, Chen Lu Yang and Olena Kyzymchuk are highly appreciated. The authors gratefully acknowledge the research grant for the additional work on Auxetic Warp Knitted PPW textiles reported in this paper.

References

1. Smith C., Grima J., Evans K., A novel mechanism for generating auxetic behavior in reticulated foam: Missing rib foam model, Acta Materiala, 48 (2000) 4349.
2. Gaspar N., Ren X.J., Smith C.W., Grima J.N., Evans K.E., Novel honeycombs with auxetic behaviour, Acta Materiala, 53 (2005) 2439.
3. Grima, J. N., Gatt, R., Empirical modeling using dummy atoms EMUDA an alternative approach for studying auxetic structures. Molecular Simulation, 31 (2005) p. 915.
4. Alderson, A and Alderson K., Expanding materials and applications: exploiting auxetic textiles, Technical Textiles International, 777, September 2005, 29-34.
5. Ravirala N., Alderson K., Davies P., Simkins V., Alderson A., Negative Poisson’s ratio polyester fibers, Textile Research Journal, 76 (2006) 540.
6. Hook, P and Evans K., 2006 Auxetix site http://www.auxetix.com/science.htm
7. Simkins,V.R., Ravirala, N., P.J. Davies, Alderson, A., Alderson, K.L., An experimental study of thermal post-production processing of auxetic polypropylene fibres, Physica Status Solidi, (2008) 1.
8. Uzun, M, and Patel, I., Tribological properties of auxetic and conventional polypropylene weft knitted fabrics, Archives of Matr. Sci. & Eng., 44 (2010) 120.
9. Hu, H, Wang, Z, Liu, S, Development of auxetic fabrics using flat knitting technology Text. Res. J., 81 (2011) 1493.
10. Alderson, K.L., Webber, R.S.; Evans, K.E, Microstructural evolution in the processing of auxetic microporous polymers, Physica Status Solidi B: Basic Solid State Physics, 244 (2007) 828.
11. Alderson, K. L, Pickles, A. P., Evans, K. E., Auxetic polyethylene: The effect of a negative Poisson's ratio on hardness. Acta Metall. Mater., 42 (1994) 2261.
12. Webber, R.S., Alderson, K.L., Evans, K.E., A novel fabrication route for auxetic polyethylene, part 2: mechanical properties, Polymer Engineering and Science, 48 (2008), 1351.83.
13. Simkins, V., Ravirala, N., Davies, P., Alderson, A. Alderson, K., An experimental study of thermal post-production processing of auxetic polypropylene fibres. Physica Status Solidi B: Basic Solid State Physics, 245 (2008) 598.
14. Ugbolue, S.C., Warner, S. B., Kim, Y.K., Fan, Q., and Yang, Chen Lu, (2006). The Formation and performance of auxetic textiles, (NTC Project F06-MD09), annual report, Pennsylvania, National Textile Center. http://www.ntcresearch.org/pdf-rpts/AnRp06/F06-MD09-A6.pdf
15. Ugbolue, S.C., Warner, S. B., Kim, Y.K., Fan, Q., and Yang, Chen Lu, Kyzymchuk, O. and Feng, Y. (2007). The formation and performance of auxetic textiles, (NTC Project F06-MD09), annual report, Pennsylvania, National Textile Center. http://www.ntcresearch.org/pdf-rpts/AnRp07/F06-MD09-A7.pdf
16. Ugbolue, S.C., Warner, S. B., Kim, Y.K., Fan, Q., and Yang, Chen Lu, Kyzymchuk, O. and Feng, Y. (2008). The formation and performance of auxetic textiles, (NTC Project F06-MD09), annual report, Pennsylvania, National Textile Center. http://www.ntcresearch.org/pdf-rpts/AnRp08/F06-MD09-A8.pdf
17. Ugbolue, S.C., Warner, S. B., Kim, Y.K., Fan, Q., and Yang, Chen Lu, Kyzymchuk, O. Feng, Y.and Lord, J (2009). The Formation and Performance of Auxetic Textiles, (NTC Project F06MD09) annual report, Pennsylvania, National Textile Center. http://www.ntcresearch.org/pdf-rpts/AnRp09/F06-MD09-A9.pdf

18. Ugbolue, S.C., Warner, S. B., Kim, Y.K., Fan, Q., Yang, C.L., Olena Kyzymchuk, Auxetic fabric Structures and related fabrication methods, World Patent No. 002479 A1, 2009

19. Ugbolue, S.C., Warner, S. B., Kim, Y.K., Fan, Q., Yang, C.L., Kyzymchuk, O., Feng, Y., The formation and performance of auxetic textiles, Part 1: Theoretical and Technical considerations, J. Text. Inst., 101 (2010) 660.

20. Ugbolue, S.C., Warner, S. B., Kim, Y.K., Fan, Q., Yang, C.L., Kyzymchuk, O., Feng, Y., The Formation and Performance of Auxetic Textiles, Part 11: Geometry and structural properties, J. Text. Inst., 102 (2011) 424.

21. Leong K., Ramakrishna S., Huang Z., Bibo G., The potential of knitting for engineering composites, Composites. Part A, 31 (2000) 197.

22. Ugbolue, S. C. et al, Auxetic Fabric Structures and related fabrication methods, US Patent 8,772,87, July 8, 2014.

ДОСТИЖЕНЯ В АУКЗЕТИК ОСНОВОВЯЗАНЫХ СТРУКТУРАХ ДЛЯ ПЕРСОНАЛЬНОЙ ЗАЩИТЫ

[1]УГБОЛУЕ С.Ч., [2]КИМ Й.К.
[1]Университет Єдвина Кларка, Нигерия
[2]Массачусетский университет, г. Дартмут, США

Цель. *Представить текущие достижения в аукзетик структурах для персональной защиты*

Методика. *Приведены детали концепции дизайна, принятой для аукзетик-структур, и методы их изготовления.*

Результаты. *Были разработаны и использованы количественные и качественные методы оценки аукзетик свойств полотен, которые используются для сравнения неаукзетик контрольного материала с аукзетик-материалом. Новые аукзетик полотна также имеют улучшенную жесткость при сдвиге, улучшенную размерную стабильность, повышенную ударную вязкость при плоском растяжении и повышенную стойкость к вдавливанию.*

Научная новизна. *Предложена концепция многослойного защитного аукзетик полотна для базовой униформы.*

Практическая значимость. *Кевларовое аукзетик полотно, изготовленное на машине с двумя игольницами, может обеспечить превосходное соответствие 3-D изогнутой поверхности.*

Ключевые слова: *аукзетик структура, коэффициент Пуассона, персональная защита.*

ДОСЯГНЕННЯ В АУКЗЕТИК ОСНОВОВ'ЯЗАНИХ СТРУКТУРАХ ДЛЯ ОСОБИСТОГО ЗАХИСТУ

[1]УГБОЛУЄ С.Ч., [2]КІМ Й.К.
[1]Університет Єдвіна Кларка, Нігерія
[2]Массачусетський університет, м.Дартмут, США

Мета. *Представити поточні досягнення в аукзетик структурах для персонального захисту.*

Методика. *Наведено деталі концепції дизайну, прийнятої для аукзетик-структур, та методи їх виготовлення.*

Результати. *Були розроблені і використані кількісні та якісні методи оцінки аукзетик властивостей полотна, які застовують для порівняння неаукзетик контрольного матеріалу з аукзетик-матеріалом. Нові аукзетик полотна також мають поліпшену жорсткість при зсуві, поліпшену розмірну стабільність, підвищену ударну в'язкість при плоскому розтягуванні і підвищену стійкість до вдавлювання.*

Наукова новизна. *Запропоновано концепцію багатошарового захисного аукзетик полотна для базової уніформи.*

Практична значимість. *Кевларове аукзетик полотно, виготовлене на машині з двома голечницями, може забезпечити гарну відповідність 3-D вигнутій поверхні.*

Ключові слова: *аукзетик структура, коефіцієнт Пуассона, особистий захист.*