PAPER • OPEN ACCESS

3D printed auxetic forms on knitted fabrics for adjustable permeability and mechanical properties

To cite this article: N Grimmelsmann et al 2016 IOP Conf. Ser.: Mater. Sci. Eng. 137 012011

View the article online for updates and enhancements.

You may also like

- <u>Methods and progress in studying inelastic</u> interactions between positrons and atoms R D DuBois
- <u>Varying fabric drape by 3D-imprinted</u> <u>patterns for garment design</u>
 T Spahiu, S Fafenrot, N Grimmelsmann et al.
- <u>Reliability of statistic evaluation of</u> microscopic pictures taken from knitted fabrics

A Ehrmann, T Blachowicz, H Zghidi et al.





DISCOVER how sustainability intersects with electrochemistry & solid state science research



This content was downloaded from IP address 18.117.137.64 on 01/05/2024 at 01:43

3D printed auxetic forms on knitted fabrics for adjustable permeability and mechanical properties

N Grimmelsmann, H Meissner and A Ehrmann¹

Bielefeld University of Applied Sciences, Faculty of Mathematics and Engineering Sciences, Bielefeld, Germany

E-mail: andrea.ehrmann@fh-bielefeld.de

Abstract. The 3D printing technology can be applied into manufacturing primary shaping diverse products, from models dealing as examples for future products that will be produced with another technique, to useful objects. Since 3D printing is nowadays significantly slower than other possibilities to manufacture items, such as die casting, it is often used for small parts that are produced in small numbers or for products that cannot be created in another way. Combinations of 3D printing with other objects, adding novel functionalities to them, are thus favourable to a complete primary shaping process. Textile fabrics belong to the objects whose mechanical and other properties can notably be modified by adding 3D printed forms. This article mainly reports on a new possibility to change the permeability of textile fabrics by 3D printing auxetic forms, e.g. for utilising them in textile filters. In addition, auxetic forms 3D printed on knitted fabrics can bring about mechanical properties that are conducive to tensile constructions.

1. Introduction

The 3D printing technology has been developing rapidly ever since last year. Besides the well-known methods of stereolithography or selective laser sintering, especially the fused deposition modelling (FDM) technique is of great importance for many companies as well as individuals due to its relatively low costs [1]. While often being considered as the base for a new industrial revolution [2,3], these primary shaping technologies are still much slower than conventional production methods, such as die casting.

In FDM printing, a filament is transported into a heated extruder nozzle where it is molten; the liquefied material is deposited on the printer bed line by line to cool down and harden. By lowering the printing plate, the second layer can be printed on top of the first one, etc. [4].

Most FDM printers can work with ABS (Acrylonitrile butadiene styrene) and PLA (polylactic acid); often other materials such as polyamide, polycarbonate or wax can be handled [5].

To reduce the printing time, combinations of FDM printing with other objects, such as textiles, can be used [6-8]. While earlier experiments concentrated on inserting textile fibres into FDM printed objects [7] or printing on woven fabrics [8] to create new multi-material systems with increased mechanical properties, this article explores the possibilities to generate filters as well as garments and other objects with adjustable permeability.

In common materials, longitudinally stretching leads to contracting laterally. Auxetic materials, however, have a negative Poisson's ratio and behave vice versa – they expand laterally when stretched

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution $(\mathbf{\hat{t}})$ (cc) of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd 1

longitudinally [9]. This unexpected behaviour does not only bring about several useful mechanical and sound-proofing properties [10] but also allows for using auxetic structures to open and close pores in a membrane uniformly in both in-plane directions. As one application, membranes with auxetic behaviour can be used as filter materials, since the permeability of circular pores is superior to the value over elliptical ones [11]. This idea is of special interest for filtering particles which are not circular themselves and should either pass a pore or be retained by the filter, independent of the orientation in which they reach the pore.

Soft and responding as auxetic knitted fabrics [12,13] are, they indeed have some defects, making them problematic for technical applications, while a combination of knitted fabrics or flexible membranes with stiffer auxetic patterns can be used to solve this problem. Additionally, mechanical properties, such as bending stiffness of the textile, are significantly altered by imprinted auxetic forms.

As a model system, investigations of knitted fabrics with imprinted auxetic patterns are depicted in this article, using different material and structure combinations.

2. Experimental

The auxetic forms used for printing were designed with Autocad Inventor[®]. After exporting them as STL files, they were imported in the repetier host and sliced into a layer model. During the slicing process, all printing parameters, such as printing velocity, layer thickness, flow rate, etc. could be defined. The sliced result was sent to the 3D printer.

The objects shown in this article were created using an FDM printer Orcabot XXL by Prodim (The Netherlands). As filament, Taulman 645 Nylon (FilamentWorld) with a filament diameter of 1.75 mm was used which is more flexible than ABS or PLA yet not as stretchable as most "soff" filaments. The extruder temperature was set to 250 °C and the printing bed temperature to 60 °C. The layer height was 0.2 mm. The structures were filled.

The knitted fabrics used as bases were created on a single bed hand knitting machine Silver Reed SK-280 (gauge E5.5). Yarns from natural fibres (cotton 75 %, linen 25 %) as well as man-made fibre yarns (acrylic 50 %, polyester 50 %) were used to create single jersey (single-face) fabrics. In addition the man-made fibre yarns were also used on a double bed hand knitting machine Orion to produce double-face fabrics.

3. Results

First, tests were performed to investigate whether the combination of knitted fabrics and 3D printed auxetic forms allowing for stretching the pores of the textile isotropically or not. Fig. 1 shows a sample with five layers of nylon printed in a typical auxetic shape on a single-face knitted fabric. It was recognized that the nylon layers could not be detached from the fabric by hand; both materials build a stable connection.



Figure 1. Auxetic shape printed on a single-face fabric.

The differences between relaxed and stretched form are depicted in Fig. 2. While the left panel shows the relaxed state, stretching the textile in horizontal (left-right) direction results in the stitches being stretched vertically (top-bottom), too. In some parts, this effect is even disproportionately high.



Figure 2. Microscopic pictures of the auxetic shape printed on a single-face fabric, depicted in Fig. 1, in relaxed (left panel) and horizontally stretched state (right panel).

Opposite to this behaviour, the pure knitted fabric – without auxetic printed forms on top – shows the typical performance of "usual" materials, as depicted in Fig. 3: While stretched longitudinally, it shrinks vertically; the shape of the pores clearly differs from the nearly square form shown in Fig. 2.



Figure 3. Horizontally stretched single-face fabric without auxetic 3D print on top.

While the principle functionality is apparently reached with this material combination, Fig. 2 nevertheless depicts that the desired proportionality of stretching in both directions is not obtained in this example. Thus, further experiments were conducted with varying parameters of both the knitted fabric and the auxetic 3D print to evaluate their influence on the shape of the pores in the different areas of the auxetic form.

First, different yarns were examined. Fig. 4 shows a single-face fabric knitted from cotton/linen. Apparently, the structure is quite "dense", with only small holes between the yarns. The auxetic structure is again printed with five layers of nylon.

Stretching the fabric (Fig. 4, right panel) results in small changes only. Significant differences in the pore sizes are invisible. For such a dense knitted fabric – with correspondingly low elasticity – the auxetic potential of the 3D print is apparently insufficient.

In comparison, Fig. 5 depicts the same auxetic structure, printed with a height of five layers on a single-face fabric produced from acrylic/polyester yarn. This yarn has a significantly smaller diameter and thus a lower bending stiffness, additionally resulting in a fabric with larger open areas. Stretching the fabric with 3D print laterally is possible without much force, which in return can make the pores open relatively homogenously, as already examined in Fig. 2 for a similar yarn.



Figure 4. Microscopic pictures of the auxetic shape printed on a single-face fabric from cotton/linen, relaxed (left panel) and stretched (right panel).



Figure 5. Microscopic pictures of the auxetic shape printed on a single-face fabric from acrylic/polyester, relaxed (left panel) and stretched (right panel).

Apparently it is necessary to choose relatively elastic structures to allow for the auxetic structure on top to significantly influence the textile fabric.

Next, different knitted structures were compared. As fundamental examples, single-face (single jersey) and double-face were chosen. While Figures 1-5 show single jersey fabrics, Fig. 6 depicts a double-face knitted fabric in relaxed and stretched state. Double-face fabrics are much more stretchable than single-face fabrics. Concerning the above-described influence of the in-plane elasticity of the textile on the auxetic performance of the whole system, a double-face fabric should show an even stronger auxetic behaviour.

Fig. 6, however, shows clearly that another factor has to be taken into account: Since the doubleface fabric has a zigzag structure, only each other stitch (i.e. only the stitches on the front side of the knitted fabric, not those on the back) gets in contact with the imprinted auxetic structure. This results in a higher irregularity of the elongated textile. In the stretched state (Fig. 6, right panel), the zigzag structure partly unfolds, while the areas where neighbouring front stitches are connected by the printed nylon cannot expand. This behaviour results in large open areas alternating with nearly completely relaxed stitches. Such performance may be attractive for distinct applications; however, it is not useful for the uniformly tailorable permeability.



Figure 6. Microscopic pictures of the auxetic shape printed on a double-face fabric from acrylic/polyester, relaxed (left panel) and stretched (right panel).

The auxetic performance of the multi-material system is not only based on the mechanical properties of the knitted fabric but also on those of the 3D print. It is of importance to use a 3D printed shape that is on the one hand not too stiff in the connection points so that the angles between neighbouring strips can be varied by an external force without breaking the material. On the other hand, it must be rigid enough to influence the knitted fabric in the desired way.

Fig. 7 shows the same knitted fabric as in Fig. 5 with a 3D print of two layers thickness, unlike Fig. 5 where the 3D print has a thickness of five layers. Stretching the system now leads to a significantly lower elongation since the mechanical properties of the knitted fabric have a much higher influence on the whole system. Apparently, the 3D printed structure should not be too weak to dominate the multi-material system's characteristics.



Figure 7. Microscopic pictures of the auxetic shape printed with a thickness of two layers on a single-face fabric from acrylic/polyester, relaxed (left panel) and stretched (right panel).

2016 Global Conference on Polymer and Composite Materials (PCM 2016)IOP PublishingIOP Conf. Series: Materials Science and Engineering 137 (2016) 012011doi:10.1088/1757-899X/137/1/012011

Finally, the influence of the angles in the chosen auxetic structure is investigated. Fig. 8 shows the same material combination as Fig. 5, with the x-axis scaling reduced to 75 % (left panel) or the length in y-direction decreased to 75 % (right panel), respectively. Both pictures are taken in a stretched state. Comparing them with Fig. 5 (right panel), apparently scaling down in y-direction supports the homogeneity of the pores while scaling down in x-direction slightly increases the irregularities of the single holes in the fabric. Therefore, the ideal structure can have other angles than the original 45° orientations of the connection lines.



Figure 8. Microscopic pictures of the auxetic shape printed on a single-face fabric from acrylic/polyester (stretched states), scaled down by 25 % in the x-direction (left panel) or in the y-direction (right panel), respectively.

Table 1 gives an overview of the ellipticity of the pores, defined as the aspect ratio of the pores with the idea to tailor the permeability by tailoring the pore size. For each sample, the average ellipticity of 50 pores was measured, using images taken on three different positions of the samples.

Table 1. Aspect ratios of different fabrics with auxetic forms, printed on single-face knitted fabrics, in relaxed and stretched states.

Aspect ratio	relaxed	stretched
Pure knitted fabric	1.30	2.77
Auxetic form on knitted fabric, 2 layers	1.28	1.49
Auxetic form on knitted fabric, 5 layers	1.27	1.31
Auxetic form scaled in x-direction on knitted fabric, 5 layers	1.32	1.25
Auxetic form scaled in y-direction on knitted fabric, 5 layers	1.28	1.19

As Table 1 shows, the aspect ratio of the pores is nearly unaltered for all samples with auxetic forms printed on them, which means that elongating this sample does not significantly change the pores' shape. The auxetic form printed with two layers only shows a slightly enhanced aspect ratio in the stretched state. The smallest aspect ratio can be found for the stretched sample with the auxetic form scaled in y-direction, as already assumed due to the images in Fig. 8. Transferring this finding to other – not knitted – base materials, however, necessitates additional tests in order to find the ideal auxetic structures and angles.

Moreover, 3D printing auxetic (and other geometric) structures on knitted fabrics helping to tailor their permeability for the possible application in filter materials etc. should be mentioned here. The 3D printed structure can also significantly modify the mechanical properties of the textile fabric under

investigation, such as bending stiffness, elasticity, elongation, etc. Fig. 9 shows the enhanced bending rigidity of the samples used in this study due to the 3D printed structure.



Figure 9. Single-face fabric with increased stiffness due to auxetic 3D print.

The mechanical properties of the knitted fabrics with additional 3D printed auxetic forms can be measured, e.g., by stress-strain experiments. Fig. 10 shows measured forces vs. relative elongations for the samples mentioned in Table 1 as well as the pure auxetic 3D print (without knitted fabric). While the fabric alone needs only a very small force to be elongated by 20 %, the pure 3D print shows higher forces for the same elongation. All combinations of both materials, however, generate much higher forces, combined with large hysteresis loops between increasing and decreasing elongation. This shows that the mechanical properties of the new multi-material system differ from those of both partners alone.



Figure 10. Comparison of the stress-strain curves for different combinations of 3D printed auxetic forms and knitted fabrics as well as for both materials alone.

Thus, a forthcoming project will focus on the examination of the influence of 3D printing diverse geometrical forms on the mechanical properties of different textile fabrics to create lightweight forms with tailorable bending stiffness and elongation, e.g. for tensile constructions and other architectural textiles.

4. Conclusion

Combining 3D printing with traditional technologies like knitting can bring multi-material systems with novel characteristics, such as homogenously variable permeability or enhanced mechanical properties. In a recent project, we have examined the possibilities to influence the permeability of knitted fabrics and other elastic, porous materials such as membranes by 3D printing auxetic structures on top. The interplay between both material partners has shown to determine the properties of the final composite, allowing for modifying the pore sizes and shapes. Thus, it is necessary to adjust carefully the mechanical properties of both partners in such multi-material systems to tailor the character of the final product.

In future projects, other auxetic forms will be tested about their influence on the knitted fabrics' pore sizes and shapes. Additionally, the mechanical properties of such composites will be investigated and explored further to develop new stiff, lightweight structures for textile buildings and other applications.

References

- [1] Chua C K, Leong K F and Lim C S 2003 *Rapid Prototyping: Principles and Applications, 2nd Edition* (Singapore: World Scientific Publishing Co. Pte. Ltd.)
- [2] Bermann B 2012 3-D printing: The new industrial revolution, Business Horizons 55 155-162
- [3] Rifkin J 2012 The Third Industrial Revolution: how the internet, green electricity, and 3-D printing are ushering in a sustainable era of distributed capitalism, World Financial Review 1
- [4] Novakova-Marcincinova L 2012 Application of Fused Deposition Modeling Technology in 3D Printing Rapid Prototyping Area, *Manuf. and Ind. Eng.* 11 35-37
- [5] Noorani R 2005 *Rapid Prototyping: Principles and Applications*, John Wiley & Sons, New Jersey
- [6] Melnikova R, Ehrmann A and Finsterbusch K 2014 3D printing of textile-based structures by Fused Deposition Modelling (FDM) with different polymer materials, *IOP Conf. Ser.: Mater. Sci. Eng.* 62 012018
- [7] Richter C, Schmülling S, Ehrmann A and Finsterbusch K 2015 FDM printing of 3D forms with embedded fibrous materials, *Design, Manufacturing and Mechatronics* 961-969
- [8] Sabantina L, Kinzel F, Ehrmann A and Finsterbusch K 2015 Combining 3D printed forms with textile structures – mechanical and geometrical properties of multi-material systems, *IOP Conf. Ser.: Mater. Sci. Eng.* 87 012005
- [9] Evans K E, Nkansah M A, Hutchinson I J and Rogers S C 1991 Molecular Network Design, *Nature* **353** 124
- [10] Grima J N, Attard D, Gatt R and Cassar R N 2009 A Novel Process for the Manufacture of Auxetic Foams and for Their re-Conversion to Conventional Form, Adv. Eng. Mater. 11 533-535
- [11] Scholz C, Wirner F, Götz J, Rüde U, Schröder-Turk G E, Mecke K, and Bechinger C 2012 Permeability of porous materials determined from the Euler characteristic, *Phys. Rev. Lett.* 109, 264504
- [12] Rant D, Rijavec T and Pavko-Cuden A 2013 Auxetic Textiles, Acta Chim. Slov. 60 715-723
- [13] Rant D, Ciobanu R, Blaga M and Pavko-Cuden A 2014 Compression of foldable links-links knitted structures, *Tekstil ve Konfeksiyon* 24 349-355