3D printing on warp-knitted fabrics

M Ayvali, I Bussieweke, G Druzinin, M Korkmaz, A Ehrmann
Bielefeld University of Applied Sciences, Faculty of Engineering and Mathematics, Interaktion 1, 33619 Bielefeld, Germany
e-mail: andrea.ehrmann@fh-bielefeld.de

Abstract. While 3D printing was in former times mostly used for rapid prototyping, nowadays it is also used for rapid manufacturing. To overcome the problems of relatively low production speed and in several cases insufficient mechanical properties of 3D printed objects, 3D printing can be combined with larger-scale production processes, e.g. by directly printing on textile fabrics. To combine the advantages of both materials, e.g. tensile strength of a woven fabric with stiffness of an imprinted layer, the adhesion between both partners under mechanical load has to be investigated. Here, we use tensile tests to examine maximum forces, elongation at break, wearing out of the composites and the adhesion under maximized or repeated tensile stress to examine the applicability of such composites for sports shoes etc.

1. Introduction
3D printing belongs to the emerging technologies of our time. 3D printing enables individualization of products or production of special items which cannot be formed with other technologies. It has, on the other hand, the disadvantages of being still relatively slow and having often reduced mechanical properties as compared to mold casting and similar technologies. This leads to the idea of combining 3D printing with other substrates, e.g. textile fabrics.

While a first proof-of-concept just proved that combining stereolithography (SLA) printing with textile fabrics [1], most research groups recently concentrate on 3D printing on textile fabrics by fused deposition modelling (FDM) [2]. In this way, not only clothing and shoes [3,4] can be produced, but also agricultural textiles [5], orthoses [6] and diverse other products [7].

A significant problem in such approaches is given by the adhesion between both partners of such composites, a challenge being investigated by many research groups recently [8-12]. Usually, this parameter is tested by detaching the 3D printed layer from the textile fabric in 90° or 180° configuration and measuring the necessary force [13].

Here, we go one step further and examine mechanical properties of the composite instead which are an important factor for using such multi-material objects, e.g., in sports shoes etc.

2. Materials and Methods
3D printing was performed using an Orcabot XXL (Prodim, The Netherlands) with a nozzle diameter of 0.4 mm, a layer thickness of 0.2 mm, nozzle temperature of 235 °C and printing bed temperature of 60 °C. The filament “NinjaFlex” (NinjaTek, Manheim, PA, USA), a thermoplastic polyurethane with shore hardness 85 A, was used for 3D printing.

Samples of dimensions 140 mm length and 50 mm width were printed, using the four patterns “full print”, “grid”, “honeycomb” and “circular grid”, as depicted in Fig. 1. The sample height was 0.2 mm,
corresponding to 1 layer. The textile fabrics were either glued onto the printing bed or onto a frame, allowing for printing “in the air”.

The polyester fabrics were produced by warp knitting an elastic structure “E” (1-0 / 2-3 // 1-2 / 1-3 // 1-0 / 1-2 //) and a less elastic structure “N” (1-0 / 0-1 // 1-0 / 1-2 // 2-3 / 1-0 //) on a HKS 3-M-EL, 42” with gauge E28 (Karl Mayer Textilmaschinenfabrik GmbH, Obertshausen, Germany).

Cyclic tensile tests were performed using a Sauter universal testing machine with a speed of 80 mm/min until an elongation of 25 % was reached, then relaxing the sample to the original length, stretching again etc. for 10 elongation cycles. Maximum elongation tests were performed by stretching the samples up to 108 % elongation, a limit defined by the machine geometry.

Figure 1. Patterns used for 3D printing on warp knitted fabrics.

3. Results and Discussion

As an example, Fig. 2 depicts force-strain curves of repeated tensile tests, performed with a full print and a grid on the elastic structure, printed while fixed on the printing bed. Generally, in both cases hysteresis loops are visible, as usual in such cyclic loading-unloading tests. The hysteresis area is correlated with the energy dissipation and in the cases here, as expected, largest for the initial loading-unloading cycle. Besides, a small residual stretch is visible after each cycle as well as the Mullins effect, a viscoelastic stress softening in elastomers [14].

In case of the grid structure, the hysteresis loops are more open, indicating higher energy dissipation, and the Mullins effect is stronger than in the full print, probably due to the smaller areas working against the respective load (cf. Fig. 1). Both effects are reduced after several hours or even days of relaxation, as it is also known from pure FDM printed thermoplastic polyurethane [15].

Figure 2. Exemplary cyclic tensile tests.
To compare the effect of a relatively small defined strain, Fig. 3 depicts the forces measured for the four different patterns, printed on the elastic and less elastic warp knitted fabrics, either directly on the printing bed or on the frame, i.e. in the air, in this way modifying the adhesion between both parts of the composites. For comparison, the values of the pure 3D printed layers are given. It should be mentioned that the tensile forces necessary for an elongation of the elastic (less elastic) warp knitted fabric are approx. 3 N (12 N).

As expected, the pure FDM printed layers show smaller forces at identical elongation than the composites. It must be mentioned that the forces measured for the composites are always larger than the sum of the pure FDM printed patterns and the pure textile fabrics.

Another general observation is that for full print and grid, the forces found for prints on the less elastic fabric are larger than those for the composites with the elastic one. Unexpectedly, this is not the case for the circular grid and the honeycomb. Both latter patterns include round spaces which leads typically to more complicated infill patterns with shorter lines to be printed, in this way possibly impeding a well-defined printing process and thus reducing the adhesion of the FDM printed material on the textile fabric. This approach is partly supported by the finding that printing on the frame is highly supportive for both patterns printed on the less elastic fabric, in this way enabling stronger adhesion and thus a composite with stronger connected yarns and matrix.

Another interesting finding is that the full print is not always the best choice. Instead, printed on the elastic material, the grid and especially the circular grid show higher tensile forces at the chosen elongation than the full print. This can be explained by partial detaching between both materials during the initial cycle since the full print cannot be elongated as easily as the other patterns, and the difference between the relative high elongation force of the pure full print and the small elongation force of the elastic fabric results in delamination on a microscopic scale. This interpretation is supported by the finding that under maximum load, all samples but the ones with full print broke as composites, while for the full print, only the textile fabrics broke under delamination from the 3D printed material on few centimetres length next to the break.

The forces at break are shown in Fig. 4 for all composites, compared with the forces at maximum elongation in case of the pure FDM printed samples. Here, no clear trend is visible. For the circular grid and the honeycomb pattern, the results are nearly independent from the warp knitted fabric and the printing process (with our without frame). The highest values are reached for the combination of the
less elastic fabric with the less elastic print patterns, full print and grid, as expected; however, these patterns are not found superior in all combinations. Apparently, as mentioned before, it is advantageous to combine partners with similar stress-strain behaviour and to focus additionally on the adhesion between both yarn and matrix.

Finally, Fig. 5 depicts the elongation at break. While the pure polymer samples do not break at the technically maximum elongation of 108 %, as mentioned before, especially the composites printed on the less elastic frame, i.e. with higher adhesion, break earlier. In most cases, the printing pattern with the smallest amount of printed material, i.e. the honeycomb structure, allows the highest elongation; however, there are again deviations from this finding. Apparently, more detailed examinations are necessary to identify the optimum composite for a defined application.
4. Conclusion

3D printing on textile fabrics was used to prepare composites with mechanical properties higher than those of both original materials. The composites showed significantly higher forces at break as well as elongation than the single materials. The patterns used for 3D printing significantly influenced the aforementioned parameters.

Separation between both partners of the composites occurred only in case of the full prints under maximum tension. The adhesion depended also on the printing method, i.e. with the textile fabric placed on the printing bed or on an open frame.

These results show that printing with flexible polymer on warp-knitted fabrics is technically possible and can be applied to improve the mechanical properties in comparison to both pure materials. Since they depend also on the imprinted patterns, varying these patterns allows for tailoring the desired mechanical properties, e.g. for sports shoes etc.

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5. References

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