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Comparison of FDM and SLA printing on woven fabrics

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ABSTRACT

Possibilities to perform 3D printing directly on textile fabrics have been investigated intensively during the last decade. Usually, fused deposition modeling (FDM) printing with often inexpensive 3D printers is applied in these experiments. Several studies revealed the influence of textile fabrics, FDM polymers and printing parameters, indicating that not all combinations of fabrics and printing materials are suitable for this task. Recently, first approaches to use stereolithography (SLA) or PolyJet Modeling (PJM) directly on textile fabrics have been reported. Here, the first comparison of the adhesion forces reached by FDM and SLA printing on different woven fabrics is shown, revealing significantly better adhesion for SLA printing.

Keywords
3D printing,
fused deposition modeling (FDM),
stereolithography (SLA),
adhesion,
textile fabric,
woven fabric

1 Introduction

Additive manufacturing, also called 3D printing, belongs to the most interesting technologies of the last years. It enables producing objects in small numbers at reasonable prices as well as creating shapes that could not be produced by other techniques. On the other hand, most 3D printing techniques still have problems with relatively slow production and inferior mechanical properties to injection-molded parts [1]. These mechanical problems are mostly based on air void and insufficient bonding between adjacent layers, but also on lower mechanical properties of the base materials for printing [2,3]. The latter can be improved by developing new filament materials or adding nano-fillers [4,5]. Alternatively, fibers or yarns can be included in the 3D printed objects [6,7].

Going one step further, several research groups investigated composites of polymers directly printed on textile fabrics in the last decade. Mostly, FDM printing is used for these approaches. The fiber-matrix adhesion depends on diverse parameters, such as the textile material and structure [8-10], nozzle and printing bed temperature [11,12], and strongly on the z-distance between nozzle and printing bed which defines the force with which the polymer is pressed into the textile fabric [13-15]. The latter is necessary due to the high viscosity of the molten polymer in FDM printing which impedes penetrating into a textile fabric.

To overcome this challenge, a few attempts have been made in the last years to use low-viscous photopolymer-based resins to form textile-resin composites. Firstly, this was proven to be possible for stereolithography (SLA) [16], while more recently, PolyJet modeling (PJM) was also shown to enable direct printing on textile fabrics [17,18]. For the SLA printing on textiles, however, no adhesion tests have been reported yet.

Here the adhesion reached by FDM and SLA printing on three different polyester (PES) woven fabrics is shown. The influence of printing parameters on the adhesion is discussed, and the advantages of SLA printing in case of densely woven, thin fabrics are underlined.

2 Materials and methods

The woven polyester fabrics used in this study are described in Table 1. They were chosen to compare fabrics of different thickness and surface roughness, while the textile material was kept constant. All fabrics were highly hydrophilic, impeding water contact angle and resin contact angle measurements due to very fast penetration of the drops into the woven fabrics.

Table 1. Woven fabrics used in this study.

Structure	Yarn	Warp density	Weft density	Areal weight	Thickness
Plain weave	PES 167 dtex	43.26/cm	32/cm	167 g/m²	0.32 mm
Twill weave 2/1	PES 167 dtex	43.26/cm	40/cm	186 g/m²	0.32 mm
Leno fabric	Weft: PES 167 dtex Warp 1: PES 150 dtex, textured Warp 2: PES 76 dtex	16/cm, i.e. 8 Leno pairs/cm	36/cm	181 g/m²	0.48 mm

To perform adhesion tests, rectangles of 25 mm x 100 mm were printed on these textile fabrics.

For FDM printing, an Ender V2 (Shenzhen Creality 3D Technology Co., Ltd., Shenzhen, China) was used with a nozzle size of 0.4 mm. Printing of two layers was performed with the parameters given in Table 2, while the z-distance was varied to find the optimum value. The FDM filament was poly(lactic acid) (PLA) (Grauts GmbH, Löhne, Germany), which was found to have a higher adhesion than some other rigid FDM materials in previous studies [19,20].

Table 2. FDM printing parameters.

Parameter	Value
Layer height	0.2 mm
Nozzle temperature	210 °C
Heating bed temperature	60 °C
Infill pattern	linear
Infill orientation	± 45°
Printing speed	25 mm/s

The textile fabrics were rigidly fixed on the printing bed using common adhesive tape, as shown in Fig. 1a. Printing starts with a skirt (the outer blue print in Fig. 1a), followed by the perimeters of the actual sample (inner blue part in Fig. 1a) which is subsequently filled (Fig. 1b), until the second layer is printed (Fig. 1c).

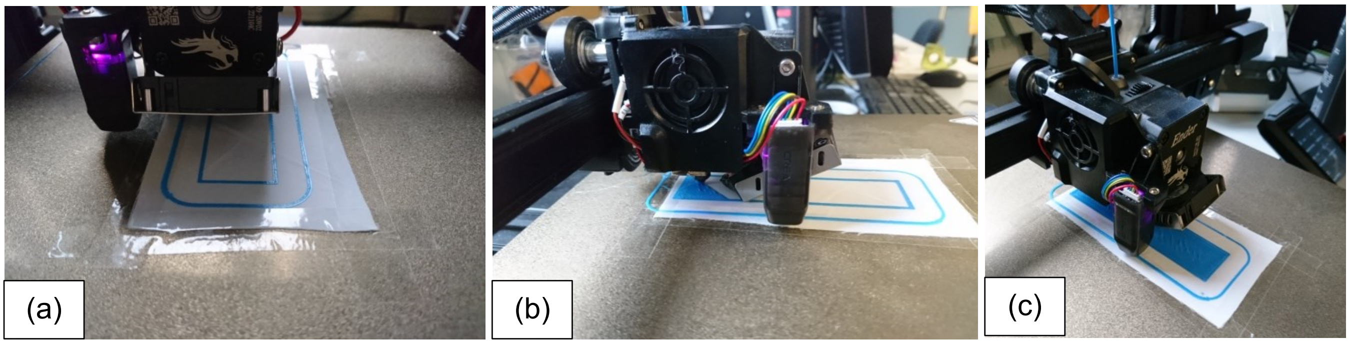

Fig. 1 FDM printing on a woven fabric. (a) Starting with skirt and perimeters, (b) filling the first layer, (c) printing the second layer.

SLA printing was performed with an Anycubic Photon S printer (Shenzhen, China) using grey “ABS-like Resin” (Anycubic) and the printing parameters given in Table 3. An overall printing thickness of 2 mm was chosen to avoid breaking of the samples during the adhesion tests, which were more brittle than the PLA specimens.

Table 3. SLA printing parameters.

Parameter	**Value**
Layer height	0.05 mm
Number of bottom layers	4
Exposure time	8.5 s
Bottom exposure time	60 s
Light-off delay	1 s
Lifting distance	6 mm
Lifting speed	2 mm/s
Retract speed	3 mm/s
Anti-alias	1
Infill	100%

The textile fabrics were fixed on a custom-made fabric holder to enable printing on them [21]. All parts were washed in isopropanol for 4 min and cured under UV light for 14 min after the printing process (Wash & Cure station, Anycubic). Figure 2 shows a woven textile in the sample holder before/after printing.

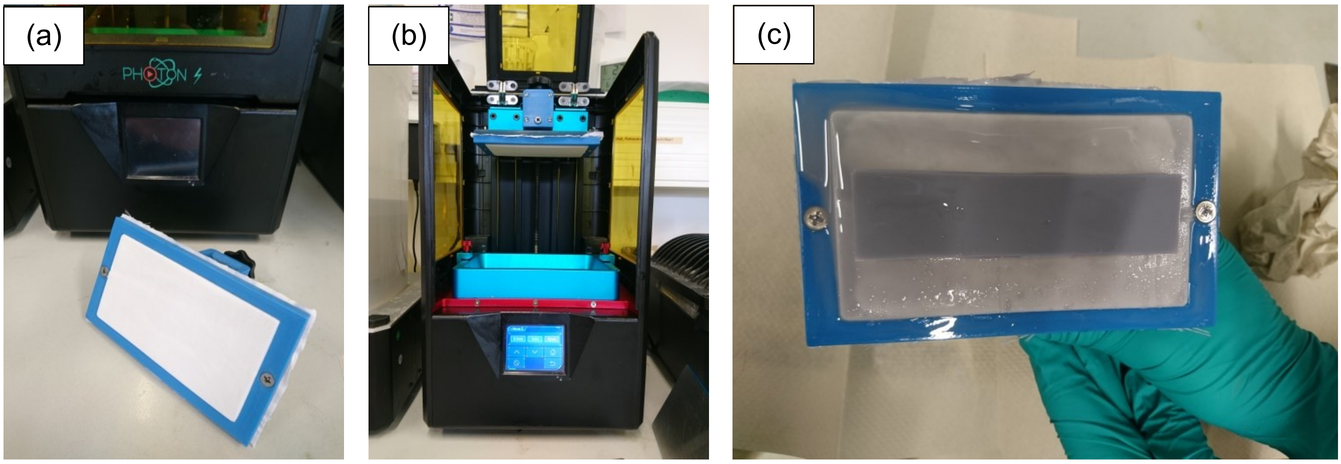

Fig. 2 SLA printing on a woven fabric. (a) Fixing the fabric in the custom-made fabric holder, (b) fabric holder inserted in the SLA printer, (c) printed sample on fixed textile fabric before washing and curing.

The adhesion of the 3D printed parts on the textile fabrics was tested by a Zwick/Roell tensile tester Z010 according to DIN 53530, as shown in Fig. 3, and evaluated according to ISO 6133. This standard describes a separation test on fabric plies bonded together. It is used to measure the adhesion force between two layers, in this paper between the textile fabric (fixed in the lower clamp in Fig. 3) and the polymer printed on it (fixed in the upper clamp), while the distance between the clamps is continuously increased. The relatively stiff SLA printed samples are held on one side of the clamps to avoid bending them too much at the beginning of the test, while the thin PLA sample shown in Fig. 3 is flexible enough to bend without any influence on the measured adhesion forces. Images were taken by an iPhone XR camera, a digital light microscope Camcolms2 (Velleman, Gavere, Belgium) and a confocal laser scanning microscope (CLSM) VK-8710 (Keyence, Neu-Isenburg, Germany).

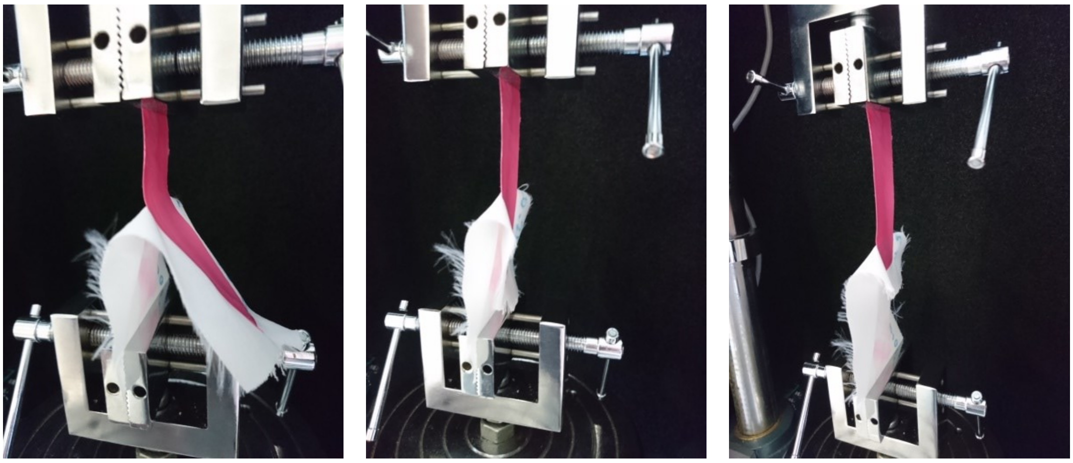

Fig. 3 Subsequent stages of an adhesion test according to DIN 53530.

3 Results and discussion

The results of the adhesion tests for FDM printing on different PES woven fabrics as well as some printed samples are depicted in Fig. 4. Here, the adhesion forces are given in dependence on the z-distance between the nozzle and the printing bed (Fig. 4a). A z-distance of 0 mm means that the nozzle touches the printing bed, while it would typically have a z-distance of ~ 0.15 mm if the polymer should be placed directly on the printing bed. The values d1 and d2 show the thicknesses of the plain weave/twill fabrics and the Leno fabrics, respectively, i.e. at the distance d2 the nozzle just touches the Leno fabric, while it touches the other fabrics at a distance d1.

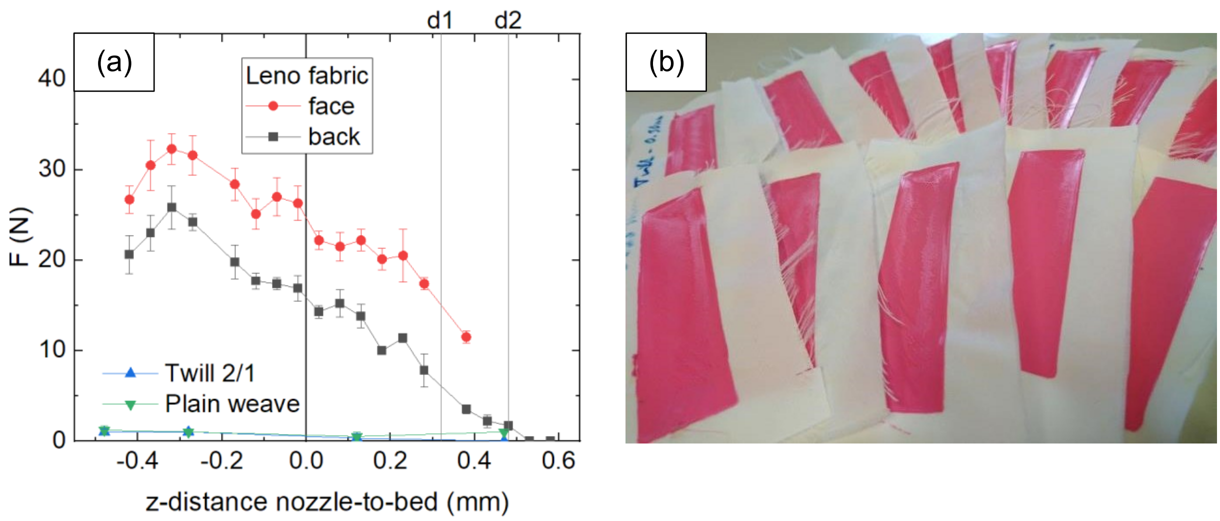

Fig. 4 (a) Adhesion forces gained by FDM printing on different textile fabrics. The distances d1 and d2 correspond to the thicknesses of plain weave/twill weave (d1) and Leno fabric (d2), respectively; (b) photographic image of samples after printing.

Firstly, the adhesion forces of PLA printed twill 2/1 and plain weave fabrics (blue and green lines) shall be discussed. All of them are very low, maximally 1 N. Similarly low adhesion values have been found before for FDM printing on very thin fabrics [13]. Here, however, the woven fabrics are not only relatively thin, but also quite densely woven, so that nearly no pores are available in which the PLA could be pressed. For a comparison of the apparent weave density, Fig. 5 depicts microscopic images of the textile fabrics under examination. While none of them shows large open pores, the weft threads of the Leno fabric appear broader and thus easier movable to allow the molten polymer being pressed into the fabric.

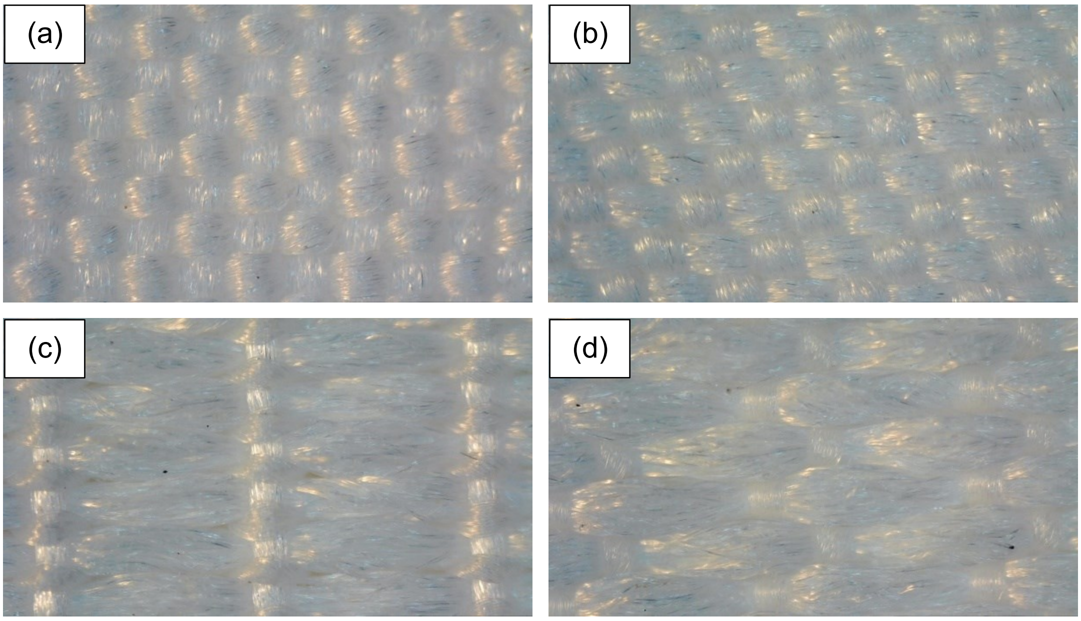

Fig. 5 Weaving structures of (a) plain weave, (b) twill 2/1, and the Leno fabric from (c) back and (d) face.

Indeed, the adhesion on the Leno fabric is much higher than on the other fabrics, which can also be attributed to its larger thickness, as shown in previous studies [9,13]. For the adhesion tests on this Leno fabric, printing was performed in different z-distances between nozzle and printing bed. The fabric thickness of 0.48 mm, marked in Fig. 4a as “d2”, indicates the starting point of the adhesion, i.e. printing with the nozzle not touching the fabric results in zero adhesion force. Printing with the nozzle being positioned lower and lower, across z = 0.0 where nozzle and printing bed would touch without the fabric between, leads to increasing adhesion forces, until a value of approx. -0.3 mm is reached. Here, the counterforce from the fabric starts clogging the nozzle, and for even lower nozzle settings, the adhesion force is decreased again.

While these findings have been reported similarly before [13-15], here a clear difference between both sides of the fabric is visible which indicates that not only thickness and porosity, but also the surface structure may influence the adhesion of an imprinted polymer.

Besides these adhesion measurements of FDM printed PLA on the fabrics under examination, the same tests were performed for SLA printed resin on these fabrics. In this technique, there is no optimization possible of the first layer position; a potential optimization by modifying the first layer thickness or curing time will be tested in the near future. The adhesion forces of the SLA printed samples as well as some exemplary SLA printed samples after the adhesion tests are given in Fig. 6, together with the highest values reached with FDM printing at the optimum z-distance.

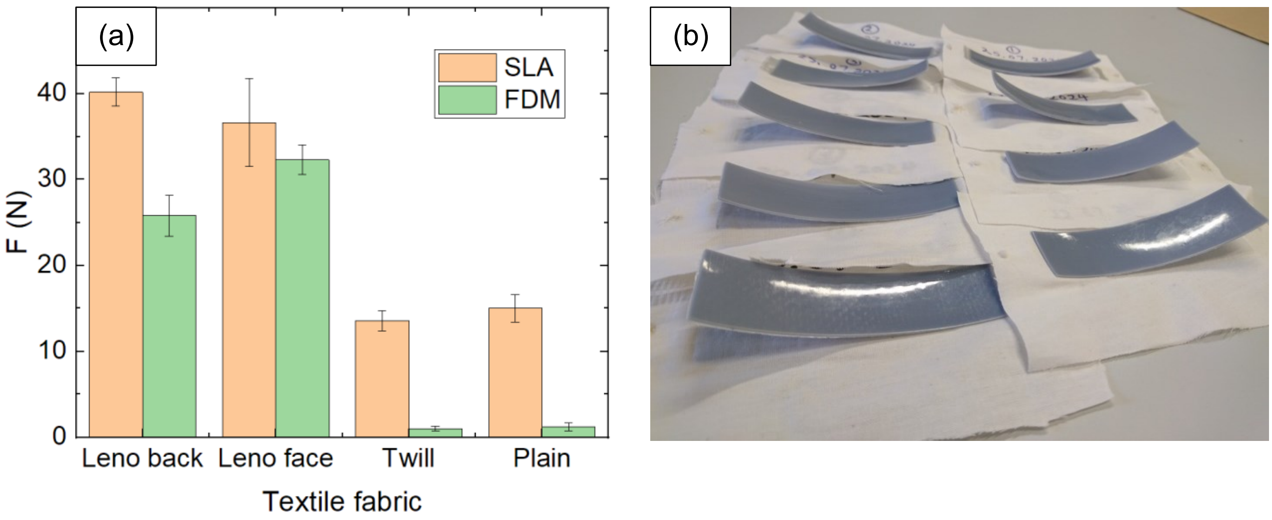

Fig. 6 Adhesion forces gained by SLA printing on different textile fabrics. The maximum values of FDM printing (cf. Fig. 4) are added for comparison; (b) photographic image of samples after testing.

Even without any optimization approaches, the adhesion forces for SLA printed material on the textile fabrics are higher than the values found for FDM printing under optimized conditions. It is especially remarkable that both the plain weave and the twill fabric reached an adhesion force around 15 N, while less than 1 N was found for the adhesion between FDM-printed PLA and these fabrics.

These differences can mainly be attributed to the different viscosity of the molten PLA and the SLA resin, leading to a much better penetration of the latter into the textile fabrics. This is visible in Fig. 7, showing the back of the SLA printed fabrics after the adhesion tests. In all dark areas, there is a large amount of hardened resin at the back of the fabric which had completely flown through the textiles, in this way resulting in a very good form-locking connection. The differences between the adhesion values for the different textiles can probably be interpreted as differently large connection areas between the resin on both sides of the fabric, i.e. the adhesion forces may actually be breaking forces of the resin connections. This idea, however, cannot be verified with the recent samples, but needs samples with well-defined pore sizes, which will be tested in a forthcoming study.

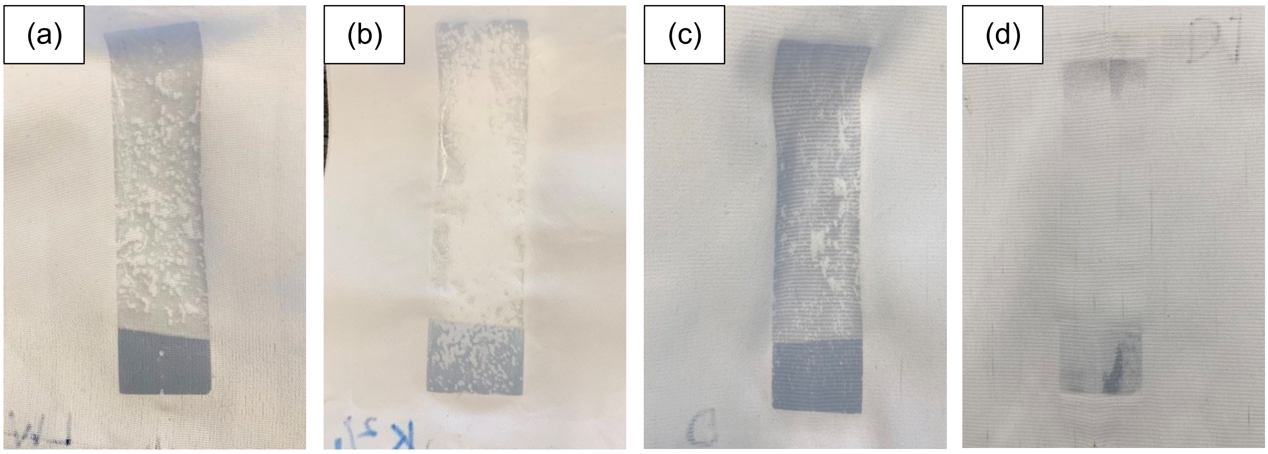

Fig. 7 Back of (a) plain weave, (b) twill 2/1, and the Leno fabric printed (c) from the back and (d) from the face, after adhesion tests. In the dark areas at the bottom, resin and fabric are not separated.

Besides adhesion measurements, CLSM images were taken of the surface structures of the printed fabrics, as depicted in Fig. 8. The highest waviness is visible for PLA printed on the Leno fabric with a z-distance of -0.35 mm (Fig. 8a,d), as can be expected due to the very thin first layer which partly penetrates into the fabric, so that the surface structure is similar to the first layer on a printing bed. For a relatively large z-distance of +0.20 mm (Fig. 8b,e), the neighboring strands are nearly interconnected, so that the waviness is nearly vanishing, while the roughness here is much higher. Finally, the SLA print (Fig. 8c,f) shows a smooth surface with very low waviness and roughness. This corresponds to the well-known high resolution of SLA printing, as compared to FDM printing.

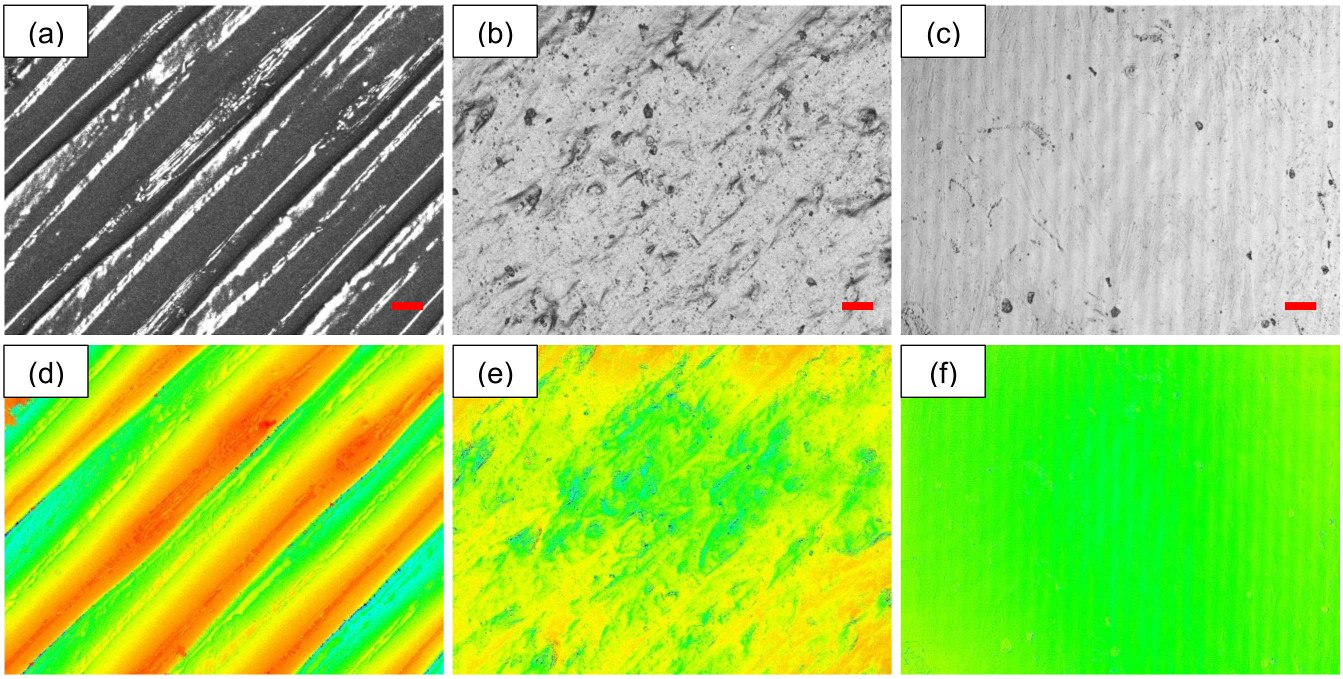

Fig. 8 CLSM images of 3D prints on the Leno fabric: (a) PLA, z = -0.35 mm, (b) PLA, z = +0.20 mm, (c) ABS-like resin, (d-f) corresponding height profiles. Scale bars indicate 100 µm.

Next, Fig. 9 shows cross-sectional images of these samples. For PLA printed at a low z-distance of -0.35 mm (Fig. 9a), the pink printed polymer is partly visible between the yarns of the Leno fabric, and the surface roughness is again clearly visible.

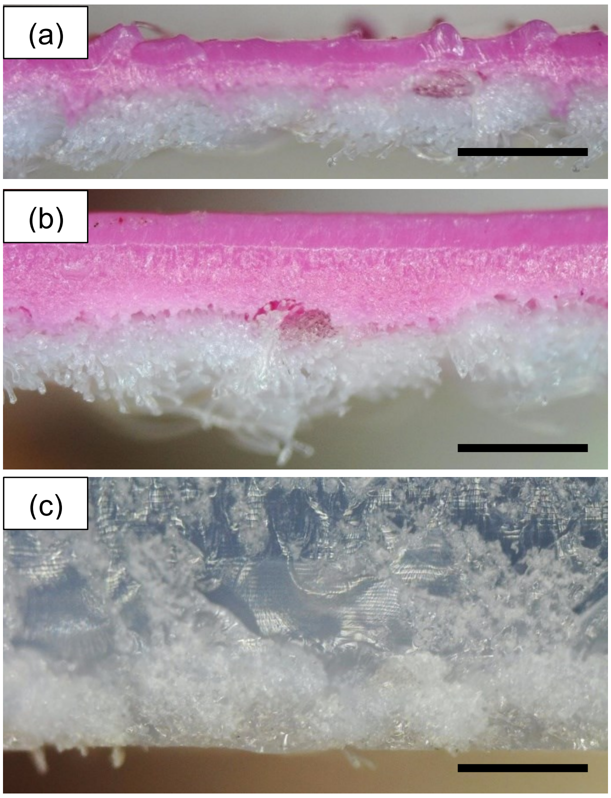

Fig. 9 Microscopic images of the cross-sections of 3D prints on the Leno fabric: (a) PLA, z = -0.35 mm, (b) PLA, z = +0.20 mm, (c) ABS-like resin. Scale bars indicate 500 µm.

Printing PLA at a much larger z-distance of +0.20 mm (Fig. 9b) results in significantly thicker printed layers, and air voids between printed polymer and fabric are visible at some positions. Finally, the greyish ABS-like resin has fully impregnated the fabric (Fig. 9c), visible here as straight lower border in contrast to the fibrous fabric, as it could already been observed in Fig. 7.

4 Conclusions and outlook

In a recent study, 3D printing on different polyester woven fabrics was performed using FDM and SLA printing. By FDM printing of PLA filament, nearly no adhesion could be reached on both thinner and less porous textiles. For the thicker Leno fabric, the usual dependence of the adhesion on the z-distance between nozzle and printing bed was found.

Oppositely, SLA printing on these fabrics led to a significantly increased adhesion for all textiles. This could be attributed to the full penetration of the low-viscous SLA resin into all woven fabrics.

In the next studies, optimizing the adhesion of SLA-printed layers by varying the first layer thickness and curing time is planned as well as an investigation of the impact of the textile pore sizes on the adhesion force.

Author Contributions

Khorolsuren Tuvshinbayar, investigation, writing – review and editing; Nonsikelelo Sheron Mpofu, methodology, investigation, visualization, writing – review and editing; Thomas Berger, investigation, writing – review and editing; Jan Lukas Storck, methodology, writing – review and editing; Alexander Büsgen, conceptualization, methodology, visualization, writing – review and editing; Andrea Ehrmann, conceptualization, investigation, formal analysis, writing – original draft preparation, visualization. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Oviedo, A. M.; Puente, A.H.; Bernal, C.; Perez, E. Mechanical evaluation of polymeric filaments and their corresponding 3D printed samples. *Polymer Testing* **2020**, *88*, 106561. DOI: 10.1016/j.polymertesting.2020.106561.
2. Szykiedans, K.; Credo, W. Mechanical Properties of FDM and SLA Low-cost 3-D Prints. *Proc. Eng.* **2016**, *136*, 257-262.
3. Zohdi, N.; Yang, R. (C. H.) Material anisotropy in additively manufactured polymers and polymer composites: a review. *Polymers* **2021**, *13*(9), 3368.
4. Dong, J.; Mei, C.T.; Han, J.Q.; Lee, S.Y.; Wu, Q.L. 3D printed poly(lactic acid) composites with grafted cellulose nanofibers: effect of nanofiber and post-fabrication annealing treatment on composite flexural properties. *Additive Manufacturing* **2019**, *28*, 621–628.
5. Syrlybayev, D.; Zharylkassyn, B.; Seisekulova, A.; Akhmetov, M.; Perveen, A.; Talamona, D. Optimisation of Strength Properties of FDM Printed Parts—A Critical Review. *Polymers* **2021**, *13*, 1587.

6. Yao, X. H.; Luan, C. C.; Zhang, D. M.; Lan, L. J.; Fu, J. Z. Evaluation of carbon fiber-embedded 3D printed structures for strengthening and structural-health monitoring. *Mater. Des.* **2017**, *114*, 424-432.
7. Richter, C.; Schmülling, S.; Ehrmann, A.; Finsterbusch, K. FDM printing of 3D forms with embedded fibrous materials. *Design, Manufacturing and Mechatronics*, pp. 961-969 (2015).
8. Calvo, J.O.; Martin, A.C.; Ferradas, M.I.R.; Morcillo, P.L.F.; Munoz, L.M.; Camo, P.M. Additive manufacturing on textiles with low-cost extrusion devices: Adhesion and deformation properties. *Dyna* 2019, 64, 8893. DOI 10.6036/8893.
9. Mpofu, N. S.; Mwasiagi, J. I.; Nkiwane, L. C.; Njuguna, D. Use of regression to study the effect of fabric parameters on the adhesion of 3D printed PLA polymer onto woven fabrics. *Fashion and Textiles* 2019, 6, 24. DOI 10.1186/s40691-019-0180-6.
10. Cuk, M., Bizjak, M., Kocevar, T. N. Influence of Simple and Double-Weave Structures on the Adhesive Properties of 3D Printed Fabrics. *Polymers* **2022**, *14*(14), 755.
11. Eutionnat-Diffo, P. A.; Chen, Y.; Guan, J. P.; Cayla, A.; Campagne, C.; Zeng, X. Y.; Nierstraz, V. Stress, strain and deformation of poly-lactic acid filament deposited onto polyethylene terephthalate woven fabric through 3D printing process. *Sci. Rep*. 2019, 9, 14333. DOI 10.1038/s41598-019-50832-7.
12. Korger, M.; Bergschneider, J.; Lutz, M.; Mahltig, B.; Finsterbusch, K.; Rabe, M. Possible applications of 3D printing technology on textile substrates. *IOP Conference Series: Materials Science and Engineering* **2016**, *141*, 012011.
13. Grimmelsmann, N.; Kreuziger, M.; Korger, M.; Meissner, H.; Ehrmann, A. Adhesion of 3D printed material on textile substrates. *Rapid Prototyping J.* 2018, 24(1), 166-170. DOI: 10.1108/RPJ-05-2016-0086.
14. Demir, M.; Seki, Y. Interfacial adhesion strength between FDM-printed PLA parts and surface-treated cellulosic-woven fabrics. *Rapid Prototyping Journal* **2023**, *29*, 1166-1174.
15. Gorlachova, M.; Mahltig, B. 3D-printing on textiles – an investigation on adhesion properties of the produced composite materials. *J. Polym. Res.* **2021**, *28*, 207. DOI: 10.1007/s10965-021-02567-1.
16. Grothe, T.; Brockhagen, B.; Storck, J.L. Three-dimensional printing resin on different textile substrates using stereolithography: a proof of concept. *Journal of Engineered Fibers Fabrics* **2020**, *15*, 1558925020933440.
17. Kozior, T.; Ehrmann, A. First Proof-of-Principle of PolyJet 3D Printing on Textile Fabrics. *Polymers* **2023**, *15*, 3536.
18. Kozior, T.; Mpofu, N. S.; Fiedler, J.; Ehrmann, A. Influence of textile substrates on the adhesion of PJM-printed MED610 and the surface morphology. *Tekstilec* **2024**, *67*, online first. DOI: https://doi.org/10.14502/tekstilec.67.2024080.
19. Rivera ML, Moukperian M, Ashbrook D, et al. Stretching the bounds of 3D printing with embedded textiles. In: Proceedings of the 2017 CHI conference on human factors in computing systems, Denver, CO, 6–11 May 2017. DOI: 10.1145/3025453.3025460.
20. Pei, E.; Shen, J.; Watling, J. Direct 3D printing of polymers onto textiles: experimental studies and applications. *Rapid Prototyping J.* **2015**, *21*, 556-571. DOI: 10.1108/RPJ-09-2014-0126.
21. Gruhn, P.; Koske, D.; Storck, J. L.; Ehrmann, A. Three-dimensional printing by vat photopolymerization on textile fabrics: method and mechanical properties of the textile/polymer composites. *Textiles* **2024**, *4*, 417-425. DOI: https://doi.org/10.3390/textiles4030024.