Göksal Erdem, Timo Grothe, Andrea Ehrmann
Faculty of Engineering and Mathematics, Bielefeld University of Applied Sciences and Arts, 33619 Bielefeld, Germany

Adhesion of New Thermoplastic Materials Printed on Textile Fabrics
Adhezija novih termoplastičnih materialov, natisnjenih na tkaninah

Original scientific article/*Izvirni znanstveni članek*
Received/*Prispelo* 3-2023 • Accepted/*Sprejeto* 4-2023

Corresponding author/*Korespondenčna avtorica:*
Prof. Dr. Dr. Andrea Ehrmann
E-mail: andrea.ehrmann@hsbi.de
ORCID: 0000-0003-0695-3905

Abstract
Combining 3D printing, especially fused deposition modelling (FDM) as a material extrusion technique, with textile fabrics can lead to full-layer composites as well as partly reinforced textiles with different mechanical properties at different positions. While the combination of both techniques enables the production of new kinds of objects different from common fibre-reinforced matrices, the adhesion between both materials is still challenging and the subject of intense research activities. Besides well-known setup and printing parameters, such as the distance between nozzle and fabric or the extrusion temperature, material combinations, in particular, strongly influence the adhesion between 3D printed polymer and textile fabric. In this study, we investigate composites of woven fabrics from cotton (CO), polyester (PES) and a material blend (CO/PES) with newly developed thermoplastic materials for FDM printing, and show that depending on the FDM polymer, the adhesion can differ by a factor of more than four for different blends, comparing highest and lowest adhesion.
Keywords: 3D printing, fused deposition modelling (FDM), high-performance polymers, high-performance polyolefin, fibre-reinforced polymers

Izvleček
Kombinacija 3-D tiskanja, še zlasti modeliranja taljenega nanosa (FDM), in tkanine lahko vodi do izdelave laminiranih kompozitov, kot tudi do delne ojačitve tekstilij z različnimi mehanskimi lastnostmi na različnih predelih. Medtem ko kombinacija 3-D tiskanja na tkanino omogoča izdelavo novih vrst večslojnih materialov, ki se razlikujejo od navadnih z vlakni ojačenih matric, je adhezija obeh materialov še vedno izziv in predmet intenzivnih raziskav. Poleg dobro znanih parametrov nastavitev tiskalnika in parametrov tiskanja, kot je razdalja med šobo in tkanino ali temperatura ekstrudiranja, na oprijem med 3-D natisnjenim polimerom in tkanino močno vpliva predvsem kombinacija materialov. V tem članku so predstavljene raziskave kompozitnih materialov, izdelanih iz bombažnih tkanin, poliestrskih tkanin oziroma tkanin iz mešanice bombaž/poliester in na novo razvitimi termoplastičnimi materiali za tisk s tehnologijo FDM. Ugotovljena je bila več kot štirikratna razlika med najslabšo in najboljšo adhezijo glede na uporabljene polimere pri 3-D tisku in tkanine.
Ključne besede: 3-D tiskanje, modeliranje taljenega nanosa, FDM, visokozmogljivi polimeri, visokozmogljiv poliolefin, polimeri, z vlakni ojačeni polimeri

1 Introduction

In recent years, 3D printing has emerged from a technique that necessitated expensive equipment and was mostly used for rapid prototyping towards a technology that is easily available at low costs, and that is also used for the rapid printing of single objects, from spare parts to gimmicks. Amongst the various additive manufacturing techniques, material extrusion, in particular FDM printing, has found its way into companies and laboratories, schools and private households due to its ease of use, non-toxic or low-toxic materials and inexpensive printers. Nevertheless, the mechanical properties of such FDM printed parts are usually weaker than those of injection moulded objects, since the layer-wise production process leads to a strong anisotropy and often induces air voids, further reducing stability [1–3].

Commonly, two different approaches are reported in literature to improve the mechanical properties of FDM printed parts: on the one hand, new filaments with improved mechanical properties can be used, e.g. fibre-reinforced polymers [4-6]; on the other hand, macroscopic combinations with mechanically stronger materials are possible, such as textile fabrics. In the latter case, the adhesion between both materials is important to avoid the detaching of the polymer from the fabric under mechanical forces. When combining stereolithography (SLA) printed areas on textile fabrics, low-viscous resin can easily penetrate into even fine fabrics [7], while FDM printed objects often adhere better to thicker fabrics with relatively large pores [8, 9]. Besides the fabric structure, primarily the nozzle-fabric distance influences the adhesion due to form-locking connections [10, 11], while the printing bed temperature [12, 13], chemical pretreatments [14, 15] or thermal post-treatments [16, 17] can also influence adhesion. It has also been shown that soft thermoplastic materials printed with FDM often have a higher adhesion on textile fabrics than rigid ones and, amongst the latter, that poly(lactic acid) (PLA) demonstrates higher adhesion on examined textile fabrics than acrylonitrile butadiene styrene (ABS), while nylon has higher or lower adhesion than PLA, depending on the substrate [18, 19].

That is why this study investigates six newly developed FDM filaments, partly glass or carbon fibre-reinforced, invented by Grauts GmbH [20]. We describe the filaments, having different elastic properties, and show their strongly varying adhesion on three different textile fabrics.

2 Materials and methods

The textile fabrics used in this study are depicted in Table 1. The pure CO and PES fabrics have a similar structure, while the CO/PES woven fabric is thicker and has a higher mass per unit area. The latter value was measured using an SE-202 analytical balance (VWR International GmbH, Darmstadt, Germany), while the fabric thickness values were measured using a J-40-T digital thickness gauge (Wolf-Messtechnik GmbH, Freiberg, Germany).

Printing was performed using an Orcabot XXL Pro 2 FDM printer (Prodim, The Netherlands), enabling printing with an extrusion temperature of up to 285 °C. The printing parameters for all filaments were as follows: nozzle diameter: 0.4 mm; layer height: 0.2 mm; unheated printing bed; 100% linear infill in ± 45° orientation; two perimeters; printing speed: 30 mm/s; and z-distance between nozzle and printing bed: 0.5 mm. A relatively high z-distance was chosen because it is well-known that near the optimum z-distance, even the smallest deviations have a large impact, while around the setting where the nozzle just slightly touches the fabric, this impact is almost negligible [10]. Thus, the chosen z-distance facilitated the comparison of the slightly thicker CO/PES fabric with thinner fabrics. The extrusion temperatures were optimized in pre-tests and were set in the range 230 °C to 250 °C, as depicted in Table 2.

Table 1: Textiles used in this study

Sample	Material	Structure	Mass per unit area (g/m²)	Thickness (mm)
CO	100% cotton	Plain weave	150	0.50
PES	100% PES	Plain weave	160	0.50
CO/PES	70% CO, 30% PES	Plain weave	205	0.65

Table 2: Thermoplastic materials for FDM processing and corresponding printing temperatures. HPP = high-performance polyolefin

Filament name	Material	Shore hardness	Extrusion temp. (°C)
PA+Carbon	Polyamide / 15% carbon fibres	75 D [a)]	250
Mid GF 1461	Polyamide / 15% glass fibres	80 D [a)]	235
Mid GF 1613	Polyamide / 15% glass fibres	93 D [a)]	230
HPP+GF 1443	HPP / 15% glass fibre	84 D [a)]	230
HPP 1444	HPP	52 D	235
HPP 1476	HPP	57 D	235

[a)] Values measured using a PCE-DD-D durometer (PCE Instruments, Meschede, Germany) on 3D printed parts with 100% infill; other Shore hardness values were provided by the manufacturer.

This table also describes the FDM printing polymers. These filaments were chosen, since they have strong mechanical properties and can withstand much higher temperatures than PLA and other common thermoplastic materials used in FDM.
Samples were designed according to DIN 53530, using Autodesk Fusion, as rectangles with an area of 150 mm × 25 mm and a height of 0.4 mm (i.e. two printed layers). Adhesion tests were performed using Sauter FH2K and Zwick-Roel Z010 universal test machines according to DIN 53530 and evaluated according to ISO 6133, procedure B, taking into account the median of the measured adhesion force peaks for each sample. Three specimens were investigated for each combination of filament and textile fabric. Microscopic images were taken using a Camcolms2 digital microscope.

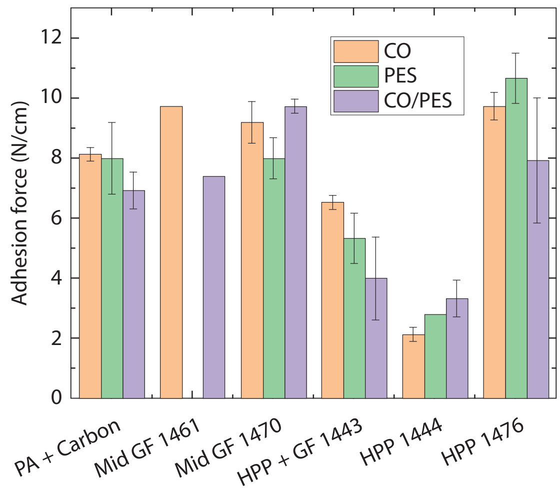


Figure 1: Adhesion forces between different textile fabrics (coloured) and novel FDM printing filaments

3 Results and discussion

The results of the adhesion force measurements are depicted in Figure 1. Since the z-distance is not optimized, the values are generally smaller than possible with these material combinations. The largely small error bars, however, indicate the reliability of the measured values.
Of all fabrics included in this study, the HPP 1444 filament shows the lowest adhesion. Much larger values are visible for HPP 1476, in particular, but also for the Mid GF 1461 and Mid GF 1470 glass-fibre reinforced filaments. It should be mentioned that Mid GF 1461 could not be printed properly on the PES fabric, so these values are omitted.
Unexpectedly, the CO/PES woven fabric, although thicker than the pure CO and PES fabrics, mostly shows smaller adhesion values than the others, while no large differences between CO and PES are visible. However, most of these differences are insignificant.
To evaluate these results, they can be compared with other 3D printing filaments reported in literature, using results that were measured for the nozzle just touching the textile surface. Some results found in literature (approximated for a z-distance identical with the fabric thickness) are given in Table 3.
As this comparison shows, the adhesion reached with the recently tested filaments is higher than some of the other results, but there are also adhesion forces more than twice the values measured in this study. One possible reason is that the new filaments tested in this study are high-temperature filaments, which should possibly be printed at even higher temperatures than in this study to reduce their viscosity during printing and enable deeper penetration into the textile fabrics under examination. Previous

Table 3: Values found in literature for adhesion forces, measured at or approximated for a z-distance identical to the fabric thickness. TPU = thermoplastic polyurethane (here with Shore hardness 86A), TPS = thermoplastic styrene (here with Shore hardness 67A and 79A)

Textile fabric	Fabric thickness (mm)	Filament material	Adhesion force (N/cm)	Ref.
Cotton woven	0.21	PLA	2	[10]
Polyester woven	0.19	PLA	0.5	[10]
Polyester woven	0.51	PLA	18	[10]
Polyester woven	0.51	ABS	3	[10]
Polyester woven	0.51	PA 6.6	11	[10]
CO/PES woven	0.45	TPU 2-86A	26	[17]
CO/PES woven	0.45	TPS1-67A	8	[17]
CO/PES woven	0.45	TPS2-79A	3	[17]
Cotton woven	0.49	PLA	8	[21]
Cotton woven	0.37	PLA	8	[21]
Cotton woven	0.39	PLA	16	[21]
Cotton woven	0.74	PLA	24	[21]
CO, PES, CO/PES	0.5–0.65	HPP 1476	8–11	This work

results from literature show that the shift in optimum z-distance is strongly correlated with the extrusion temperature [21], meaning future tests with increased printing temperatures are necessary.

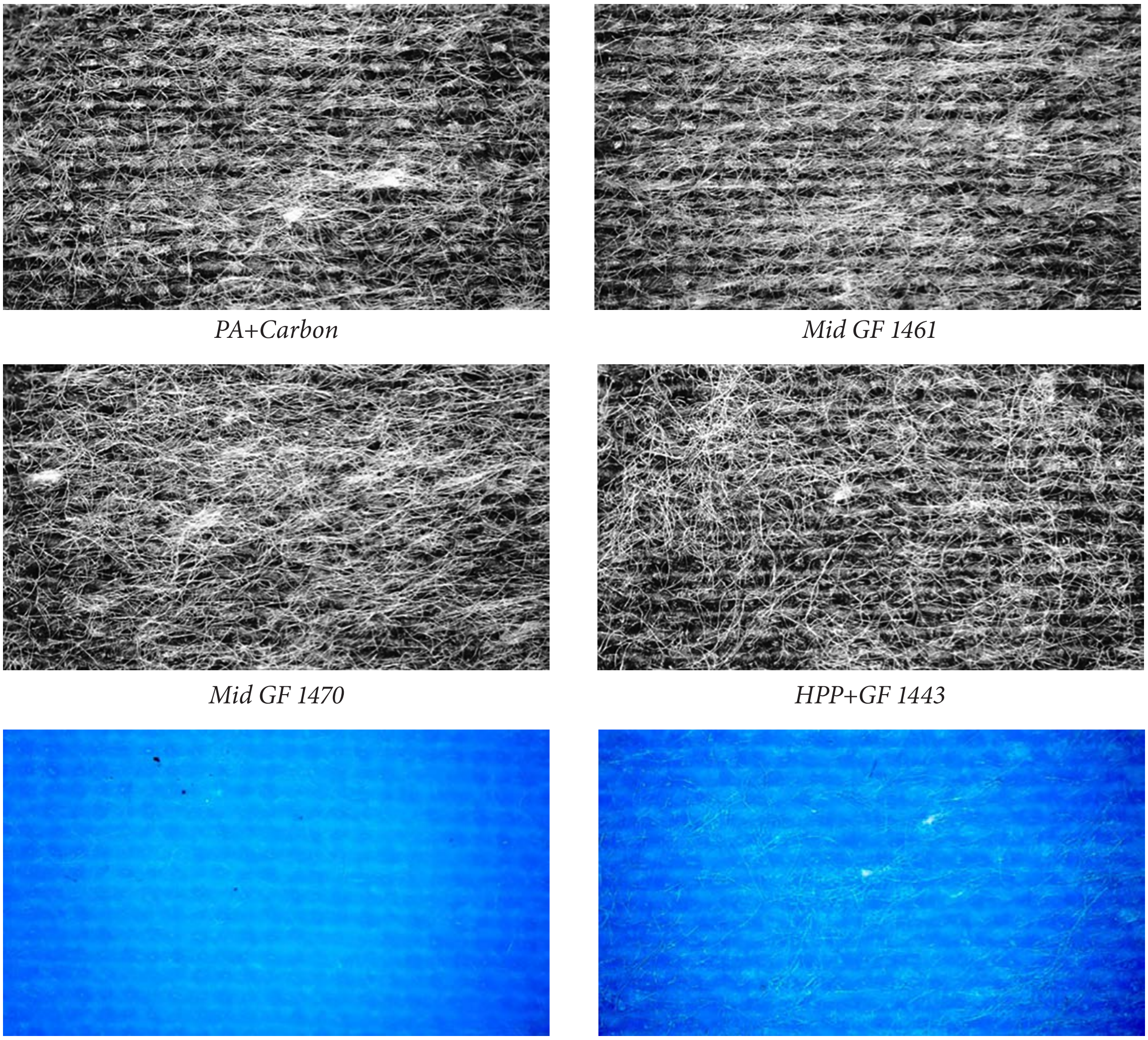
On the other hand, previous studies showed that the textile fabrics used also played an important role, not only due to their pore dimensions, but also with respect to the fibre lengths in the fabrics, where hairy fabrics with long – and thus well-fixed – fibres in the yarn resulted in higher adhesion than fabrics from short-staple yarns, where the fibres are more easily pulled out of the yarn and thus cannot fix the imprinted polymer layers properly.

To investigate this possibility, Figure 2 shows microscopic images of the detached back of different polymers printed on the cotton fabric under investigation here. On the back of the black filaments, white cotton fibres are clearly visible, especially on the sample from the Mid GF 1470 filament. This matches the results of the adhesion tests where both Mid GF filaments gave high values on the cotton fabric. For HPP 1444, only very few fibres are visible, while a more in-depth look at HPP 1476 shows several fibres, but with optically reduced contrast on the blue filament. None of the images on HPP 1444 reveals more than a few fibres, which is in line with the finding that this filament has the lowest adhesion of all three textile fabrics. It should be mentioned, however, that here only small parts of the printed samples are depicted and that variations of the amount of fibres stuck on the polymer are visible for all samples.

While the filaments investigated here do not reach the maximum adhesion forces reported in previous studies, most of them (especially HPP 1476) show reliable adhesion on all three tested textile fabrics. Due to their good mechanical properties and high heat distortion temperature, compared with PLA, further experiments in combination with other fabrics, at higher extrusion temperatures and with optimized z-distance will be performed to enable the use of these filaments in composites for high-temperature applications or improved mechanical properties.

4 Conclusion and outlook

Six new filaments were FDM printed on different woven fabrics. Most of them showed reliable adhesion forces on PES, CO and CO/PES fabrics and fibre bundles attached to their back after separation during adhesion tests. The largest differences were found between two high-performance polyolefin materials, unexpectedly with the softest material (HPP 1444) having the lowest adhesion amongst the tested samples. The chosen substrates did not have a significant influence on adhesion to the thermoplastic materials printed on them.



PA+Carbon *Mid GF 1461*

Mid GF 1470 *HPP+GF 1443*

HPP 1444 *HPP 1476*

Figure 2: Back of the printed polymer, detached from cotton fabrics by adhesion tests according to EN 53530

Future tests will concentrate on optimizing the z-distance between fabric and printing nozzle, as well as the extrusion temperature, and on the investigation of more fabrics with different woven structures to further improve adhesion, so that applications, especially in high-temperature surroundings where PLA cannot be used, are enabled.

Acknowledgments

The authors would like to thank Grauts GmbH, Löhne, Germany, for providing the special thermoplastic materials for FDM printing. The study was partly funded by the German Federal Ministry for Economic Affairs and Climate Action via the AiF, based on a resolution of the German Bundestag, grant no. KK5129708TA1.

References

1. POPESCU, Diana, ZAPCIU, Aurelian, AMZA, Catalin, BACIU, Florin, MARINESCU, Rodica. FDM process parameters influence over the mechanical properties of polymer specimens: a review. *Polymer Testing*, 2018, **69**, 157–166, doi: 10.1016/j.polymertesting.2018.05.020.
2. 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**, 1–17, doi: 10.1016/j.polymertesting.2020.106561.
3. ZOHDI, Nima, YANG, Richard (Chunhui). Material anisotropy in additively manufactured polymers and polymer composites: a re-

view. *Polymers*, 2021, **13**(9), 1–28, doi: 10.3390/polym13193368.
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, doi: 10.1016/j.addma.2019.06.004.
5. CHALGHAM, Ali, WICKENKAMP, Inge, EHRMANN, Andrea. Mechanical properties of FDM printed PLA parts before and after thermal treatment. *Polymers*, 2021, **13**(8), 1–10, doi: 10.3390/polym13081239.
6. STEPASHKIN, A.A., CHUKOWV, D.I., SENATOV, F.S., SALIMON, A.I., KORSUNSKY, A.M., KALOSHKIN, S.D. 3D-printed PEEK-carbon fiber (CF) composites: structure and thermal properties. *Composites Science and Technology*, 2018, **164**, 319–326, doi: 10.1016/j.compscitech.2018.05.032.
7. GROTHE, Timo, BROCKHAGEN, Bennet, STORCK, Jan Lukas. Three-dimensional printing resin on different textile substrates using stereolithography: a proof of concept. *Journal of Engineered Fibers Fabrics*, 2020, **15**, 1–7, doi: 10.1177/1558925020933440.
8. UNGER, Lena, SCHEIDELER, Marvin, MEYER, Pia, HARLAND, Julia, GÖRZEN, Andreas, WORTMANN, Martin, DREYER, Axel, EHRMANN, Andrea. Increasing adhesion of 3D printing on textile fabrics by polymer coating. *Tekstilec*, 2018, **61**(4), 265–271, doi: 10.14502/Tekstilec2018.61.265-271.
9. LOH, Giselle Hsiang, SOTAYO, Adeayo, PEI, Eujin. Development and testing of material extrusion additive manufactured polymer-textile composites. *Fashion and Textiles*, 2021, **8**, 1–21, doi: 10.1186/s40691-020-00232-7.
10. GRIMMELSMANN, Nils, KREUZIGER, Mirja, KORGER, Michael, MEISSNER, Hubert, EHRMANN, Andrea. Adhesion of 3D printed material on textile substrates. *Rapid Prototyping Journal*, 2018, **24**(1), 166–170, doi: 10.1108/RPJ-05-2016-0086.
11. DEMIR, Murat, SEKI, Yasemin. Interfacial adhesion strength between FDM-printed PLA parts and surface-treated cellulosic-woven fabrics. *Rapid Prototyping Journal*, 2023, online first, doi: 10.1108/RPJ-10-2022-0369.
12. 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. *Scientific Reports*, 2019, **9**, 1–18, doi: 10.1038/s41598-019-50832-7.
13. GONCU-BERK, Gozde, KARACAN, Burak, BALKIS, Ilke. Embedding 3D printed filaments with knitted textiles: investigation of bonding parameters. *Clothing and Textiles Research Journal*, 2022, **40**(3), 171–186, doi: 10.1177/0887302X20982927.
14. 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**, 1–6, doi: 10.1088/1757-899X/141/1/012011.
15. KOZIOR, T., DÖPKE, C., GRIMMELSMANN, N., JUHÁSZ JUNGER, I., EHRMANN, A. Influence of fabric pretreatment on adhesion of three-dimensional printed material on textile substrates. *Advances in Mechanical Engineering*, 2018, **10**(8), 1–8, doi: 10.1177/1687814018792316.
16. GÖRMER, D., STÖRMER, J., EHRMANN, A. The influence of thermal after-treatment on the adhesion of 3D prints on textile fabrics. *Communications in Development and Assembling of Textile Products*, 2020, **1**(2), 104–110, doi: 10.25367/cdatp.2020.1.p104-110.
17. KORGER, M., GLOGOWSKY, A., SANDULOFF, S., STEINEM, C., HUYSMAN, S., HORN, B., ERNST, M., RABE, M. Testing thermoplastic elastomers selected as flexible three-dimensional printing materials for functional garment and technical textile applications. *Journal of Engineered Fibers and Fabrics*, 2020, **15**, 1–10, doi: 10.1177/1558925020924599.
18. PEI, Eujin, SHEN, Jinsong, WATLING, Jennifer. Direct 3D printing of polymers onto textiles: experimental studies and applications. *Rapid Prototyping Journal*, 2015, **21**(5), 556–571, doi: 10.1108/RPJ-09-2014-0126.
19. SANATGAR, R.H., CAMPAGNE, C., NIERSTRASZ, V. Investigation of the adhesion properties of direct 3D printing of polymers and nanocomposites on textiles: effect of FDM printing process parameters. *Applied Surface Science*, 2017, **403**, 551–563, doi: 10.1016/j.apsusc.2017.01.112.

20. Print your ideas with our filament [online]. Grauts [accessed 4. 3. 2011]. Available on World Wide Web: <https://grauts.com/>.
21. SPAHIU, T., AL-ARABIYAT, M., MARTENS, Y., EHRMANN, A., PIPERI, E., SHEHI, E. Adhesion of 3D printing polymers on textile fabrics for garment production. *IOP Conference Series: Materials Science and Engineering*, 2019, **459**, 1–6, doi: 10.1088/1757-899X/459/1/012065.