Investigation of the Interfacial Adhesion Strength of Parts Additively Manufactured on Fabrics

Maxwell Blais
Department of Mechanical Engineering,
University of Maine,
Orono, ME 04469
e-mail: maxwell.blais@maine.edu

Scott Tomlinson
Advanced Structures and Composites Center,
University of Maine,
Orono, ME 04469
e-mail: scott.tomlinson@maine.edu

Bashir Khoda[1]
Department of Mechanical Engineering;
Advanced Structures and Composites Center,
University of Maine,
Orono, ME 04469
e-mail: bashir.khoda@maine.edu

This research first presents a method of peel testing developed by the researchers to characterize the strength of the interface between fabric and additively manufactured material. Experimentation is next presented that characterizes the interfacial strength relative to a set of parameters which include fabric fiber morphology, thickness of sizing applied to fabric, 3D printer bed temperature, and angle of additive manufacturing relative to the fabric warp direction. The interface strength within the parameter space presented was then searched and found to have a maximum of 5.18 N/mm using a novel set of parameters. This interface strength indicates the method of additive manufacturing direction on fabric may be suitable for use in a broader range of applications than previously proven feasible. Relatively rough, thick, and loose weave fabrics were found to promote interface strength compared to smoother, thinner, and finer woven fabrics. Relatively higher bed temperatures also promoted higher interface strength. Sizings on the fabric were found to promote interface strength with relatively smooth, thin, or fine fabrics which do not themselves promote high mechanical interlocking. Using these research findings, interface strength between fabric and additively manufactured material can be modified to suit the application.
[DOI: 10.1115/1.4062281]

Keywords: additive manufacturing, print on fabric, peel testing, adhesion, mechanical properties, smart manufacturing, 3D printing, advanced manufacturing, advanced materials and processing

1 Introduction

Additive manufacturing or 3D printing on fabric (3DPF) involves the creation of objects directly on fabrics. This is done to adhere 3D-printed parts and fabric together at an interfacial layer and create objects with flexibility. The 3DPF process can reduce the need for post-processing work in comparison to assembly-based processes. Additionally, 3DPF can facilitate the manufacturing of larger objects with smaller parts demonstrating localized controlled mechanical properties to combat anisotropy and add multi-functionality [1,2]. Specific applications of additive manufacturing on fabrics could be used to make wearable products and even wearable electronics [3–6]. A better understanding of 3DPF processes can impact state-of-the-art research and development in the field of smart fabrics, self-powered skins, biological sensors, etc.

To ensure the desired functionality of 3DPF objects, the interface between the additively manufactured part and fabric must be strong. Various literature have studied the adhesion strength of the interface of samples created by 3DPF. The creation of objects by 3DPF would help in controlling the anisotropy of additively manufactured parts as well where parts could be tailored for desired mechanical properties [7–9]. Previous testing determined that adhesion strength when using thicker and rougher fabrics was preferred to thin polymer fabrics. Warp and weft counts were also found to increase adhesion at the interface [1,10]. Polylactic acid (PLA) filament was preferred among the common 3D printer materials. For more uncommon materials, thermoplastic polyurethanes (TPUs) and co-polyester showed potential [11–13].

In previous research, it was determined that the use of peel testing based on the DIN 53530 standard is desired to test the adhesion strength of the interface [5,8,11,12,14]. When 3DPF is used to test adhesion strength it has been shown that promoting mechanical interlocking and chemical bonding is preferred to increase interfacial adhesion [1]. This is accomplished by either keeping the deposited material at a low viscosity for a long period of time or by treating or covering the fabric with a sizing before using it for 3DPF. Changes in fabric properties relating to wetting, diffusion, and with hydrophilic materials promote adhesion well. Changes in the pressure the deposited material is experiencing when being put onto the fabric also greatly affect adhesion strength. The pressure itself is related to the Z-distance and temperature. Without putting the fabric in the correct amount of pressure, samples can either fail during creation or have low adhesion strength [1].

Z-distance would depend on the thickness of the fabric as well as any additional thickness that the coverings on the fabric may add. Setups with a Z-distance where the nozzle barely touches the fabric are desired, which is dependent on the fabric used and application. This allows the highest promotion of adhesion strength from Z-distance without increasing the chance of sample creation failure from the nozzle moving the fabric or material backing up [10,11,13]. However, it was determined that the promotion of adhesion strength by Z-distance was not as great as when higher bed and nozzle temperatures were used, making temperature the more important process parameter to test. This is likely due to the greater mechanical bond it promotes by allowing the deposited material to remain at a low viscosity when put on the fabric [10,15–18]. Post-ironing of created samples was also found to be effective in increasing adhesion in a similar way [13]. Physical, mechanical, morphological, and chemical differences as well as surface energies of materials all matter when using the 3DPF process [1,5]. Fill angle also was determined to affect adhesion

[1]Corresponding author.
Manuscript received March 22, 2023; final manuscript received April 3, 2023; published online April 20, 2023. Assoc. Editor: Hameed Metghalchi.

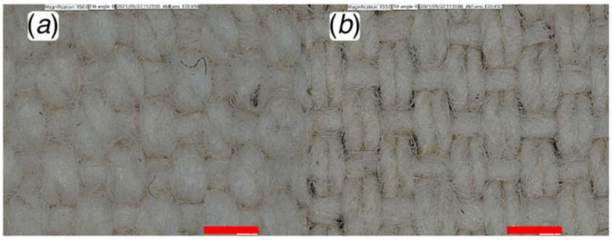

Fig. 1 Microscopic pictures of both cotton duck cloth samples: (*a*) thicker, tight, Type 1 weave and (*b*) looser, Type 2 weave; scale bar is 1.0 mm

strength with different roughness being encountered depending on the angle the material is deposited [14].

The promotion of the interface adhesion with chemical bonding appears to show potential when using similar materials as well [14,19]. Accordingly, diffusion theory explains the adhesion of polymers by diffusion of chainlike molecules leading to a stronger bond.

In this research, the adhesion strength at the interface is tested to determine the highest adhesion strength possible. Compared to previous literature this is done by testing two different weaves of cotton duck cloth to determine if different weaves and morphology greatly change adhesion strength. Additionally, sample sets involving the bed temperature of the 3D printer and testing different coverings of polymers were done. This was to determine if changes in the promotion of adhesion strength through greater mechanical interlocking or chemical bonding acquire greater adhesion strength. Tests with varying fill angles and different thicknesses of polymer coverings were completed as well, with Z-distance being kept consistent for each sample set. From these results, an optimal set of process parameters and coverings would be determined for the promotion of adhesion strength.

2 Materials and Methods

2.1 Fabric Preparation. The two cotton duck cloths used in this research were purchased from Fabric Wholesale Direct.[2] The two fabrics can be seen in Fig. 1, where Type 1 is 15 oz per square yard cloth whereas Type 2 is 7 oz per square yard. The difference between Type 1 and Type 2 twisted filament weaves is that Type 2 can visibly be seen with a looser weave that can be seen through. Comparing Type 2 weave to Type 1, Type 1 has a much thicker and tighter weave. Type 1 is rougher in both micro and macro scales due to the abundance of individual loose fibers from the excess material along with higher highs and lower lows that the tight weave provides, as shown in Fig. 1(*a*).

All samples were created on the fabrics using an Ultimaker S5 3D printer with Ultimaker PLA, and four peel testing samples were created per set. Unless otherwise stated all process parameters and settings are kept the same between sample sets. Specifically, the bed temperature would be kept at 70 °C, the angle the infill will be laid down at is 45 deg, and the layer height is 0.2 mm. The fabric was taped into place on the print bed and the part was created without the auto-bed leveler compensating around the fabric. All samples were stored according to the ASTM D4933 standard.

The samples tested involved the additive manufacturing on the two fabrics both with and without polymer coverings on them. For samples where the fabric is covered in a polymer, the polymer is first dissolved in a solvent. The polymer is dissolved into a solvent to pour on the fabric, the solvent is then left to dry and leaves behind a smooth covering of the polymer. Polymethylmethacrylate (PMMA) was used as the main covering polymer with acetone as the solvent. Additionally, a nylon 6/6 covering was created to compare to PMMA with formic acid as the solvent. A magnetic stirrer is used for 6 h to fully dissolve the polymer. The solution is then poured on the fabric at one end, a film applicator is slid over to get an even coating over the fabric.

The fabrics are then clipped onto a pan that is kept at an angle as to prevent curling of the samples during drying and to allow extra solution to pool away from the fabrics. The solution is then left to dry in a ventilated hood overnight in order to leave behind an even coating on the fabric. After the creation of the coverings on the fabric, the peel sample parts would be additively manufactured on the fabric as normal

The amount of solution created along with the thickness settings on the film applicator was curated in order to get specific thicknesses of coverings on the fabrics. Thickness of fabrics and their coverings was done by using calipers to measure the thickness at six locations on the fabric and taking the average.

2.2 Process Parameters. Along with the coverings, both high and low printing bed temperatures were tested for both sample sets. Bed temperature at 70 °C or room temperature, 25 °C, is considered as low while 100 °C and 120 °C are considered as high bed temperatures in our experiment. For PMMA covered samples, 120 °C bed temperature is used which is higher than the glass transition temperature of the PMMA.

Different fill angles were also tested separately to determine if they would be greatly influential for untreated sample sets for high and low bed temperatures. For PMMA covered samples, Type 2 fabric samples were created with covering thicknesses at both 70 °C and 120 °C. This was to determine if thinner coverings allow chemical bonding with the PMMA without the PMMA blocking the mechanical interlocking of the deposited PLA with the fabric.

Changes to the Z-distance were necessary to prevent sample creation failure due to the nozzle either backing up with material or moving the fabric around from being too low into the fabric. Table 1 compares the average thicknesses of the fabrics used with coverings and the Z-distance compensation used. When the Type 1 fabric had the coverings applied, a much higher Z-distance at +0.9 mm was required to prevent print failure due to the material backing up in the nozzle. The Type 2 fabric had the nozzle barely inside the fabric and no compensation for the added thickness from coverings on the fabric. All thinner PMMA coverings also still used a +0.4 mm Z-distance compensation as well. All covered samples were created with a 45 deg fill angle too.

2.3 Peel Testing. The peel testing used to find the adhesion strength between the additively manufactured part and fabric is based on the DIN 53530 standard for testing adhesion strength between two fabrics. This repurposed testing method involves the creation of a 25 × 152 mm long flat tab on a 76 × 305 mm piece of fabric as to be able to find adhesion strength in N/mm. This is done by peeling the part away from the fabric with a 5966 universal electromagnetic Instron machine. The testing setup for peel testing is shown in Fig. 2 where 100 mm was peeled off at a rate of 25 mm/min by the machine for the standardized result. The remaining 52 mm was peeled back by hand so that the machine could properly grab onto it. Figure 2(*a*) shows the infill orientation of the 3D printed part to the weft of the fabric where normally the part is created with a 45 deg infill if not stated otherwise. Samples were tested using a 180 deg testing orientation compared to a 90 deg angle orientation stated in the testing method, as shown in Fig. 2(*c*). This was so that the additively manufactured part would not break during testing by forcibly bending it into the 90 deg testing orientation. After the force over time is found during the testing, the results would be evaluated according to the ISO 6133:2015 standard using the method for more than 20 peaks. This would end up with a limited number of data points where an average could be found.

[2] https://www.fabricwholesaledirect.com/

Table 1 Thickness of fabric samples, including covered samples, compared the Z-distances used with them

Textile	Structure, Material	Thickness (mm)	Additional Z-distance added (mm)
Duck cloth, Type 1	Woven, Cotton	0.93	+0.4
PMMA covering Type 1 duck cloth	Woven, Cotton with PMMA covering	1.00	+0.9
Duck cloth, Type 2	Woven, Cotton	0.65	+0.4
PMMA covering Type 2 duck cloth	Woven, Cotton with PMMA covering	0.79	+0.4

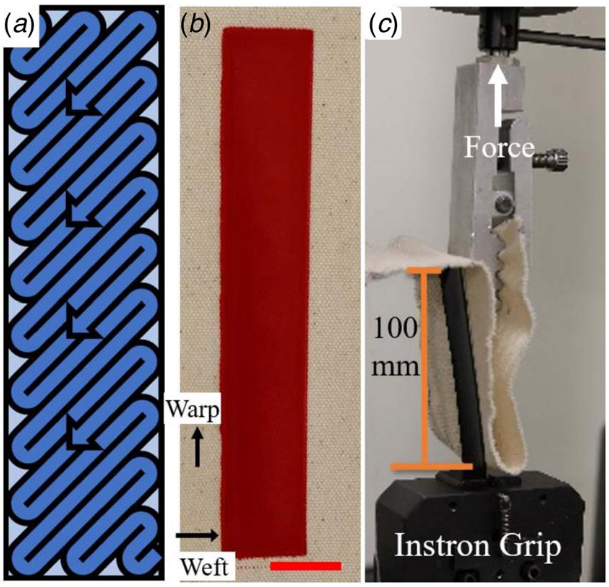

Fig. 2 Peel sample preparation for din 53530 standard: (*a*) fill orientation, (*b*) sample with warp and weft directions, and (c) testing setup

3 Results and Discussion

The adhesion strength of created peel samples is measured, using the DIN 53530 standard. Type 1 and Type 2 fabrics, high and low bed temperatures, and PMMA covered and uncovered samples were created, tested, and analyzed here, as shown in Table 2.

Results found that the Type 2 fabric assists in the promotion of adhesion strength through mechanical interlocking. This can be observed due to the Type 2 weave, high bed temperature, no covering sample set being 15.37% greater in adhesion strength compared to the Type 1 fabric sample sets. Where the loose, Type 2 weave would allow the deposited PLA to flow into the weave much easier than the tight Type 1 weave. Performing multiple two-sample *t*-test with unequal variances between the Type 1 and 2 fabrics find that uncovered high bed temperature samples are significantly different from each other with a *P*-value of 0.033. For low bed temperature uncovered fabrics, a *P*-value of 0.08 was found, for low and high bed temperature samples with PMMA *P* values of 0.058 and 0.38 were observed. The significant difference between the two at higher bed temperatures it can be observed that the adhesion strength of the Type 2 fabric is influenced more by temperature than the Type 1 fabric. PMMA covered samples showed that the fabric used in sample creation did not significantly change adhesion strength.

Table 2 Comparison of interfacial strength of samples between both the Type 1 and Type 2 cotton duck cloths

Fabric	Coating	Temperature (°C)	Adhesion strength (N/mm)
15 oz per square yard cotton duck cloth (Type 1)	PMMA	70	2.63 ± 0.26
	PMMA	120	3.15 ± 0.22
	No covering	70	1.67 ± 0.26
	No covering	100	4.29 ± 0.31
7 oz per square yard cotton duck cloth (Type 2)	PMMA	70	2.38 ± 0.27
	PMMA	120	3.03 ± 0.27
	No covering	25	1.43 ± 0.19
	No covering	100	5.01 ± 0.33

When comparing the weaves between temperatures the Type 1 weave has a 15.2% higher adhesion strength of the two for the lower bed temperatures. This is entirely due to the 70 °C bed temperature of the Type 1 weave compared to the room bed temperature of the Type 2 weave, however. These results show that the assistance of the bed temperature was the reason the Type 1 weave has a higher adhesion strength for the lower bed temperature sample sets.

Comparison between high and low temperatures, for uncovered samples, showed that the adhesion strength substantially increases due to the bed temperature. Where specifically a 111% and 88.1% difference can be observed between the high bed temperature sample sets and the low bed temperature sample sets for the Type 1 and Type 2 weaves.

For all uncovered samples created with a high bed temperature it was also observed had deposited PLA go through the weave of the fabric, as shown in Fig. 3. Deposited material going through the fabric during 3DPF had not been previously observed and was likely the reason for the significant jump in adhesion strength. After testing it was observed that some of the additively manufactured part was left behind in the fabric which also had not been previously observed, as shown in Fig. 4. A very even pattern of fabric was left behind on the removed part and the location where the part had been removed was roughed up compared to control samples. The material that had flowed through to the other side of the fabric had stayed in the fabric after testing.

For covered sample sets it was determined that the difference between weaves used when covered was unsubstantial. Differences in adhesion strength were attributed to variations in covering thickness between each sample set. Higher bed temperatures were found to increase adhesion strength by 24.2% and 17.8% respectively for both Type 2 and Type 1 weaves. This shows that the higher bed

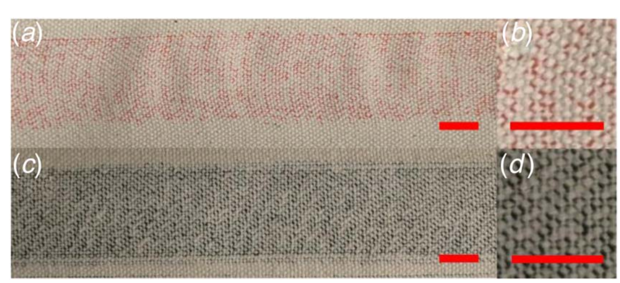

Fig. 3 Back of uncovered peel samples created with a bed temperature of 100 °C after part is created on fabric: (*a*) Type 1 fabric sample; scale bar is 10 mm, (*b*) close up of Type 1 sample, (c) Type 2 fabric sample, and (*d*) close up of Type 2 sample

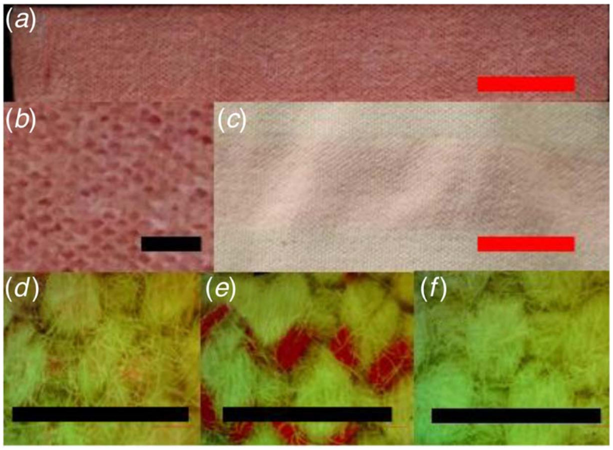

Fig. 4 Material left behind on uncovered Type 1 samples using 100 °C: (*a*) removed additive manufactured part; scale bar is 25 mm, (*b*) close up of removed part; scale bar is 2 mm, (c) location part was removed from the fabric, (*d*) microscope picture of fabric where part was removed, (e) back of fabric sample where sample was removed, and (*f*) control fabric

temperature assists in the interfacial strength between PMMA and the fabric. It is unclear if this assists in the PMMA's bond with the deposited PLA, because after testing it can be observed that no PMMA is left behind on the fabric for all covered samples. This is shown in Fig. 5 for the low bed temperature with Type 1 and high bed temperature with Type 2 sample sets. It can be determined that the PMMA fabric interface is the one that is failing from the lack of PMMA left behind on the fabric. From this, it was determined that higher temperature and thicker coverings contribute to greater strength at the PMMA fabric interface. Additionally, it can be observed in Fig. 5(*a*) that the fabric left behind on the sample was not evenly distributed, likely due to some uneven coating of PMMA.

For the Type 2 fabric samples additional tests were done comparing thinner coverings of PMMA on the fabric at both bed temperatures. Results from this testing, shown in Fig. 6, found that the thinner coverings performed significantly worse. Due to no PMMA being left behind after testing for all samples it was determined that the thinner layers of PMMA would have a worse interfacial strength with the fabric than the thicker coverings. This is likely due to the PMMA causing a weak boundary layer for the PLA to properly bond with the fabric during additive manufacturing. One exception is that the thinnest covering improved more than expected at the high bed temperatures. This is potentially due to the covering being thin enough to allow small amounts of interweaving of the PLA and the fabric. By comparing the thinnest covered fabric shown in Fig. 6 with the uncovered fabric shown in Fig. 1(*b*), little difference can be observed. When compared to thicker coverings no shiny film can be easily observed. This potentially shows that both chemical and mechanical bonding occurred between the PLA and the fabric.

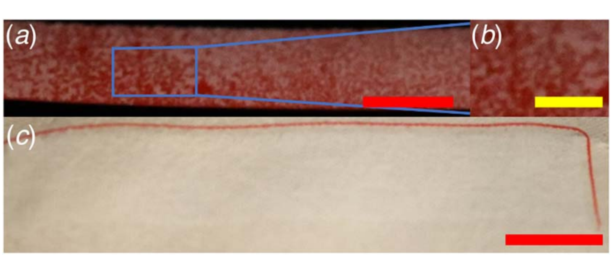

Fig. 5 PMMA covered peel sample created at 70 °C bed temperature with Type 1 fabric, after testing: (*a*) removed part; scale bar is 25 mm, (*b*) close up of removed part; scale bar is 10 mm, and (c) fabric part was removed

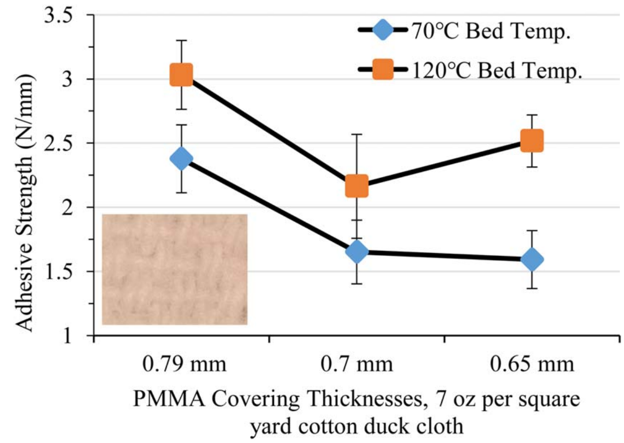

Fig. 6 Comparison of the interfacial strength of peel samples with different thicknesses of PMMA coverings on Type 2 fabric at 70 °C and 120 °C bed temperature, a visualization of the thinnest covered fabric, at 0.65 mm, is also included

Testing continued with the low bed temperature, Type 1 weave samples with a control, a 90 deg fill angle, a nylon covered, and PMMA covered sample sets, as shown in Fig. 7. All process parameters were kept the same between all samples where specifically the fill angle was kept at 45 deg and bed temperature at 70 °C, except for the 90 deg fill angle used on the uncovered sample set. Comparing the control 70 °C bed temperature uncovered sample set to the 90 deg fill angle results found that the adhesion strength increased significantly for the change in fill angle. A 57% difference between the two with additional adhesion strength likely because of the increased surface area the deposited material encounters when initially being laid down on the Type 1 fabric with a 90 deg fill. This shows potential for other methods of increasing adhesion strength by mechanical bonding and interlocking of the deposited material with the fabric.

No nylon was left behind on the fabric after the part was removed similar to the PMMA samples. From these results, it was determined that the nylon samples were unsuitable for future testing due to their extremely low adhesion strength to the fabric. The control sample with no covering had a 45% difference from the PMMA covered samples. From this, it was determined that if samples could not be created with high mechanical bonding between the fabric and the additively manufactured part then polymer coverings would be preferred. However, coverings still get lower adhesion strength compared to samples promoting mechanical interlocking.

A comparison of fill angles was done for both low bed temperature samples, and high bed temperature uncovered Type 2 weave samples, shown in Fig. 8. It was determined that adhesion strength

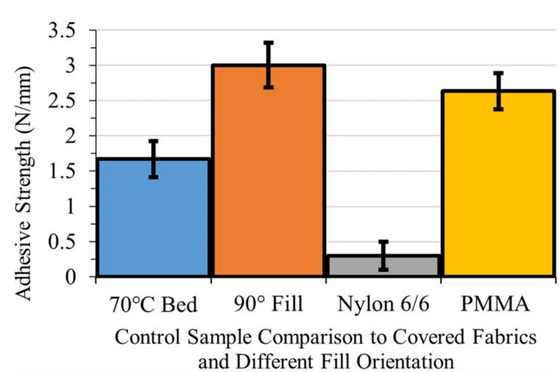

Fig. 7 Comparison of interfacial strength of Type 1 fabric samples, both uncovered and covered samples are compared

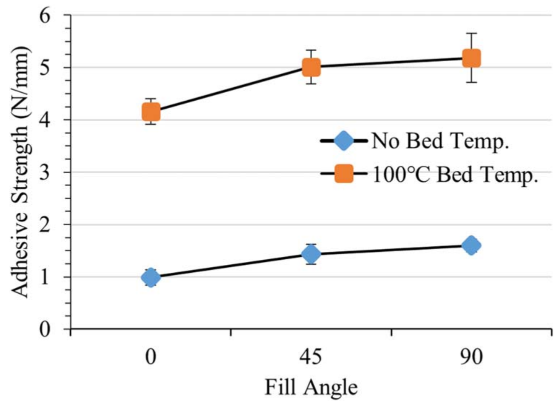

Fig. 8 Comparison of interfacial strength between no bed temperature and 100 °C, uncovered, peel samples with different fill angles, Type 2 weave was used

Table 3 Comparison of interfacial strength results to literature

Peel test results	Interfacial strength (N/mm)
Duck cloth 100% cotton woven 0.9 mm 15 oz with 70 °C bed temperature 45 deg fill angle	1.7
Duck cloth 100% cotton 0.58 mm thick with 100 °C bed temperature and 90 deg fill angle	5.2
Cotton woven 0.21 mm thick [11]	0.70
Cotton woven 0.39 mm thick [15]	2.2
Cotton twill 3:1 woven 0.9 mm thick [14]	0.70
Cotton polyester knitwear 0.44 mm thick with polyester based TPU as filament [12]	5.0
Aramid knitwear 0.42 mm thick with polyester based TPU as filament [12]	5.0

is higher the closer to the 90 deg angle, along the weft of the fabric. There were diminishing returns observed the closer the fill angle was to the weft, this can be observed from the curved results in Fig. 8. Comparing to the differing fill angle results in Fig. 7 it was determined that the thicker Type 1 weave promoted mechanical interlocking more through changes in fill angle than the Type 2 weave. This is because of the morphology of the fabrics being much different from each other. However, the thicker Type 1 weave is much rougher than Type 2 weave. This would cause the deposited PLA to encounter more surface area causing more adhesion strength to occur by mechanical interlocking. It can also be determined that changes in temperature are far better at influencing adhesion strength through mechanical interlocking than changes in fill angle. For the Type 1 fabric, this is also likely true even with the higher influence from fill angle.

After all testing had been completed, results for adhesion strength were compared to previous results found in literature, as shown in Table 3. The highest adhesion strength was observed with our novel combination of parameters involving high bed temperature, uncovered, Type 2 weave, with a 90 deg fill angle at 5.18 N/mm. A comparative result from literature is presented in Table 3. Close to our results was a TPU that was deposited on multiple knitwear fabrics finding 5 N/mm. More comparison to rough fabrics like knitwear and other deposited materials like TPUs would be desired. Other reported results from literature were much lower in terms of adhesion strength.

4 Conclusion

From the peel testing conducted utilizing the discussed process parameters, it was determined that the promotion of interface strength through mechanical interlocking combined with adhesion is preferred to adhesion alone. Loose weave fabrics, high bed temperatures, and fill angles along the weft all promote interface strength through mechanical interlocking. This is done either by increasing the surface area of the fabric fibers the deposited material or by allowing material to flow more easily between the fibers of the fabric.

Polymer sizings have potential for use on fabrics, to increase interface strength, where mechanical interlocking cannot be easily improved. Sizings of PMMA on fabrics fail at the connection between the PMMA and fabric before reaching interface strengths of samples using both mechanical interlocking of fabric to additively manufactured material and adhesion. The interface strength is affected by both thicknesses of the sizings and the 3D printer bed temperatures. Thin coverings have potential to provide interfacial strength through both mechanical and chemical mechanisms. However, a weak boundary layer between sizing and additively manufactured material could also be created causing lower interface strength.

Based on this research, future work to further increase interface strength, and expand the use of fabric as a composite material within additive manufactured parts, is recommended. This future research should involve interface strength testing with a wider variety of fabrics, Z-distance, deposited materials, print parameters such as bed geometry, and could include methods of sandwiching fabric within layers of additively manufactured material and characterizing this construction. Ultimately, future research should include strength and durability testing of final parts created with the 3DPF process.

Acknowledgment

This material is based upon work supported by the U.S. Army Combat Capabilities and Development Command—Soldier Center (DEVCOM SC) under Contract Nos. W911QY-18-C-0101 and W911QY-20-C-0053. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the DEVCOM SC.

Conflict of Interest

There are no conflicts of interest. This article does not include research in which human participants were involved. Informed consent was obtained for all individuals. Documentation provided upon request. This article does not include any research in which animal participants were involved.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Nomenclature

3DPF = 3D printing on fabric
PLA = polylactic acid
PMMA = polymethyl-methacrylate
TPUs = thermoplastic polyurethanes
Type 1 = tight thick weave cotton cloth
Type 2 = loose thinner weave cotton cloth
Z-distance = distance between nozzle and print bed

References

[1] Kozior, T., Blachowicz, T., and Ehrmann, A., 2020, "Adhesion of Three-Dimensional Printing on Textile Fabrics: Inspiration From and for Other Research Areas," J. Eng. Fibers Fabr., **15**(1), p. 155892502091087.

[2] Koch, H. C., Schmelzeisen, D., and Gries, T., 2021, "4D Textiles Made by Additive Manufacturing on Pre-Stressed Textiles—An Overview," Actuators, **10**(2), p. 31.
[3] Uysal, R., and Stubbs, J. B., 2019, "A New Method of Printing Multi-Material Textiles by Fused Deposition Modelling (FDM)," Tekstilec, **62**(4), pp. 248–257.
[4] Grimmelsmann, N., Martens, Y., Schäl, P., Meissner, H., and Ehrmann, A., 2016, "Mechanical and Electrical Contacting of Electronic Components on Textiles by 3D Printing," Procedia Technol., **26**(1), pp. 66–71.
[5] Korger, M., Bergschneider, J., Lutz, M., Mahltig, B., Finsterbusch, K., and Rabe, M., 2016, "Possible Applications of 3D Printing Technology on Textile Substrates," IOP Conf. Ser.: Mater. Sci. Eng., **141**(1), p. 012011.
[6] 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**(1), p. 012005.
[7] Ayvali, M., Bussieweke, L., Druzinin, G., Korkmaz, M., and Ehrmann, A., 2021, "3D Printing on Warp-Knitted Fabrics," IOP Conf. Ser.: Mater. Sci. Eng., **1031**(1), p. 012019.
[8] Pei, E., Shen, J., and Watling, J., 2015, "Direct 3D Printing of Polymers Onto Textiles: Experimental Studies and Applications," Rapid Prototyp. J., **21**(5), pp. 556–571.
[9] Tadesse, M. G., Dumitrescu, D., Loghin, C., Chen, Y., Wang, L., and Nierstrasz, V., 2018, "3D Printing of NinjaFlex Filament Onto PEDOT: PSS-Coated Textile Fabrics for Electroluminescence Applications," J. Electron. Mater., **47**(3), pp. 2082–2092.
[10] Gorlachova, M., and Mahltig, B., 2021, "3D-Printing on Textiles—An Investigation on Adhesion Properties of the Produced Composite Materials," J. Polym. Res., **28**(6), p. 207.
[11] Grimmelsmann, N., Kreuziger, M., Korger, M., Meissner, H., and Ehrmann, A., 2018, "Adhesion of 3D Printed Material on Textile Substrates," Rapid Prototyp. J., **24**(1), pp. 166–170.
[12] Korger, M., Glogowsky, A., Sanduloff, S., Steinem, C., Huysman, S., Horn, B., Ernst, M., and Rabe, M., 2020, "Testing Thermoplastic Elastomers Selected as Flexible Three-Dimensional Printing Materials for Functional Garment and Technical Textile Applications," J. Eng. Fibers Fabr., **15**(1), p. 155892502092459.
[13] Ehrmann, A., Görmer, D., and Störmer, J., 2020, "The Influence of Thermal After-Treatment on the Adhesion of 3D Prints on Textile Fabrics," Commun. Dev. Assem. Text. Prod., **1**(2), pp. 104–110.
[14] Kozior, T., Döpke, C., Grimmelsmann, N., Juhász Junger, I., and Ehrmann, A., 2018, "Influence of Fabric Pretreatment on Adhesion of Three-Dimensional Printed Material on Textile Substrates," Adv. Mech. Eng., **10**(8), p. 168781401879231.
[15] Spahiu, T., Al-Arabiyat, M., Martens, Y., Ehrmann, A., Piperi, E., and Shehi, E., 2018, "Adhesion of 3D Printing Polymers on Textile Fabrics for Garment Production," IOP Conf. Ser.: Mater. Sci. Eng., **459**(1), p. 012065.
[16] Yan, Y., Zhang, R., Hong, G., and Yuan, X., 2000, "Research on the Bonding of Material Paths in Melted Extrusion Modeling," Mater. Des., **21**(2), pp. 93–99.
[17] Yin, M., Xie, L., Jiang, W., and Yin, G., 2018, "Design and Fabrication of Integrated Micro/Macrostructure for 3D Functional Gradient Systems Based on Additive Manufacturing," Opt. Commun., **414**(1), pp. 195–201.
[18] Legoinha, C., Afonso, D., and Pires, L., 2021, "Fused Filament Fabrication Over Fabrics—Experiments and Applications," IOP Conf. Ser.: Mater. Sci. Eng., **1193**(1), p. 012031.
[19] Unger, L., Scheideler, M., Meyer, P., Harland, J., Gorzen, A., Wortmann, M., Dreyer, A., and Ehrmann, A., 2018, "Increasing Adhesion of 3D Printing on Textile Fabrics by Polymer Coating," Tekstilec, **61**(4), pp. 265–271.