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Design for Material Extrusion on Mesh Fabrics

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Abstract
The use of additive manufacturing strides in textile development, from fashion design to technical textiles. Fashion designers can utilise AM technologies to rethink and reinterpret traditional textiles structures to produce 3D printed textiles. 3D printed textiles promote novel applications especially on individualize garments production, new vision of textile functionalization, new multi-material composite explorations and the development of innovative aesthetic print techniques (Innovation in Textiles, 2018). The purpose of this paper was to explain the procedure of direct 3D printing off-the-shelf PLA on selected mesh fabrics using fused-deposition modelling (FDM). This is a pilot study for designers to understand the key design considerations and necessary 3D printing adjustments for successful polymer-textile adhesion. This work formed part of a PhD study on the application of 4D printing shape-memory textiles.

Keywords: 3D Printed Textiles; Material Extrusion; Mesh Fabric; Polymer-Textile Composite; Polymer-Textile Adhesion.

1. Introduction

Additive Manufacturing (AM), commonly known as 3D printing or Rapid Prototyping (RP) enable fabrication of geometrically complex components with fine details by accurately placing material(s) in position within a design domain. General AM benefits from design freedom, reduced time to market in product development, service and increased R&D efficiency (AM Platform, 2014). AM is constantly progressing with future perspectives in hardware, software and materials to develop novel methodologies that expand the potential of prototyping and applications across different industries. The use of additive manufacturing also strides in textile development, from fashion design to technical textiles. Fashion designers can utilise AM technologies to rethink and reinterpret traditional textiles structures to produce 3D printed textiles. 3D printed textiles do not replace conventional fibre-based production but characterise traditional techniques like knit, weave and prints with futuristic vision and enhancing new functionalities that cannot be achieved by conventional textile fabric itself. 3D printed textiles can be divided into different categories, grouped into fully 3D printed flexible structures, and, direct 3D printing of polymers onto textile fabrics (Figure 1). Fully 3D printed flexible structures are usually fully printed materials that uses the shapes and patterns of interlocking structures or tightly woven meshes to resemble the fluidity and flexibility of cloth (Chua, 2010). Direct 3D printing of polymers onto textile fabrics is an add-on process to apply 3D structures on textile fabric. The free movement and aesthetics of a traditional textile fabric can be preserved.

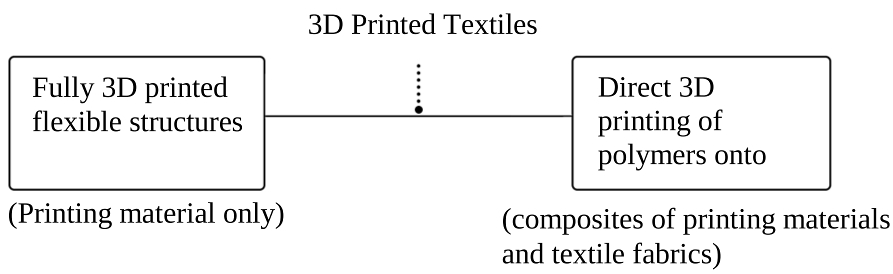


Figure 1: Types of 3D printed textiles.

3D printed textiles promote novel applications especially on individualize garments production, new vision of textile functionalization, new multi-material composite explorations and the development of innovative aesthetic print techniques (Innovation in Textiles, 2018). It also helps to promote a more sustainable future for the material use in the garment industries. In order to optimise 3D printed textiles for applications, advanced studies are required to overcome some of its key challenges, especially on the adherence of the 3D printed structure to the textile substrate, 3D CAD data for conformal 3D printed textile (Godazandeha et al, 2010), understanding the mechanical properties, free-moving assembly, finishing processes, tailoring durability of the print and managing the fabrication costs of complex structures in 3D printed textiles.

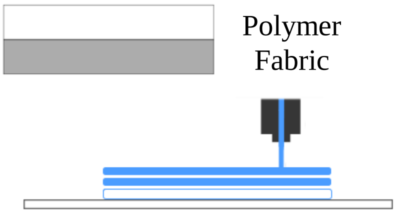
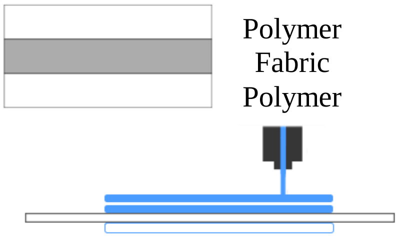
2. Methodology

The methodology in this work was to explain the procedure of direct 3D printing off-the-shelf PLA on selected mesh fabrics using fused-deposition modelling (FDM), alongside with proposed structure design, CAD model and fabric set up to additive manufacture. The key parameters and their effects on the polymer-textile adhesion were also highlighted. In this study, the Prusa PLA was used. It is easy to print at low melting temperature between180 to 210°c, with a relatively low thermal conductivity and glass transition temperature of approximately 44°c to 63°c (Simplify3D, 2018). It has relatively good strength, long-term biodegradable, aesthetically pleasing, high detail finishes and post-processing friendly (Rigid.Ink, 2017). The chosen mesh fabrics are specified in Table 1.

	Tulle name	Types of netting and meshes	Types of fibers	Compositio n	Fabric type	Fabric thickness
F1	Net Fabric	Tulle	Synthetic	100 Nylon	Knitted	0.25mm
F2	Voile Net	N/A	Synthetic	100 Polyester	Woven (Voile)	0.13mm
F3	Lill Polyester Lace	Power mesh	Synthetic	100 Polyester	Knitted	0.18mm

Table 1: List of mesh fabrics.

F1, F2 and F3 are all lightweight mesh fabrics with different types of mesh structures and flexibility. F1 and F3 have equally large mesh openings of $1mm^2$ while F2 is closely transparent with very fine mesh openings. F1 is the thickest and stiffest among the 3 selections, followed by F2 and F1. F3 is stretchable while F1 and F2 have extremely low stretch-ability. The thickness of the fabrics was measured to be taken account for the z-distance adjustment. To read the fabric thickness, a flat piece of 21cm x 25mm cut fabric was placed on the thickness gauge. It is important that the fabric is crease-free and not stretched. The pressure foot was gradually brought down and aligned to rest on the fabric for 30 seconds. The gauge reading was taken. These steps were attended at different places of the sample to obtain the mean of these readings as the average value of the fabric thickness. Two structures were proposed at the initial of this study to identify which print layering give better adhesion and 3D printed structures stability on the fabric (Table 2). Meanwhile, the warping, linear surface structure finishing and flexibility of all printed samples were also evaluated through visual and haptic inspections. Structure 1 is printing directly on fabric layer while Structure 2 is embedding textile fabric in a three-dimensional print. Samples of Structure 1 and Structure 2 were printed at 215°c onto different textile fabrics F1, F2 and F3 (25 x 23cm) using the same filament material Prusa PLA 1.75mm in separate batches using the original Prusa i3 MK3 printer with smooth double-sided PEI sheet build surface. The print settings such as the nozzle temperature, printing speed, fill density, fill angle, layer height and extrusion width were kept consistent as documented in Table 3.

Structure 1	Structure 2
	

: 0.1mm layer height
: First layer.

Table 2: Structure 1 and Structure 2.

Sample Size	25mm x 25mm x 0.4mm
Base fabric type	F1, F2, F3
Size of cut fabric	25cm x23cm 
Filament material	Prusa PLA 1.75mm Silver
Print settings	0.10 detail MK3
Fill density	100%
Fill angle	45º
First layer height	0.2mm
Layer height	0.1mm
First layer extrusion width	0.42mm (optimum)
Extrusion width	0.45mm`
Nozzle temperature	215°c
Bed temperature	60°c
First layer speed	20mm/s
Z-distance between bed and nozzle without base fabric	-0.820mm
Z-distance between bed and nozzle with base fabric	Structure 1: -0.815mm (-0.005mm increment) Structure 2:
Support material	None
Print surface	PEI sheet

Table 3: Settings for material extrusion on mesh fabric.

For Structure 1, the fabric was laid down flat on the build platform and securely clipped on all edges. It is extremely important to position the clips carefully to prevent any obstruction in the path (top – bottom and the sides of the built platform). The new z-distance between bed and nozzle with base fabric must be adjusted before the print begin. Whereas for Structure 2, the procedure started by allowing the printer to print the first or two layer(s) at the initial z-distance without the base fabric (-0.825mm). The 3D printer was then paused immediately when the prior layer (s) completed in order to lay the mesh fabric over the print. The new z-distance was set immediately (-0.820mm) when the print is resumed (Table 5). The print was let to complete. Multiple times of first layer calibration (figure) and print trials were conducted on the mesh fabrics to obtain the optimum z-distance adjustment (Table). The tested z- values range from -0.572mm to -0.822mm (Table 4). Experiment trials results given that the optimum z-value is around -0.815mm to -0.817mm for all 3 selected mesh fabrics adhesion despite of little thickness variations between the fabrics. All perimeters including the skirt of the component printed well on the fabric with good surface finishing and no warping when an increment of -0.005mm from the original z-distance was used. This distance is close enough to press the filament into the fabric without catching on the fabric or clogging the extruder. Based on trials and errors, there was no need to manually calculate the z-distance by adding the Initial Z-axis height with the respected fabric thickness and tolerance. The thickness of fabrics does not have large impact on the z-distance adjustment (Note: only if they have approximately same range of thickness, unlike mesh fabric versus thick leather).

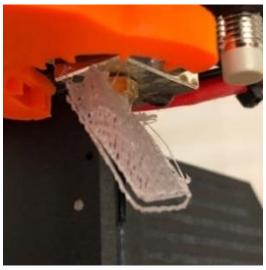
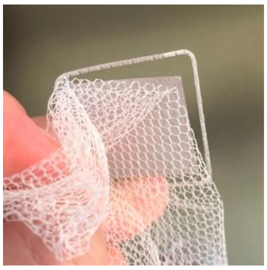
Filament - Fabric	Prusa PLA-F1	Prusa PLA-F1	Prusa PLA-F1
Z-distance between bed and nozzle with base fabric	-0.565mm 	-0.608mm 	-0.815mm 
Comments	The z-distance was too high. The 3D printed component was dragged by the nozzle forming a blob. The print stuck on the nozzle when it was being lifted.	There were minor filament dragging. The print has a sparse bottom fill with highly visible gaps between perimeters.	All perimeters including the skirt stuck well on the build platform. The middle print area has improved adhesion but can be peeled off with force.

Table 4: Z-distance adjustments and print evaluation for Structure 1.

Filament - Fabric	First layer z-distance without fabric	PLA – F1 (After + fabric)	PLA – F2 (After + fabric)	PLA – F3 (After + fabric)
The optimum Z-distance	-0.825mm	-0.820mm	-0.820mm	-0.820mm

Table 5: Structure 2 Z-distance adjustment with a standard increment of -0.005mm while adding fabric. Note: The larger the z-distance value, the larger the gap between the nozzle and the build platform (-0.820mm > -0.825mm).

The procedures were repeated with a raised printing temperature of 5 – 20°c from suggested filament temperature while the z-distance kept constant at -0.815mm. Print results at 215°c - 220°c presented improved adhesion of the component on the fabric. Despite of good printability of Structure 1 on all selected fabrics, the first layer adhesion and stability of the 3D printed structures on the fabric were extremely poor. All printed components can be peeled off easily from their respective fabrics using a small amount of manual force. Results showed that Structure 1 did not meet the criteria and incompatible for the T-peel test. On the other hand, Structure 2 gave a positive result to be carried forward for T-peel adhesion test.

All printed parts adhere well to their respected fabric with excellent surface finishing and no warping at optimum z-distance (Table 5). The molten PLA of the second layer was able to flow through the single threads of the fabric to form an intermolecular bond with the first base layer. Experiment trail revealed that the z-distance can be lowered further to -0.003mm, but it was recommended to keep the increment at -0.005mm to prevent the nozzle from catching on the fabric. The procedures were also repeated with adjustment on the printing speed and polymer flow. Results showed no substantial differences on the polymer-textile adhesion. Therefore, the printing speed was remained at 20 – 22.5mm/s and 100% flow rate. Agreeing with Spahiu (2017), a higher flow rate above 100% did not reflect higher penetration of extruded polymer into the woven fabric. For the adhesion test, the relative peel resistance of Structure 2 3D printed polymeric layers laminated with embedded fabric F1, F2 and F3 were measured using the T-peel method. 3 sets o T-peel specimens (Figure 2) were fabricated according to the print settings in Table 6 and Table 7. The 3D model of rectangle sample was developed with SolidWorks, exported as STL. file and imported into Slic3r PE for slicing. The sliced result was sent to the original Prusa i3 MK3 with 0.4mm nozzle. The printing procedure was the same as printing Structure 2 with minor adjustments (Figure 3). One side of the printed rectangle was unbonded from the fabric to be fixed in one of the clamps of the testing machine. This was done by placing a section of blue painters tape on one end of the printed rectangle in between the 3D printing process, right before the fabric was placed (Table 8). Experiment trials advised that it is best to place the blue painters tape onto the polymer part. It did not adhere well onto the fabric which can affect the quality of the print and increase the risk of print failure.

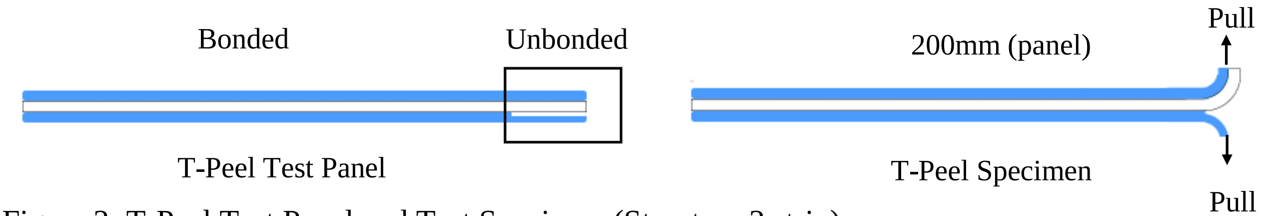


Figure 2: T-Peel Test Panel and Test Specimen (Structure 2 strip).

Sample Size	200mm x 25mm x 0.5mm 
Printing Settings	0.10mm Detail MK3
Print Layers	5 layers
Printing Instruction	
Sample Quantity	3 of each kind
Printing Material	Prusa PLA
Types of Mesh Fabric	F1, F2 and F3
Test Equipment	Universal testing machine DIN 53530
Standard	T-Peel Test ASTM D1876
Specimen	T-Peel
Test Types	T-Peel Test
Print temperature	215°c
Layer height	0.1mm
First layer z-distance	-0.825mm
Second layer z-distance	-0.820mm
First layer printing	20mm/s

speed	
Fill density	100%
Fill angle	45º
Fill pattern	Rectilinear

Table 6: Adhesion test specimen print settings.

Skirt Loops (minimum)	1
Distance from object	2mm
Skirt height	3 layers (=0.3mm)
Minimal filament extrusion length	4mm

Table 7: Skirt settings.

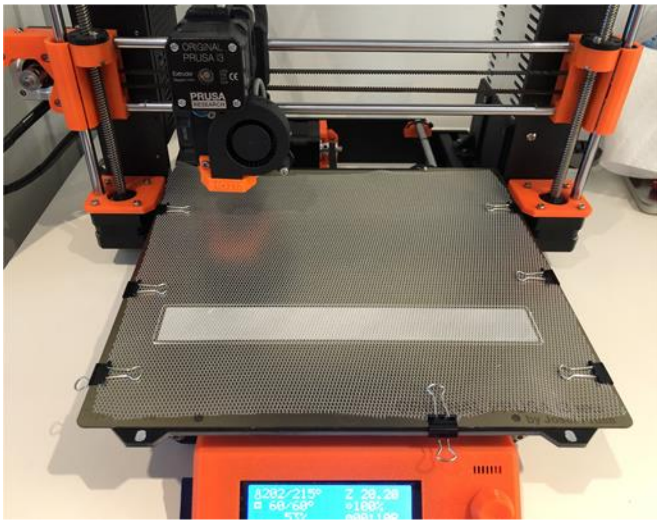


Figure 3: The fabric set up secured using clips. It is recommended to cut the fabric to the size of the build platform (25cmx23cm) so that it can be stretched flat on the build platform, preventing the nozzle to be caught on the fabric.

		
The 3D printer was paused once the base layers were completed.	A small section of blue painters tape (approx. 20mm) was adhere on one end of the print. The skirt area was avoided to bond with subsequent layer (optional).	The fabric was then placed on top of the print and secured smoothly on the build platform. The printing process was resumed to complete.

Table 8: 3D Printing of T-Peel Test Panel.

The unbonded edges of the T-Peel test panel were separated by hand and pulled apart to form a T-Peel specimen. The specimen was clamped firmly on the grips of the testing machine without slippage throughout the test (ASTM D1876-01) (Figure 4). The adhesive forces of composites were measured using a universal testing machine. The haul-off speed of the clamps was set constant on 50mm/min. The separation force-displacement curve was measured. 3 samples of each kind were produced and tested for an accurate result.

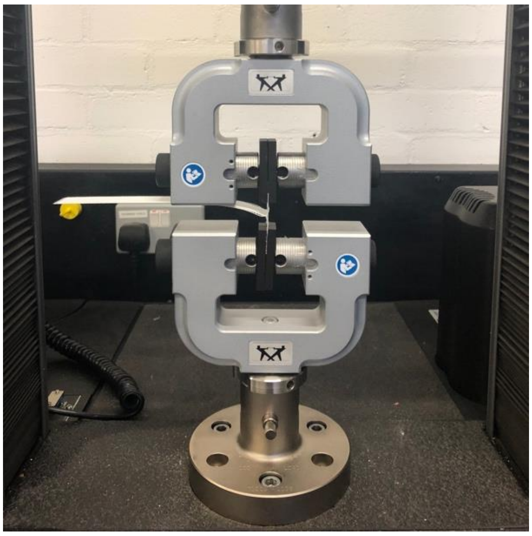


Figure 4: The specimen set up on a Universal Testing Machine for T-Peel Test. The specimen was clamped firmly on the grips of the testing machine without slippage throughout the test.

3. Results and conclusion

The variation of the adhesion force of the printed PLA polymer on the selected mesh fabrics F1, F2 and F3 are specified in Figure 5, 6 and 7.

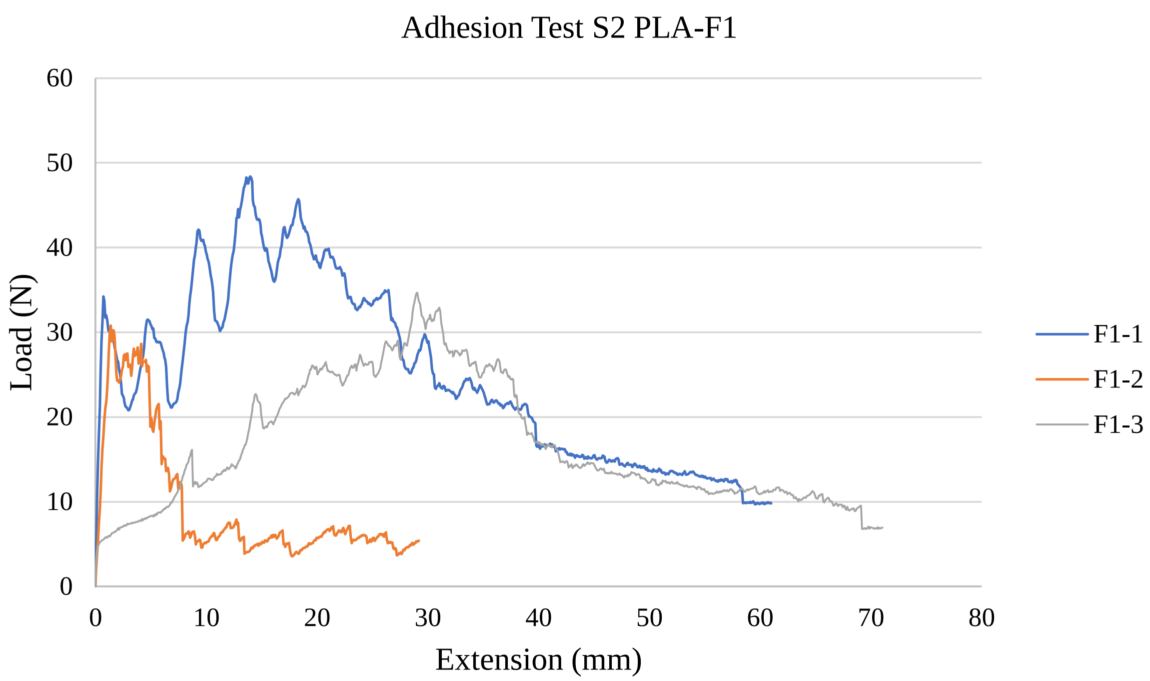


Figure 5: S2 PLA-F1 net fabric with 1mmx1mm pores and low stretch-ability.

According to Figure, it can be seen that the line pattern for F1-3 differed from F1-1 and F12 with a gradual increase of load for delamination throughout the extension. This inaccuracy was resulted by a 3D printing deposition issues while producing the specimen F1-3. There was a sparse infill at the beginning of the first layer which caused a direct effect on the overall adhesion result. As the reading for F1-3 is not accurate, it was ignored at the calculation for average load.

Specimen S2 PLA-F1	Sum of Load (N) with reading greater or equal to 25N	The number of loads with reading greater or equal to 25N	Average (μ)
F1 – 1	11432.24418	325	35.17613594
F1 – 2	1035.26786	38	27.24389105
Total average load (μN)	12467.51204	363	34.3457632

Table 9: The average load required for delamination for S2 PLA – F1 is 34.35N.

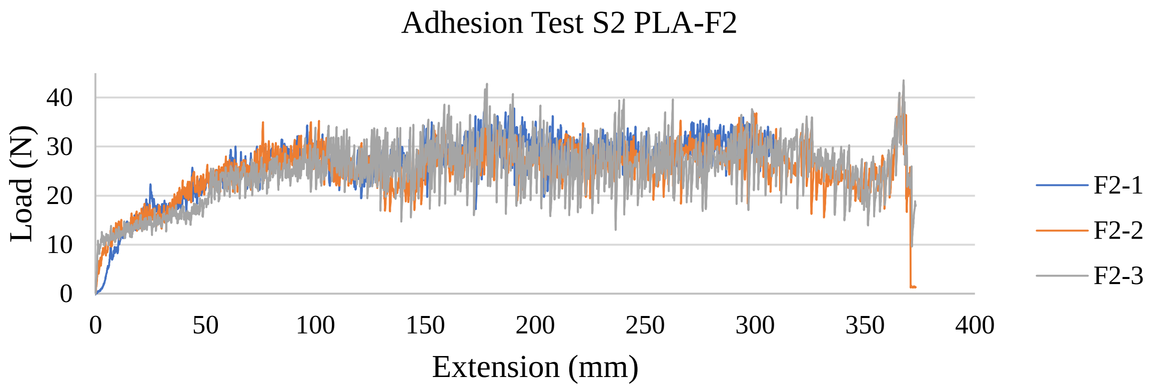


Figure 6: S2 PLA-F2 voile net with very fine pores and low stretch-ability.

Specimen S2 PLA-F2	Sum of Load (N) with reading greater or equal to 10N	The number of loads with reading greater or equal to 10N	Average (μ)
F2 – 1	96707.16927	3582	26.998093
F2 – 2	111268.1751	4403	25.2709914
F3 – 3	111755.4551	4516	24.74655781
Total average load (μN)	319730.7995	12501	25.57641784

Table 10: The average load required for delamination for S2 PLA – F2 is 25.58N.

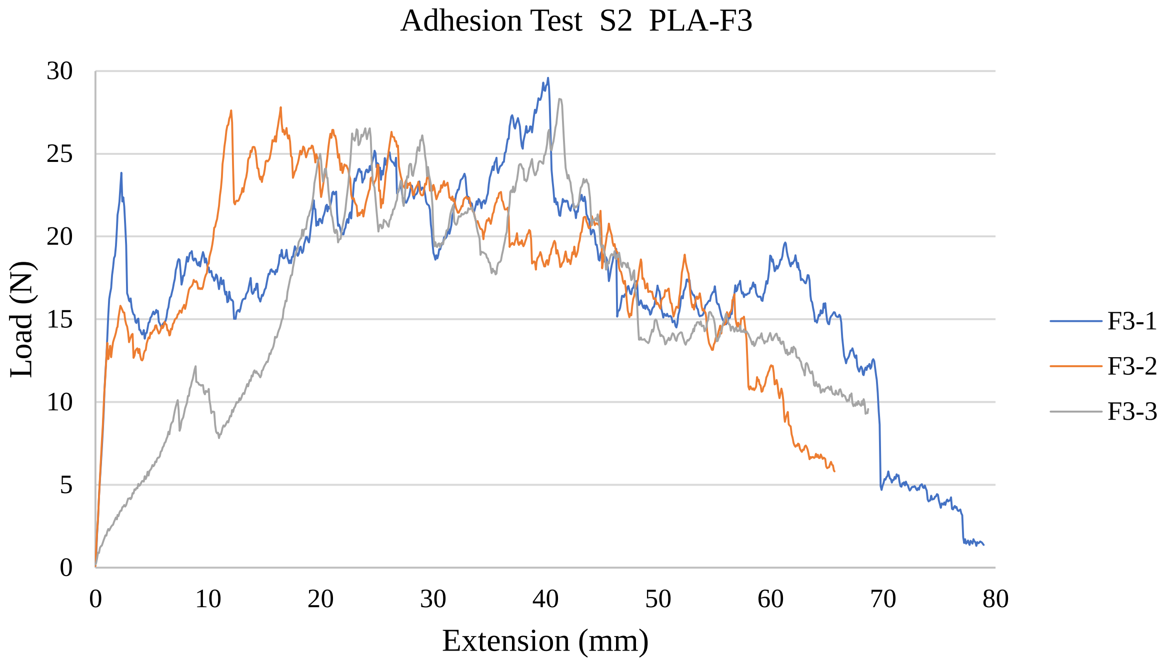


Figure 7: S2 PLA-F3 polyester lace with 1mmx1mm pores and high stretch-ability.

Specimen S2 PLA-F3	Sum of Load (N) with reading greater or equal to 15N	The number of loads with reading greater or equal to 15N	Average (µ)
F3 –1	14511.56843	741	19.58376306
F3 – 2	12261.42329	588	20.8527607
F3 – 3	8410.58166	388	21.67675686
Total average load (µN)	35183.57338	1717	20.49130657

Table 11: The average load required for delamination for S2 PLA – F3 is 20.49N.

For a basic pilot study, results showed that the larger the pore size, the better the intermolecular bond between two subsequent printing layers. PLA-F1 and PLA-F3 both have large pore size of 1mx1m, both have short extension results. The top layer broke shortly after being T-peeled apart (Figure 8). PLA-F1 has the best intermolecular bond between two subsequent printing layers as it took a higher amount of force to start delaminating the polymer-textile composite. The peak load required went up to a maximum of 48.4N (Figure 5. However, despite of the pore size differences, 3D printing on mesh fabrics can eliminate most difficulties in polymer-textile adhesion as they have opening gaps to allow deposited polymer to protrude through the textile layer for firm adhesion. On the other hand, the stretch-ability of mesh fabrics have no direct effect on polymer-textile adhesion. However, working with fabrics with lower stretch-ability can keep the consistency of adhesion, increase the ease of print and reducing the rate of print failures.

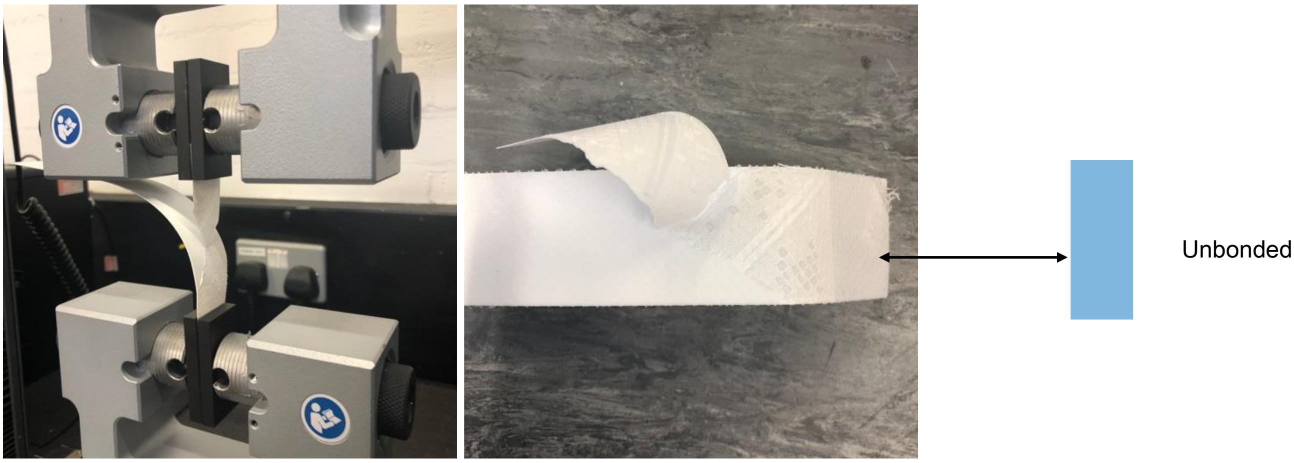


Figure 8: The delamination of PLA-F3 sample.

Table 12 is a map of key parameters to be considered when direct 3D printing of polymers onto textile fabrics. Tested parameters give us preliminary results about the adhesion on mesh fabrics. In conclusion, structure 2 design of laminating the choice of fabrics in between two layers of polymers allow the extruded materials to form an intermolecular bond between two subsequent printing layers, known as the form-locking connections (Unger, 2018). This structure is ideal for 3D printing on fabric with a larger pore size, loose weave structure, low weft and stitch density. While working with tightly woven fabrics, the choice of structure is less important, but the surface properties and chemical properties of the textile substrate are the key factors to influence polymer-textile adhesion. Studies have demonstrated that 3D printed polymers adhere well on cotton, polyester, wool and viscose (Spahiu, 2017; Korger, 2016). According to Unger (2018), hydrophilic textile fabrics tend to have better adhesive properties compared to hydrophobic textile fabrics. Regarding to the 3D printing settings, an optimum z-distance height provides the best polymer-textile adhesion. The risk of print failures increases when the z-distance was not set properly. 3D printing at a higher temperature of 5 – 10°c from suggested filament temperature reduce the viscosity of the printing material which allow the extruded material to penetrate deeper into the woven fabric. Experiments results showed that the printing speed and polymer flow have no substantial impact on the adhesion force, but it is recommended to print at a slower speed of 20 – 22.5mm/s and 100% flow rate for slightly better adhesion result. Future work will extend the study of interface adhesion of 3D printed polymers on textile fabric using microscopic images, testing on washing cycles and explorations of new materials for 3D printed textiles.

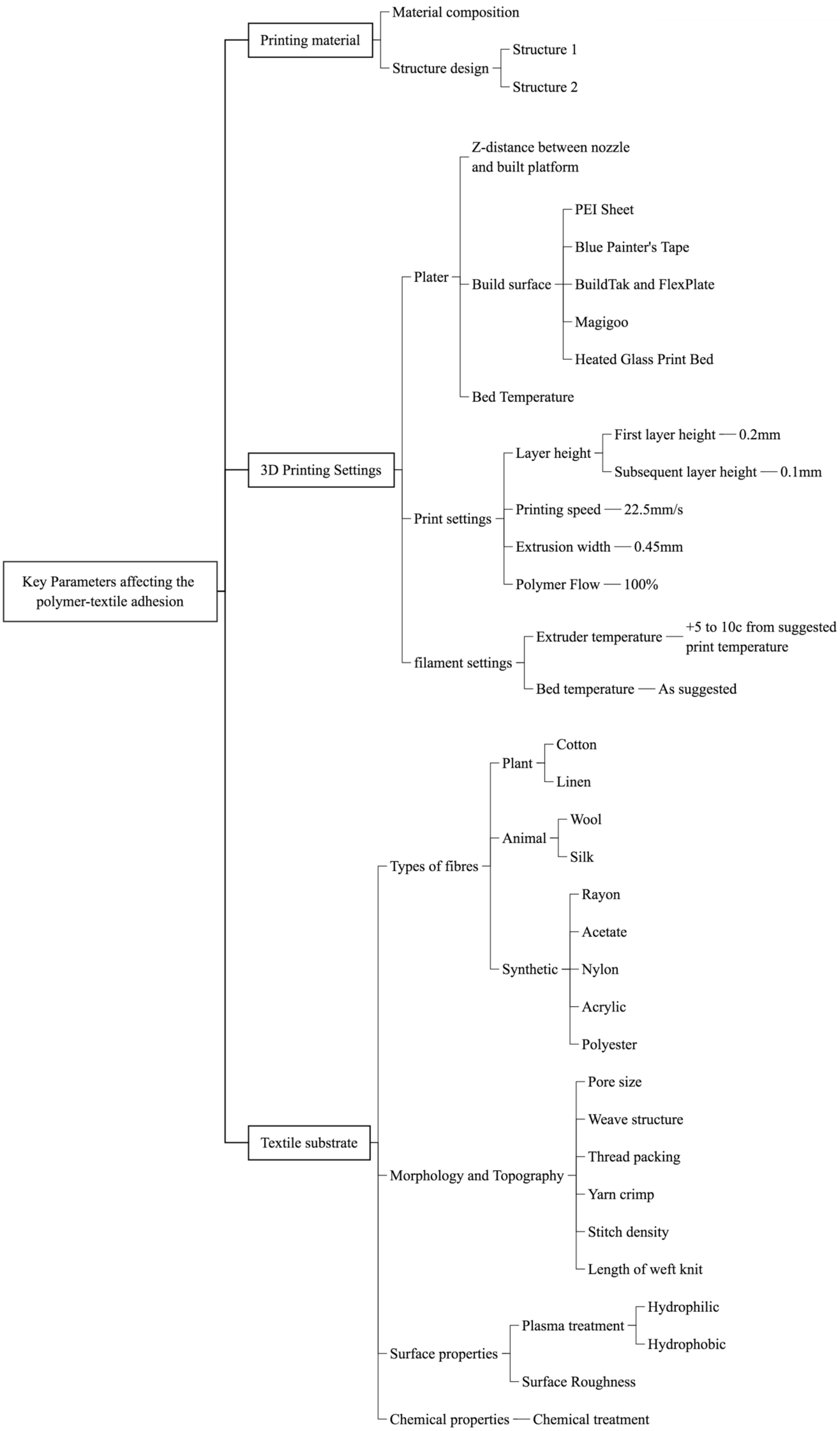


Table 12: The key parameters affecting the polymer-textile adhesion.

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