Fibers and Polymers (2023) 24:4073–4088
https://doi.org/10.1007/s12221-023-00357-8
Online ISSN 1875-0052
Print ISSN 1229-9197

REGULAR ARTICLE

3D Printing Based on Material Extrusion to Create Surface Patterns on Textile Fabrics

Randa Alsabhi[1,3] · Angela Davies[1] · Guy Bingham[2,4] · Jinsong Shen[1]

Received: 12 April 2023 / Revised: 31 July 2023 / Accepted: 5 September 2023 / Published online: 26 September 2023

Abstract
3D printing technology has been developing rapidly in recent years. This technology is extensively used for producing prototypes of products and their designs with a wide range of materials in the manufacturing industry. The Fused Deposition Modelling (FDM) process uses the extrusion of molten thermoplastic materials through heated printing nozzle to create design objects layer by layer. The current research was to develop 3D printing technology on textile fabrics to create surface design based on FDM process using the Ultimake 3D printer. Printing parameters play an important role for printing on fabrics specially to achieve strong adhesion between the printed patterns and the surface of the fabrics. This research developed a method for assessing the attachment strength in the interface between the printed objects and the surface of fabrics. The effect of the initial setting distance between the printing nozzle and the printing platform on the performance of 3D printed fabrics was investigated. The research work demonstrated the ability to create different design patterns in 3D on the fabrics with excellent durability to washing, which shows potential for the commercial application in fashion industry.

Keywords 3D printing · Textile patterns · Rapid prototyping · Material extrusion · Fused deposition modelling

1 Introduction

The accessibility and availability of 3D printing have been developing rapidly. There are many types of 3D printers and different techniques available. Three popular printing technologies developed in the current market are SLS (Selective Laser Sintering), FDM (Fused Deposition Modelling) and SLA (Stereolithography) [1, 2]. The creation of three-dimensional objects can be achieved by 3D printing using additive layer by layer processes. Currently, 3D printing techniques are extensively used for producing prototypes of products and their designs with a wide range of materials including plastics, resins, metals and ceramics in the manufacturing industry [3].

The Fused Deposition Modelling (FDM) process uses the extrusion of molten thermoplastic materials through heated printing nozzle to create design objects layer by layer. A wide range of thermoplastic materials can be used in 3D printing. Acrylonitrile butadiene styrene (ABS) was the first thermoplastic polymer developed for 3D printing [4]. Recently, polylactic acid (PLA) has been commonly used, because it is biodegradable with a lower melting temperature and more stable than ABS. Other varieties of thermoplastic filaments are also available such as nylon, polyurethane, polyvinylchloride, polycarbonate, high-impact polystyrene, lightweight thermoplastic elastomers, polyethylene terephthalate and wood-based bio-linen filaments [4].

3D printed designs can be combined with fabrics to create exciting new textiles. Fashion designers Jiri Evenhuis and Janne Kyttanen explored Additive Manufacturing (AM) to create 3D designed textiles and fashion [5]. 3D printing technology has been used to produce simulated textile weaving or knitting structure of materials [6, 7] despite they are not suitable to wear on a daily basis. The basic extrusion technology has also been used to attempt printing of conductive tracks on textile substrates [8]. Small patterns

✉ Jinsong Shen
jshen@dmu.ac.uk

1 Textile Engineering and Materials Research Group, School of Fashion and Textiles, De Montfort University, Leicester, UK

2 School of Art, Design and Architecture, De Montfort University, Leicester, UK

3 Present Address: Department of Art and Design, University of Tabuk, Tabuk, Saudi Arabia

4 Present Address: Nottingham School of Art and Design, Nottingham Trent University, Nottingham, UK

have been printed on fabrics to create unique three-dimensional effect using SLS technique rather than FDM technique from Pringle of Scotland [9]. Iris van Herpen's Spring Summer 2013 collection at Paris Fashion Week showcased 3D-printed ensembles and gowns created with laser sintering [10].

Pei et al. [4] published the preliminary research of 3D print on different textile fabrics with FDM systems, which provided the foundation for further investigation of the material compatibility, polymer-textile adhesion and material deposition of textile 3D print. Recently there is an increasing interest for the development of 3D printing on fabrics at various scales [10]. Different testing methods for evaluating the performance of 3D print on fabrics including the adhesion of printed materials on the fabrics have been explored [11–15]. Perpendicular tensile test, shear test and peel test to characterise the adhesion of a 3D printed shape on different textile fabrics were attempted. The development of the testing methods becomes important to establish the standard evaluation methods for further research and development in the application of 3D printing technology on textile materials.

3D printing technology not only shows the innovation on textile surface design with novel textures and designs but also demonstrates the benefit of reduction in the lead times and excessive cost [16]. This technology can also have potential for contributing to sustainability in the manufacturing, recycle ability and reuse of waste materials. The development and application of 3D printing technology in textiles and fashion design has been reviewed by Xiao and Kan [17].

The current research was to develop 3D printing technology on textile materials to create surface design based on FDM process using the Ultimake 3D printer. Printing parameters for textile printing play an important role for the adhesion between printed patterns and the surface of the fabrics. The current research developed a method for assessing the attachment strength in the interface between the printed object and the surface of textile and investigated the effect of the initial setting distance between the printing nozzle and the printing platform on the performance of 3D printed fabrics. The research work demonstrated the ability to create different design patterns in 3D on the fabrics with excellent durability to washing and their potential for the commercial application in fashion industry.

2 Materials and Methods

2.1 Textile Materials

100% wool and 100% polyester woven fabrics in same weave structure, supplied by Camira Fabrics, were selected for the 3D printing investigation. The characteristics of both fabrics in terms of fabric construction, weight and fabric thickness are shown in Table 1. The thickness of fabric and surface structure might be the major factors for affecting the quality of 3D print (Hernandez 2015). Therefore, these two typical fabrics (wool and polyester) with same surface structure and similar thickness were used.

2.2 PLA, TPU and ABS Filaments Used for 3D Printing

There are various filaments commercially available on the market. Different filaments have varying mechanical and thermal properties including hardness and flexibility. In the current research, polylactic acid (PLA) and polyurethane (TPU) filaments in same diameter of 2.85 mm but having different levels of hardness and flexibility were selected for 3D print. Polylactic acid (PLA) with shore hardness of 83D was supplied by Ultimaker, whereas polyurethane (TPU) with shore hardness of 85A was supplied by Ninjaflex. Another thermoplastic filament, acrylonitrile butadiene styrene (ABS), supplied by Formfutura, was used in the pattern design on textile fabrics.

2.3 Determining Thickness of Fabric Samples Under Various Pressures

Thickness and weight of the fabric are two basic characteristics. They might be relevant to the quality of 3D print on the fabrics with thermoplastic filaments. The selected fabrics (wool and polyester) have the same surface structure which is the reason for being used in the experiments, but the thickness of the fabrics could be changed when they are subjected to the applied pressure during 3D printing on the fabric at the first layer. Therefore, the thickness of these fabric samples under different pressures from 20 to 1440 g/cm^2 was determined using the fabric thickness gauge.

Table 1 Characterisation of wool and polyester fabric samples

Properties	Fabric samples	
	Wool	Polyester
Composition	100% virgin wool	100% recycled polyester
Construction	Plain weave	Plain weave
EPI	211	214
PPI	161	133
Thickness (mm) at 20 gf/cm^2	1.06	1.30
Weight per area (g/m^2)	370	310

2.4 Ultimaker 2 3D Printer

3D printer Ultimaker 2 used in the current research was supplied by Ultimaker B.V., Geldermalsen, The Netherlands (see Fig. 1). Ultimaker 2 utilises the fused deposition modelling (FDM) technology to build the patterns of the objects layer by layer on a platform from the bottom to the top by heating and melting the filament using a pre-heated nozzle.

2.5 Design of Printing Patterns to Be Printed on Fabrics

3D printing patterns were designed using the software: SketchUp and Cura. In order to assess the attachment strength between printed patterns and fabric surface, the cube-shaped pattern was designed for printing on the fabric to be tested using Instron tensile tester (Fig. 2). The structured channel through the cubic patterns was used to allow a narrow lanyard passing through to hold the printed cubic pattern, so that the cubic pattern can be pulled away from the fabric using the Instron tensile tester to determine the attachment strength in the interface between printed patterns and fabrics.

In order to determine the durability to washing of 3D printed patterns on the fabrics, a series of shapes, including strips, flat pieces, solid circles, rings, and triangles were designed using Sketch up and Cura software based on the previous work published by Pei et al. [4]. The specific geometries of the patterns designed for 3D printing on the fabrics are listed below (see Fig. 3).

(a) Rectangular strip, with dimensions of 50 mm long × 3 mm wide × 0.25 mm thick;
(b) Rectangular strip, with dimensions of 50 mm long × 5 mm wide × 0.5 mm thick;

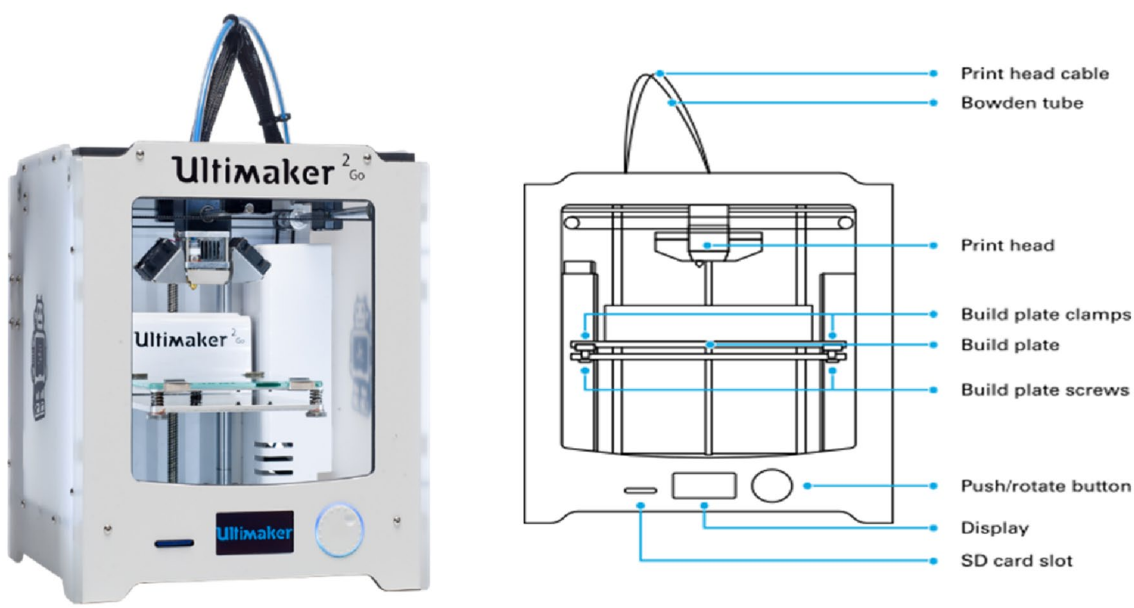


Fig. 1 Ultimaker 2 used for 3D printing [18]

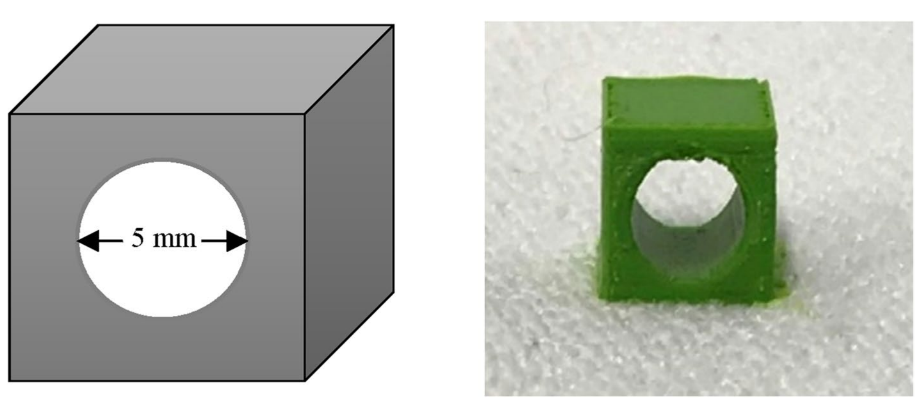


Fig. 2 The structure and size (10 mm × 10 mm × 10mm) of PLA prints on fabric samples tested on the Instron tensile tester

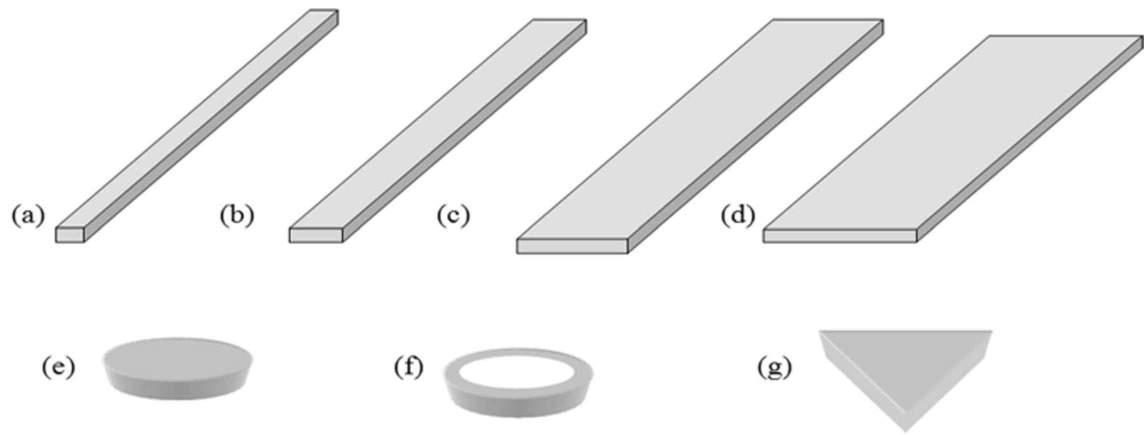


Fig. 3 The geometry of the 3D shape patterns designed to be printed onto the fabrics for washing test

(c) Flat rectangular piece, with dimensions of 50 mm long × 10 mm wide × 1 mm thick;
(d) Flat rectangular piece, with dimensions of 50 mm long × 15 mm wide × 1.5mm thick;
(e) Solid circle, with a diameter (*Φ*) of 15 mm, and a thickness of 1mm;
(f) Annulus, with outer and inner diameters (*Φ*) of 25.75 mm and 21.3 mm, respectively, and a thickness of 1 mm;
(g) Flat triangular piece, with each side of 31 mm, and a thickness of 1 mm.

These patterns were printed on the fabrics with PLA and TPU filaments, respectively, using Ultimaker 2 as shown in Fig. 3.

2.6 3D Printing Parameters of PLA and TPU on Fabrics

Ultimaker 2 is required to calibrate the build plate as printing platform before use. For printing, it is very important that the first layer adheres to the glass, the build plate. If the distance between the nozzle and the build plate is too big, the printed pattern might not adhere properly on the surface. Also, if the nozzle is too close to the platform, it can prevent the filament to be extruded from the nozzle. The distance between the printing nozzle and the platform was set up using different number of A4 80 g papers based on the thickness of paper. The thickness of paper was determined by measuring a pack of 40 papers and their thickness was about 0.4 mm, which indicates that the thickness of each A4 paper is around 0.01 mm. Therefore, the distance between the nozzle and the platform was set up using the accounted number of papers to 0.14, 0.12, 0.10, 0.08, 0.06, 0.04 and 0.02 mm, respectively. The papers were then removed and replaced by fabric on the platform for the subsequent printing. The major printing parameters for printing patterns on fabrics are listed in Table 2.

2.7 Determination of Attachment Force of 3D Print on Fabric

One important factor which is related to the quality of 3D printed fabric is the attachment or bonding force in the interface between printed pattern and fabric. In order to assess the strength of the attachment, the Instron Tensile Tester (model: 3345) was used (Fig. 4). The cubic pattern was designed and printed on the wool and polyester fabrics. The printed fabric was folded and held at the upper jaw of the Instron. The channel in the cube-shaped pattern can be allowed for a narrow lanyard passing through and to be held at the bottom jaw of the Instron tensile tester as shown in Fig. 4. During the tensile test, the 3D print was pulled away from the fabric so that the Instron was able to test the attachment force in the interface between the printed pattern and fabric. The parameters of tensile test are shown below:

- The grab method used with a 5 KN load cell

Table 2 3D printing parameters for printing patterns with PLA and TPU filaments on fabrics

Printing parameters	Printing filaments	
	PLA	TPU
Nozzle temperature	260 °C	230 °C
Platform temperature	60 °C	50 °C
Fan speed beside nozzle for cooling the extruded materials	100 m/s	
Filament flow	100 mm/s	
Printing speed	100 mm/s	
Infill density	60%	

Fig. 4 The tensile test method for 3D printed fabrics

- Cross-head speed of 300 mm/min
- Gauge length: 100 mm
- Width: 10 mm

2.8 Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) (Carl Zeiss Ltd, Cambridge, UK) was used to investigate the interface and the attachment between the fabric and designed 3D print in order to find out how the 3D printed PLA or TPU were embedded into the weaving structures of fabric surfaces. The surface of the printed patterns and the fabrics from the interface were prepared by detaching the 3D prints from the fabrics and then gold-coated in order to provide a clearer SEM image of the surface under high magnification. The samples were analysed by SEM with a beam accelerating voltage of 20 kV, 20 µm beam aperture, a probe current of 100 pA and a working distance of 8.5 mm. Alternatively, 3D printed patterns on the fabrics were also cut cross the interface between printed pattern and the surface of the fabrics. The cross-section of the interface was also examined by SEM.

2.9 Washing Test of Fabric Samples Printed with 3D Shaped Patterns

The wool and polyester fabric samples printed with 3D patterns were washed in a Wascator washing machine using a gentle washing programme at 40 °C (4G), and a mild washing programme at 60 °C (6M). The details of washing programmes are provided in Table 3. For both washing programmes, a mixture of 20 g ECE reference detergent, and 5 g of sodium perborate was used. After washing, the fabric samples were dried at room temperature around 20 °C.

After fabric samples were washed, they were assessed for durability to wash in term of printing quality. The first step of the testing process was to identify the adhesion quality of 3D print on the fabrics using both a visual and a haptic inspection. For this study, the visual inspection was performed using the naked eye, without the aid of equipment, to determine the adhesion quality of the 3D print on the fabric. The haptic inspection was conducted by feeling the 3D printed fabrics, in order to detect any defects, and if any defects were present, to determine their severity. During the haptic inspection, suitable care was taken to ensure that no printed parts were removed from the fabrics while they were being felt using fingers. Based on the visual and haptic inspection, the adhesion quality of the printed parts was rated using a Likert scale, ranging from 1 (worse print quality) to 5 (excellent print quality). The warping (W) was similarly ranked on a Likert scale from 1 to 5, with 5 indicating no warping, and 1 the worst warping, as follows:

Warping 5: No warping, and no change to the original samples;
Warping 4: Warping on a few sharp edges of the patterns;
Warping 3: Warping on the small or narrow patterns;
Warping 2: Warping on almost all of the patterns;

Table 3 Details of the washing programmes used to test the durability of 3D printed fabrics to washing

Washing programme number	Agitation during heating, washing and rinsing	Wash temperature (°C)	Wash time (min)	Cool down	1st rinse time (min)	2nd rinse time (min)	3rd rinse time (min)
4G (Gentle wash)	Gentle	40 ± 3	3	NO	3	3	2
6M (Mild wash)	Mild	60 ± 3	15	NO	3	2	2

Warping 1: Pattern distortion and warping occurred on all of the printed patterns.

The bonded attachment (B) was also ranked from 1 to 5 on a Likert scale, with 5 indicating the strongest bonding, and 1 indicating the weakest bonding, as follows:

Bonding 5: Very strong attachment;
Bonding 4: Good attachment;
Bonding 3: Fair attachment;
Bonding 2: Weak attachment;
Bonding 1: Poor attachment.

3 Results and Discussion

3.1 Characterisation of Textile Fabrics

Wool and polyester fabrics in the same weaving structure were characterised before they were used to undertake 3D printing. Figure 5 shows the thicknesses of both polyester and wool fabrics against the pressure applied by the specific loads from 20 to 1440 gf/cm^2. It can be seen that there is a correlation between the thickness of fabric and the pressure. The thickness of the fabrics decreased with increasing pressure. With increasing pressure from 20 to 1440 gf/cm^2, the polyester fabric decreased thickness from 1.30 to 0.45 mm, whereas wool fabric decreased from 1.06 to 0.59 mm. During the 3D printing, the printing nozzle actually applies pressure on the fabric to print the first layer deeply into the fabric.

3.2 The Attachment Strength of 3D Printed Patterns on the Fabrics

The durability of 3D print on the fabrics is dependent on the adhesion strength of the printed pattern on the surface of the fabrics. The 3D cube-shaped pattern was designed and printed on the fabrics as described in Sect. 2.5 for assessing the strength of the attachment force between the fabric and 3D printed pattern using Instron tensile tester. The cube-shaped print was pulled away from the fabric by the Instron so that the Instron was able to record the applied load during the extension. The typical load versus extension for breaking the printed cubic pattern from the fabric is shown in Fig. 6. Only one peak occurred in the tensile curve, the maximum load required for detaching the cubic pattern from the fabric could be recorded. The average maximum load after 5 repeat tests was calculated to express the adhesion strength between printed pattern and fabric. This method is simple and cost-effective in terms of time and effort, therefore, it was used for assessing the attachment force between print pattern and surface of the fabric for further research of 3D printing of fabrics.

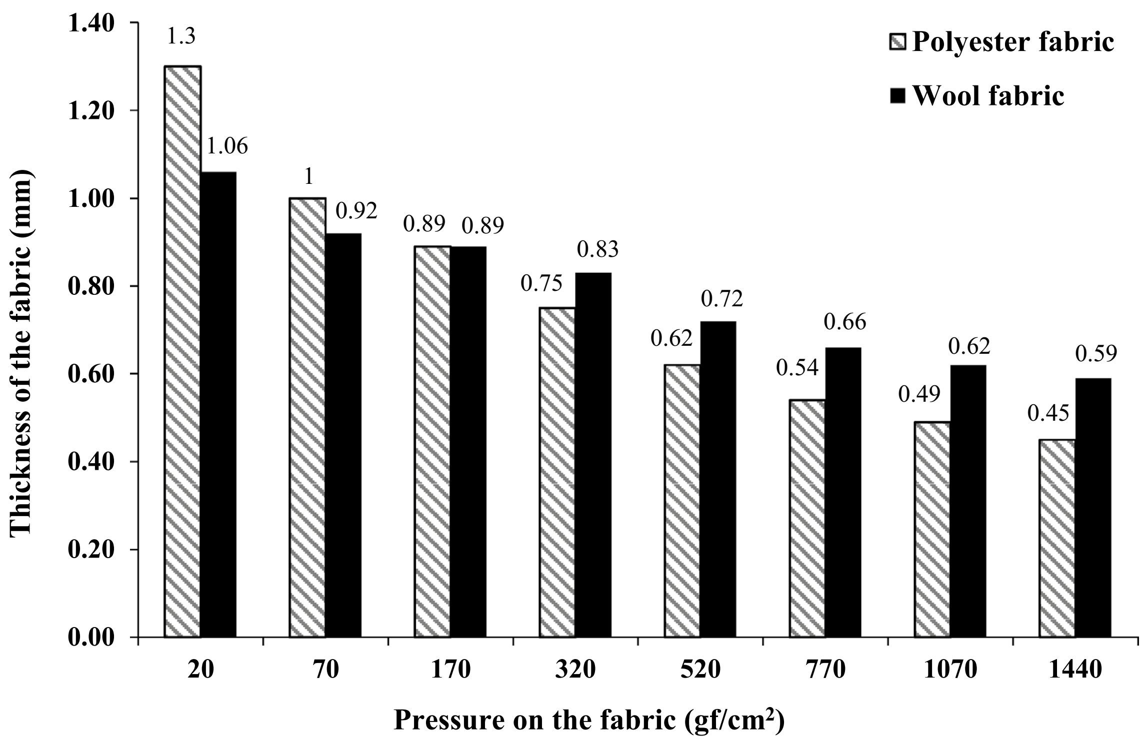


Fig. 5 Thicknesses of both polyester and wool fabrics against the pressure gained from the load applied by gauge

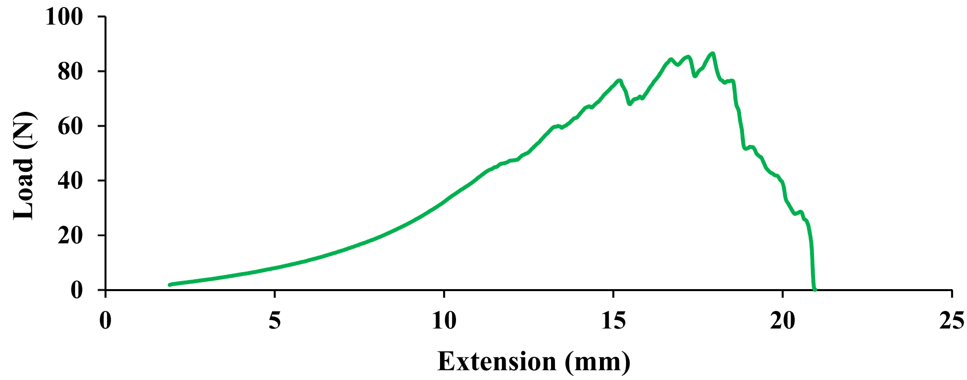


Fig. 6 Relationship between load and extension for tensile test of PLA cubic-shape printed fabric

In order to achieve the strongest attachment of 3D print on textile fabric, it was found that the initial setting for the distance between printing nozzle and the platform (the build plate) is crucially important. Therefore, the effect of the initial setting for the distance between the printing nozzle and the platform was investigated. The initial distance between printing nozzle and the platform was set to 0.14, 0.12, 0.10, 0.08, 0.06, 0.04 and 0.02 mm, respectively, as described in Sect. 2.6. Then, PLA cube-shaped pattern was printed on both wool and polyester fabrics for their tensile test to assess their attachment forces.

Figure 7 shows the influence of the initial printing nozzle distance to the platform on the attachment force of 3D print on the surface of wool fabric. When 0.14 mm was set between the glass platform and the printing nozzle, the attachment of the cube-shaped print on wool fabric was extremely weak, indicating that the 3D printed pattern could be easily detached by the force of 11.38 N, resulting in poor durability to use. However, reducing the initial setting distance between printing nozzle and the platform, the attachment strength in the interface between cube-shaped print and fabric surface increased gradually. It was found that the distance 0.02 mm provided the strongest attachment up to 130.59 N, thereby making it more durable.

After setting 0.02 mm for the distance between printing nozzle and the platform, the 1.06 mm thick wool fabric was placed on the surface of the glass platform. During printing the first layer of PLA, the surface of wool fabric could experience the pressure from the printing nozzle much higher than 1440 g/cm^2 according to the relationship between pressure and thickness of wool fabrics as shown in Fig. 5. Actually, the platform was not rigidly held at the level. Under the pressure, the platform could be flexibly pushed down due to the spring support underneath. The printing nozzle was

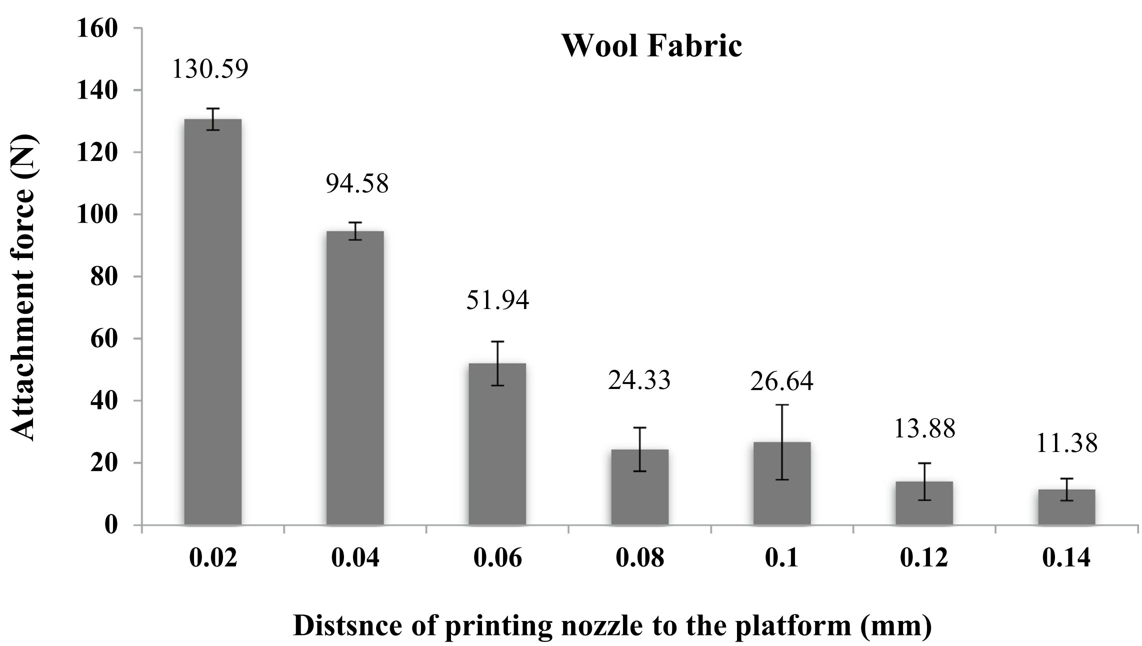


Fig. 7 The influence of the initial printing nozzle distance to the platform on the attachment strength of 3D print on the surface of wool fabric

actually squished into the surface of the fabric for the first layer printing. Therefore, the distance between the printing nozzle and the platform smaller than the thickness of the fabric could be used for 3D printing on the wool fabric to achieve the strongest attachment strength of the 3D print on the surface of the wool fabric.

Comparing to 3D printing on wool fabric, the cube-shaped pattern of PLA was also printed on the polyester fabric under the setting of the different distances between the initial printing nozzle and the platform. Figure 8 shows the influence of the initial printing nozzle distance to the platform on the attachment force of 3D print on the surface of polyester fabric. It was the same trend in which with reducing the initial setting distance between printing nozzle and the platform, the attachment strength in the interface between cube-shaped print and fabric surface increased. When 0.12 mm were set between the glass platform and the printing nozzle, the attachment of the cube-shaped print on polyester fabric was extremely weak, which indicates that the 3D printed pattern could be easily detached by the force of 6.24 N. The attachment strength of the print on the fabric rapidly increased when the initial distance was reduced to 0.06 mm. Further reducing the initial distance to 0.02 mm, the attachment strength was not increased much further. Therefore, the initial distance reduced to 0.06 mm, the attachment of the print on the polyester fabric reached almost the highest strength. The initial distance between the initial printing nozzle and the platform could be set at between 0.06 and 0.02 mm for 3D print on this polyester fabric.

3.3 SEM to Observe the Interface Between Printed Patterns and the Surface of Fabrics

The initial distance set between the printing nozzle and the platform had an influence on the attachment strength of the 3D print on fabrics. The interface between PLA printed patterns and surface of wool and polyester fabrics was investigated using SEM to find out how the printed polymers were embedded into the surface woven structures of the fabrics. After 3D printed patterns were detached from the printed fabrics using the tensile tester, the surfaces of 3D printed patterns and the fabrics from the interface between the fabric and printed pattern were examined using SEM. Table 4 presents the microscopy SEM images of the detached PLA surfaces from the wool fabrics printed under different levels of distances (0.02 mm, 0.04 mm and 0.06 mm) between printing nozzle and the platform. SEM clearly reveals that after peeling off fabric from the 3D printed pattern, a significant amount of the wool fibres remained on the detached PLA surface. The surface of PLA also showed that the footprint of fabric texture in which the surface scales of wool fibres were clearly visible. This indicated that the melted PLA was pressed deeply into fabrics in the first layer of the print. SEM images also confirmed that there was the strong attachment of PLA 3D print on the wool fabric from printing with the setting of the initial distance between the printing nozzle and platform at 0.02 mm, 0.04 mm or 0.06 mm.

Table 5 presents the microscopy SEM images of the detached PLA surfaces from the polyester fabrics printed under different distances (0.02 mm, 0.04 mm and 0.06

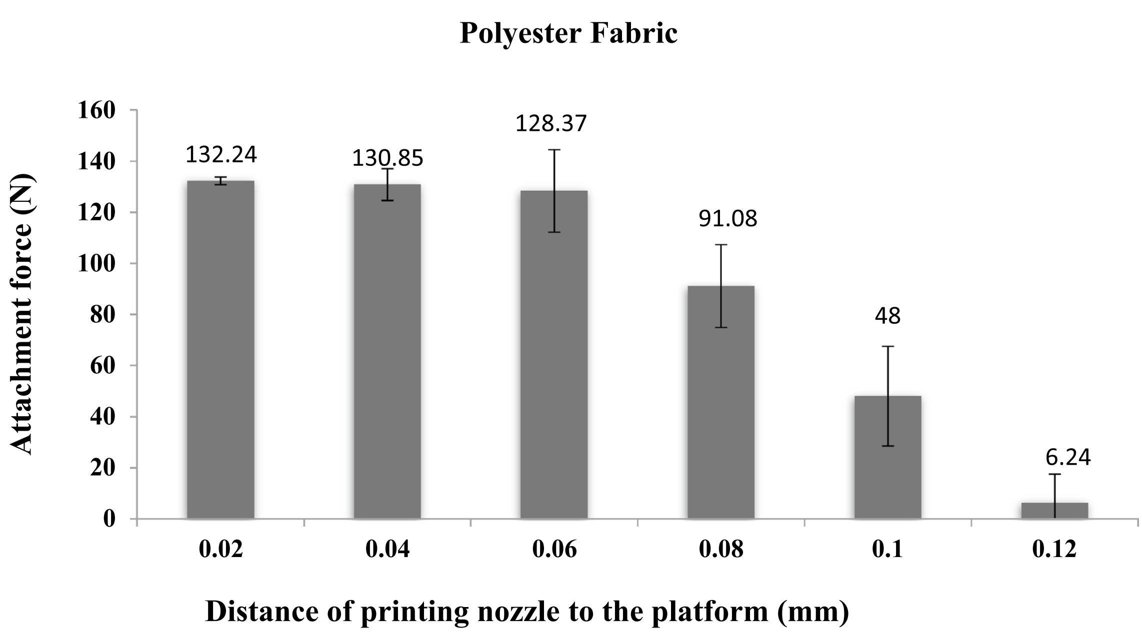
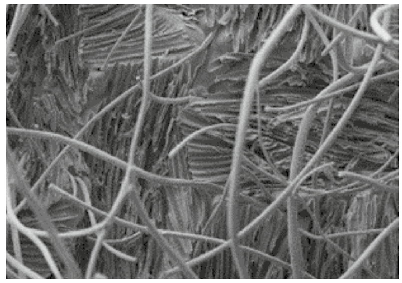
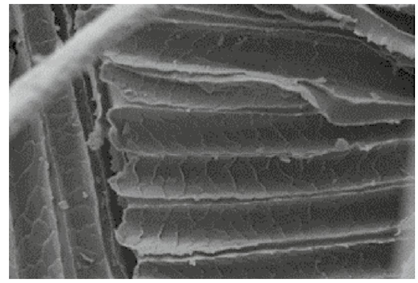
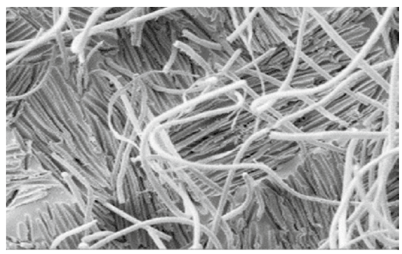
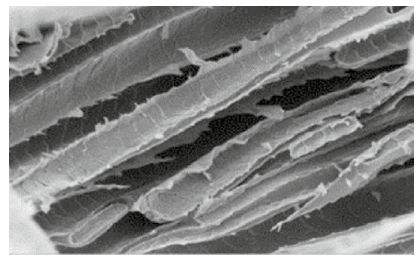
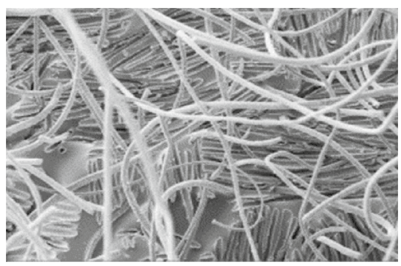
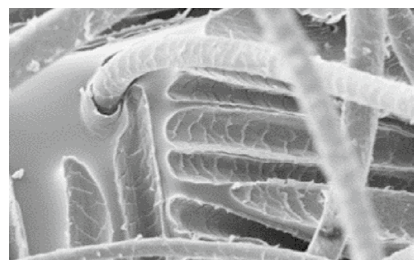


Fig. 8 The influence of the initial printing nozzle distance to the platform on the attachment strength of 3D print on the surface of polyester fabric

Table 4 SEM images of the PLA surface detached from wool fabric at different magnifications: 150× and 1k×

Surface of the detached PLA pattern surface with residual wool fibres			
Magnification		150x	1kx
Initial distance of printing nozzle to the platform	0.02 mm		
	0.04 mm		
	0.06 mm		

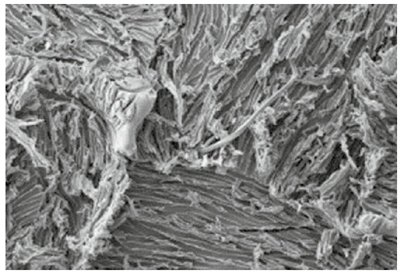
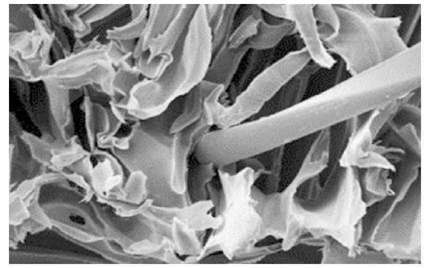
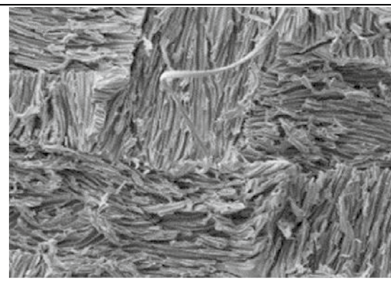
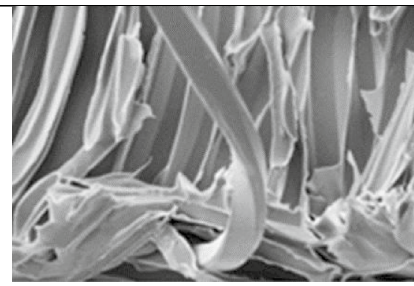
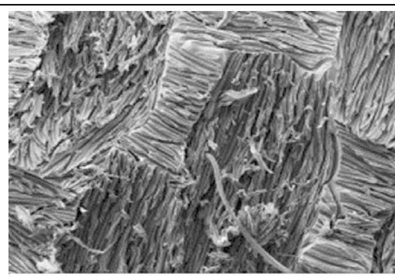
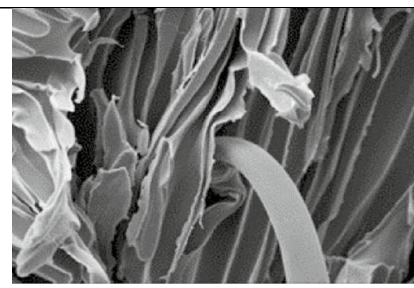
mm) between printing nozzle and the platform same as the wool fabrics. Comparing with wool fabrics, similar results were obtained. The microscopy SEM images can explain how the PLA 3D prints attached on polyester fabrics. A considerable amount of the polyester fibres also remained on the detached PLA surface. All images show the visible footprint of the polyester fibres on the detached PLA surfaces. This indicates that the melted PLA was deeply printed into the fabrics during the first layer of printing process. To conclude, despite the different distances between the printing nozzle and the platform at 0.02 mm, 0.04 mm and 0.06 mm, all SEM images do not show the significant difference in the way of the attachment of PLA 3D print on the wool and polyester fabrics.

3D printed patterns on the fabrics were cut cross the interface between printed polymers and the surface of the fabrics. The cross-section of the interface was examined by SEM to provide information on the depth of the printed filament polymer into the surface of the fabric structure and to explain the degree of the adhesion of printed pattern on the fabrics.

Figure 9 shows the SEM images of the cross-section of the interface between the PLA printed pattern and the wool fabric under different magnifications: 70×, 150× and 1000×. It is found that the printed PLA was fused and merged with the wool fabric. Figure 9b and c shows that the printed PLA polymer penetrated into the surface structure of wool fabric, and the PLA partially surrounded the surface yarns and fibres of wool fabric. This is due to melting of PLA filament by the high temperature of the printing nozzle used to fuse deeply into the surface woven structure of the fabric, resulting in the strong adhesion of printed PLA on wool fabric.

For TPU-printed wool fabrics, it is clearly shown that the first few layers of printed TPU were fused into the surface of wool fabric. The printed TPU had surrounded the surface yarns of wool fabrics (Fig. 10b), and covered the individual fibres completely (Fig. 10c). Comparing between hard PLA and flexible TPU, TPU penetrated into the woven surface structure of wool fabric deeper than PLA. Therefore, the flexible printing materials like TPU could be better integrated with the fabrics to achieve the strong adhesion of printed TPU on fabric and good flexibility. It was also found

Table 5 SEM images of PLA surface detached from polyester fabric at different magnifications: 150× and 1k×

Surface of the detached PLA pattern surface with residual polyester fibres			
Magnification		150x	1kx
Initial distance of printing nozzle to the platform	0.02 mm		
	0.04 mm		
	0.06 mm		

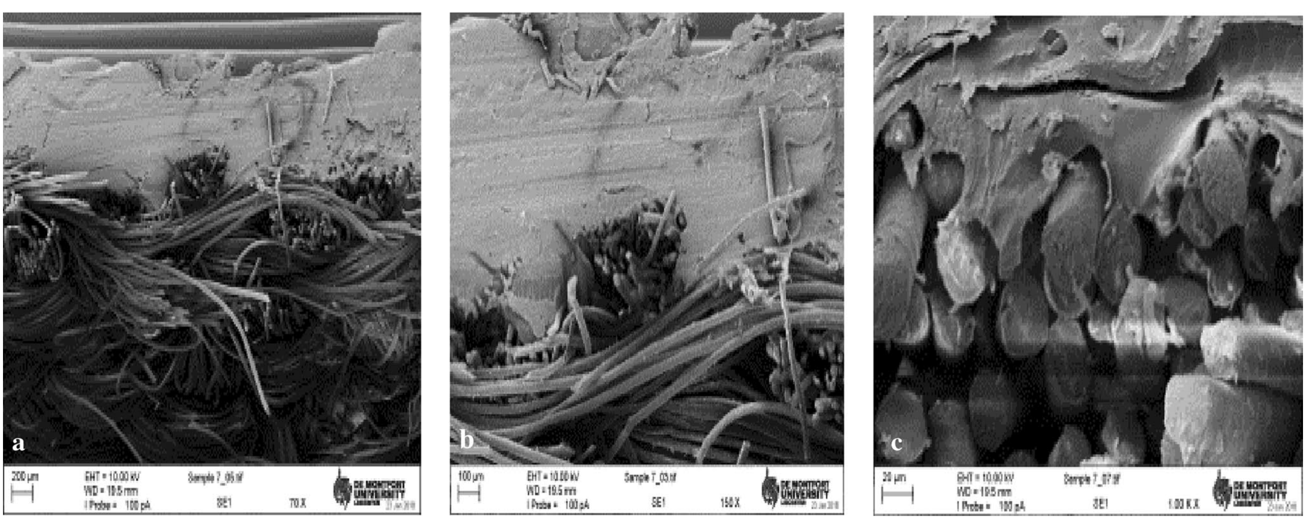


Fig. 9 SEM images of the cross-sections of the interface between PLA 3D pattern and the wool fabric printed at 0.02 mm distance of printing nozzle to the platform under magnifications: **a** 70×, **b** 150× and **c** 1k×

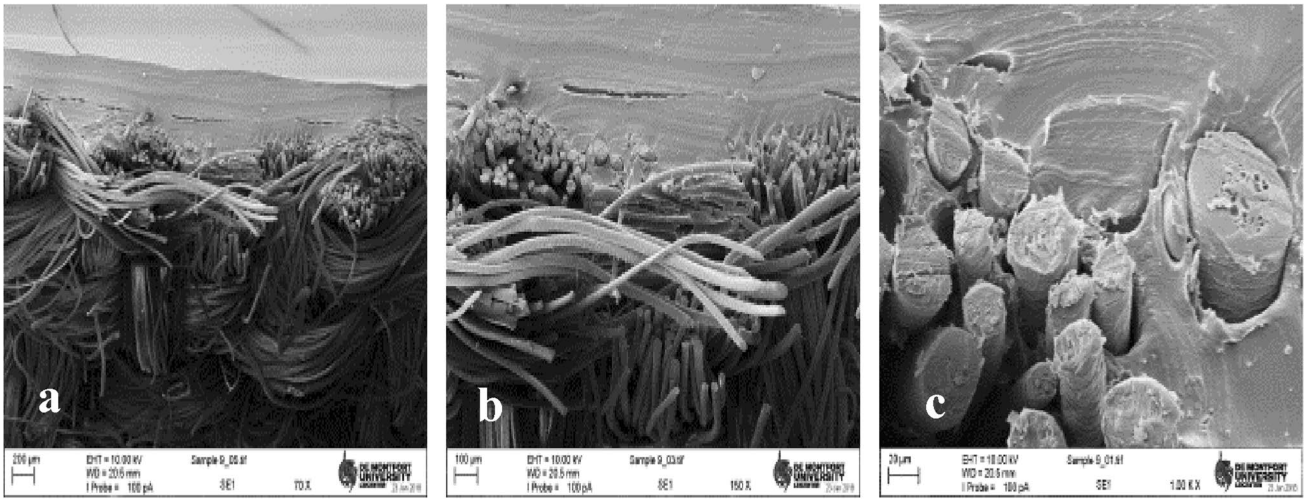


Fig. 10 SEM images of the cross-sections of the interface between TPU 3D pattern and the wool fabric printed at 0.02 mm distance of printing nozzle to the platform under magnifications: **a** 70×, **b** 150× and **c** 1k×

that TPU printed material can be easily cut with fabric, potential for garment pattern making and subsequent sewing.

3.4 The Durability to Washing of 3D Printing on Wool and Polyester Fabrics

The wool and polyester fabrics printed with various 3D patterns using filaments PLA and TPU were washed 10 times in a Wascator washing machine under a gentle washing programme (4G) at 40 °C. Table 6 presents images of the 3D printed wool and polyester fabric samples after one, five, and ten gentle washing cycles at 40 °C. It was observed that there was no distortion and no warping to either the fabrics or the printed patterns after ten washing cycles. There was also no visual detachment of any of the printed patterns from the fabrics. All of the patterns printed using two different printing filaments were firmly attached to the fabrics, and there was no noticeable change to them. Therefore, the wool or polyester fabric printed with PLA and TPU filament materials was durable to gentle washing at 40 °C, for at least ten washing cycles.

Based on the visual and haptic inspection of the washed fabric samples, the durability to washing of the 3D print on the wool and polyester fabrics, in terms of warping and bonding attachment, was ranked after one, five, and ten gentle washes. The results are shown in Table 7. After ten washes, all of the fabric samples achieved the highest ranking of five for both warping and bonding. This indicates that the 3D printed wool and polyester fabric samples remained the same visually as the original samples after ten gentle washes at 40 °C. The 3D printed patterns were firmly bonded to the wool and polyester fabrics, and there was no warping of the printed patterns.

Table 8 presents images of the 3D printed wool and polyester fabric samples after one, five, and ten washing cycles under a mild washing programme (6G) at 60 °C. The results were found that wool fabric had shrunk considerably due to the configuration of overlapping scales of wool fibre surface, and the pattern of the PLA print on the fabric had warped noticeably due to the effect of the high temperature on the PLA. It was also observed that the edges of the triangle were broken, and the large circle started warping. After the fifth wash, the warping increased to affect the edge of the pattern. This increased up to the tenth wash, although the bonding of the PLA filaments remained strong. The results, therefore, clearly showed that the PLA filaments were unable to withstand a washing temperature of 60 °C due to the poor heat resistance of PLA filament.

Meanwhile, the TPU filaments used for 3D printing on the wool fabric retained excellent print quality after undergoing the washing test at 60 °C, based on shape maintaining and adhesion quality of the printed parts, although felting shrinkage of wool fabrics occurred. Therefore, the TPU patterns on wool fabrics were able to withstand a 60 °C washing temperature and retained an excellent quality of adhesion.

The polyester fabric samples printed with the 3D patterns using the PLA and TPU filaments exhibited excellent bonding. However, the PLA filament printing on the polyester fabric had begun to warp at the edge after the first wash, and this increased to the tenth wash. The more washes the polyester fabric printed with PLA filaments was subjected to, the greater the warping effect became. It was, therefore, concluded that it is not appropriate to use PLA filaments for 3D printing on polyester fabric, if the fabric is to be washed at 60 °C. However, the TPU printed patterns exhibited

Table 6 3D printed wool and polyester fabric samples after one, five, and 10 machine washing cycles under a gentle washing programme (4G) at 40 °C

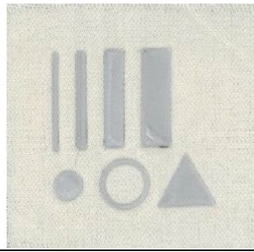
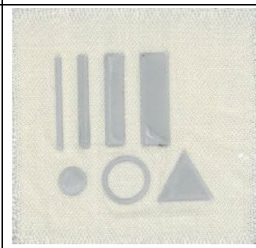
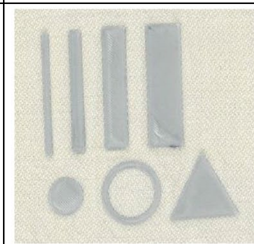
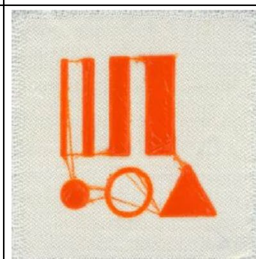
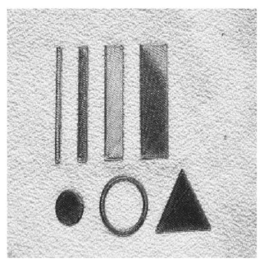
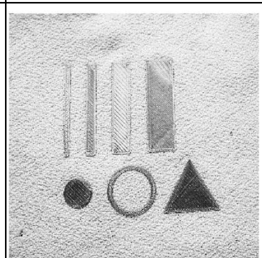
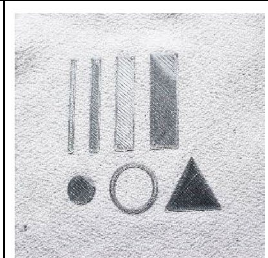
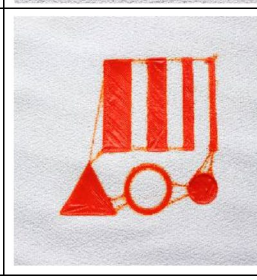
Fabric	Filament	After 1st wash	After 5th Wash	After 10th wash
wool	PLA			
	TPU			
polyester	PLA			
	TPU			

Table 7 Ranking of the durability to washing of the 3D printed wool and polyester fabrics subject to gentle washing at 40 °C

Fabric	Filament	After 1 wash cycle			After 5 wash cycles			After 10 wash cycles		
		W	*B*	Total ranking	*W*	*B*	Total ranking	*W*	*B*	Total ranking
Wool	PLA	5	5	10	5	5	10	5	5	10
	TPU	5	5	10	5	5	10	5	5	10
Polyester	PLA	5	5	10	5	5	10	5	5	10
	TPU	5	5	10	5	5	10	5	5	10

excellent print quality on the polyester fabric, and a high adhesion quality of the printed parts.

Following a visual and haptic inspection of the washed wool and polyester fabric samples, the durability to washing of the 3D print on both wool and polyester fabrics, in terms of warping and bonding attachment, was ranked after one, five, and ten mild washes at 60 °C. The results of the ranking are shown in Table 9. After ten washes, all of the wool and polyester fabric samples achieved the highest ranking of 5 for bonding, which indicated that the 3D printed patterns can firmly attach on the fabrics over 10 mild washing cycles at 60 °C. However, the warping of the PLA printed patterns to the fabrics became appearing after washing. Whereas the results obtained from the

Table 8 3D printed wool and polyester fabric samples after one, five, and 10 machine washing cycles under a mild washing programme (6G) at 60 °C

Fabric	Filament	After 1st wash	After 5th Wash	After 10th wash
Wool	PLA			
	TPU			
Polyester	PLA			
	TPU			

Table 9 Ranking of the durability to washing of the 3D printed wool and polyester fabrics subject to mild washing at 60 °C

Fabric	Filament	After 1 wash cycle			After 5 wash cycles			After 10 wash cycles		
		W	*B*	Total ranking	*W*	*B*	Total ranking	*W*	*B*	Total ranking
Wool	PLA	4	5	9	3	5	8	2	5	7
	TPU	5	5	10	5	5	10	5	5	10
Polyester	PLA	4	5	9	3	5	8	2	5	7
	TPU	5	5	10	5	5	10	5	5	10

TPU filament print were good in terms of the warping and bonding, as there was no warping of the printed patterns. It was, therefore, concluded that attachment bonding of printed patterns on the fabrics can withstand a high washing temperature at 60 °C if the thermoplastic printed materials can cope with the washing temperature without causing warping or shape distortion.

3.5 Prototypes of 3D Patterns on Fabrics Printed with PLA and TPU

The ability of 3D printing technology to produce 3D models or patterns on fabrics has been proved to have their flexibility and durability to washing. FDM technology was used to print 3D patterns on different fabric materials including lace fabrics.

Figure 11 demonstrates different design patterns printed on different textile fabrics with various filaments including TPU (red), ABS (white) and PLA (silver and green). Figure 11a shows 3D pattern printed with PLA on wool fabric to display aesthetic appearance with high quality and symmetrical details. The flexibility of printed patterns could be depending on not only the hardness of 3D printed materials but also the thickness of the patterns. Therefore, the PLA pattern with the thickness of 1.8 mm on fabrics could be statically displayed with minimum bending required.

The symmetrical design patterns printed with TPU filament show good flexibility with high precision and strong adhesion on wool fabric (Fig. 11b) due to excellent flexibility of TPU polymer material. These 3D patterns can be easily folded and twisted with the fabric without any deformation in the design.

3D designs with hollow or lattice structures require sufficient strength to resist the external forces, therefore, the proper extruded materials with certain level of hardness need to be considered for the use in 3D printing. ABS was printed on yellow wool fabric to create unique attractive 3D structure pattern with the 5 mm thickness of the shape (Fig. 11c).

3D printing can be used to print 3D shaped patterns as parts of textiles by combining the shape and showing part of the fabric. Figure 11d, PLA was printed with different thicknesses on red wool fabric from transparent few layers to multiple layers. The printed layers of PLA were around 10 in the transparent area, whereas 22 layers around 2 mm of thickness in the solid colour area of these 3D shapes. This allows the red wool in transparent areas to appear.

Interlocking lines and chain lines were printed in 3D form with different filaments on different fabrics in either perforated or plain structure. Figure 11e shows that PLA was used to print interlocking chain lines on yellow woven wool fabric. The thickness of printed PLA is 2 mm. The interlocking chain structured pattern could provide not only the visual unique appearance but also certain level of bending ability. In Fig. 11f, 3D braided chains were designed and printed with 30 layers (3 mm thickness) of ABS on net black polyester fabric. This kind of shaped pattern has aesthetic appearance and can be used in

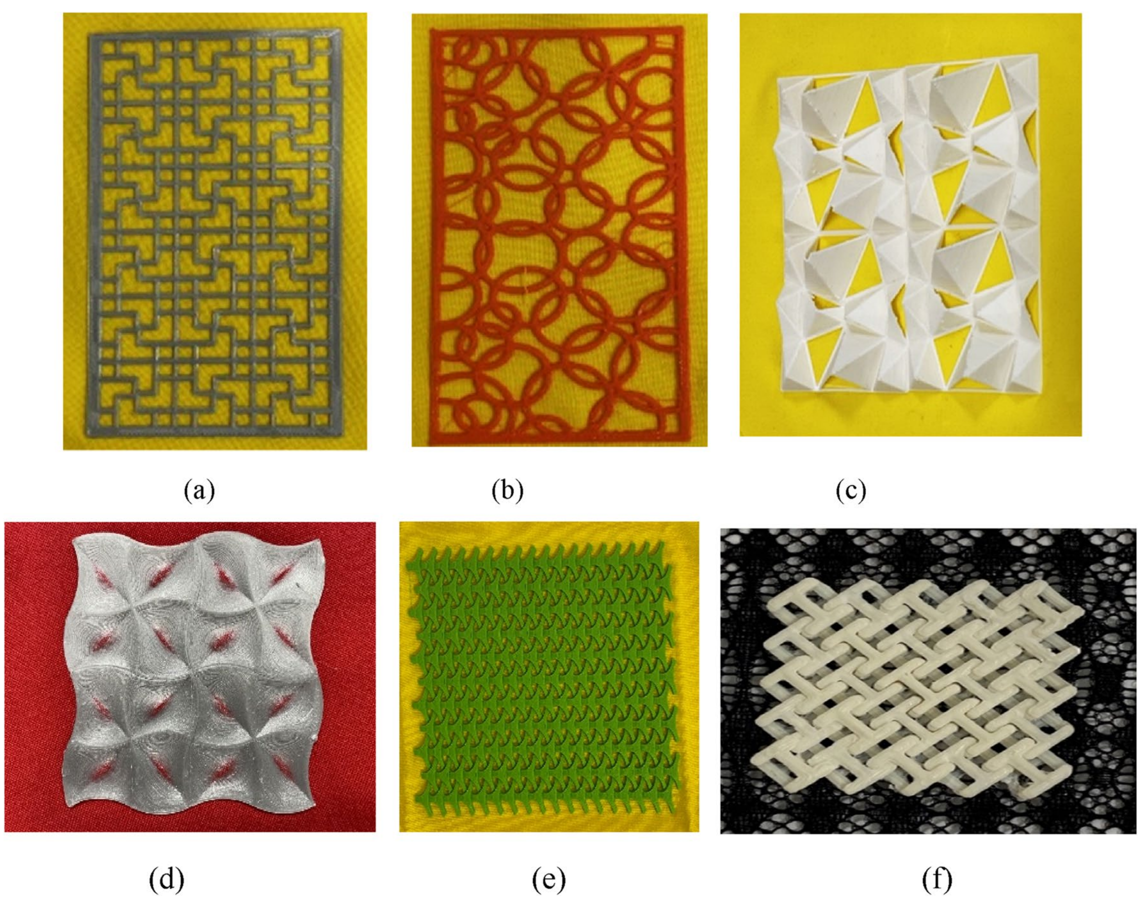


Fig. 11 Different structures of 3D patterns printed on fabrics with different printing filaments

different areas on the garment such as elbow or knee area for protection.

3D printing could be successfully applied on various textile materials including garments and upholstery fabrics to create logos, designed patterns or functional polymers on fabrics. By controlling the attachment strength of printed patterns on the fabrics, the printed objects or polymer materials could be removed from the fabrics for recycle and reuse, when the fabrics come to the end of life or need to be redesigned with new patterns. The filaments for 3D print could be produced from the waste thermoplastic materials through recycling processes. The current research could make contribution to the textile sustainability.

4 Conclusion

3D Printing technology using desktop FDM equipment is still complicated, especially in the new field of 3D printing on textile fabrics with various printing filaments. It was important to optimise the control parameters of 3D print like printing nozzle temperature, printing platform temperature, printing speed, cooling fan speed, density of printing objects or patterns, density of printing base layer, the initial distance between printing nozzle and platform, so that a high quality of 3D print on fabrics could be achieved. Among these parameters, a key variable influencing the adherence of printed material to the fabrics is the initial distance of printing nozzle to the fabric surface. From the research based on the Ultimaker 2, it was found that the attachment strength of printed pattern on the surface of the fabrics was directly reliant on the original distance between the printing nozzle and the platform set at the Ultimaker 2 printer. The attachment strength in the interface between printed pattern and fabric surface can be improved once the initial setting distance between printing nozzle and the platform was decreased. If the shorter distance between printing nozzle and the platform was set up, the first layer was printed deeply into the surface of the fabrics since high pressure could be applied by the printing nozzle on the fabric during the printing of the initial layer to create a solid attachment of printed patterns on the surface of the fabrics. This is also confirmed through SEM on the first layer of the print that the molten polymer was pressed deeply into fabrics, resulting in the printed polymer can be intergraded into the surface structures of the fabric to gain the strong attachment of 3D print on the fabrics.

The thickness of patterns to be printed on the fabrics can be controlled by the 3D printer from a few layers for thin patterns to more layers for thick 3D patterns. The flexibility of printed patterns could be affected not only by the hardness of 3D printed materials but also the thickness of the patterns.

Polyurethane-based printing materials are soft, flexible and elastic with high elongation. When TPU printing filaments are used to print the 3D patterns on knitted or stretchable fabrics, it was found that this printed fabric can be stretched with printed patterns with good recovery in their shape and firmly attaching on the fabrics. Therefore, 3D printing on textile fabrics can be engineered to achieve variable stretching ability.

The current work also demonstrated the ability to create different design patterns in 3D on the fabrics. The patterns can be printed with different thicknesses ranging from transparent few layers to solid multiple layers. 3D patterns on the fabrics could be created by the combination of the 3D shape, colour of printed polymers and the background colour of the fabric appeared in the area of the transparent layers.

FDM technology allow the development of novel and constructed patterns to be printed on fabrics that would be impossible to create with conventional methods. High quality of 3D patterns with precise and detail design can be printed on fabrics in strong attachment.

Data Availability The authors confirm that the data supporting the findings of this study are available within this published article.

Declarations

Conflict of Interest The authors have no conflicts of interest to declare.

References

1. B. Berman, 3-D printing: the new industrial revolution. Bus. Horiz. **55**(2), 155–162 (2012)
2. M. Mehrpouya, A. Dehghanghadikolaei, B. Fotovvati, A. Vosooghnia, S.S. Emamian, A. Gisario, The potential of additive manufacturing in the smart factory industrial 4.0: a review. Appl. Sci. **9**(18), 3865 (2019)
3. R. Singh, M. Chhabra, Three-dimensional printing, in *Reference Module in Materials Science and Materials Engineering*. (Elsevier, 2017)
4. E. Pei, J. Shen, J. Watling, Direct 3D printing of polymers onto textiles: experimental studies and applications. Rapid Prototyp. J. **21**(5), 556–571 (2015)
5. M. Lin, A brief introduction to body-oriented parametric design for 3D-printed fashion and textiles. TEXTILE **20**(1), 55–73 (2022)
6. T. Spahiu, N. Grimmelsmann, A. Ehrmann, E. Piperi, E. Shehi, Effect of 3D printing on textile fabric, *1st ICEE-2017 Proceedings*, Available from https://www.researchgate.net/publication/321228371_Effect_of_3D_printing_on_textile_fabric. Accessed 19 Sept 2018
7. T. Spahiu, E. Canaj, E. Shehi, 3D printing for clothing production. J. Eng. Fiber. Fabr. **15**, 1–8 (2020)
8. G. Brinks, M. Warmoeskerken, R. Akkerman, W. Zweers, The added value of 3D polymer deposition on textiles. In: 13th AUTEX World Textile Conference, 22–24 May 2013, Dresden, Germany, 1–6 (2013)
9. R. Beckett, 3D-printed fabrics by Richard Beckett woven in pringle of Scotland's ready to wear garments, *dezeen* (2014). Available from https://www.dezeen.com/2014/02/17/3d-print

ed-fabrics-by-richard-beckett-woven-into-pringle-of-scotlands-ready-to-wear-garments/. Accessed 30 Mar 2023
10. Iris Van Herpen Showcases Haute Couture with 3D Printing, Available from https://senatus.net/article/iris-van-herpen-showcases-haute-couture-3d-printing/. Accessed 29 July 2023
11. G. Lazzari, 3D printing on fabric. Wasp, Available from https://www.3dwasp.com/en/3d-printed-on-fabric/ (2021). Accessed 16 Jun 2022
12. M. Korger, J. Bergschneider, M. Lutz, B. Mahltig, K. Finsterbusch, M. Rabe, Possible applications of 3D printing technology on textile substrates. IOP Conf. Ser.: Mater. Sci. Eng. **141**, 012011 (2016)
13. B. Malengier, C. Hertleer, L. Cardon, L. Van Langenhove, 3D Printing on textiles: testing of adhesion, In: *ITMC2017 - International Conference on Intelligent Textiles and Mass Customisation*, 16–18 October 2017, Ghent, Belgium
14. B. Mahltig, M. Gorlachova, 3D-printing on textiles - an investigation on adhesion properties of the produced composite materials. J Polym Res **28**, 207 (2021)
15. G.H. Loh, A. Sotayo, E. Pei, Development and testing of material extrusion additive manufactured polymer-textile composites. Fash. Text. **8**, 2 (2021)
16. J. Liu, S. Jiang, Effect of sodium hydroxide and acetone pretreatments on the adhesion of three-dimensional printed polylactic acid filaments on linen and polyester fabrics. Text. Res. J. **93**(1–2), 161–171 (2023)
17. S. Chakraborty, M.C. Biswas, 3D printing technology of polymer-fiber composites in textile and fashion industry: a potential road-map of concept to consumer. Compos. Struct. **248**, 112562 (2020)
18. Y.Q. Xiao, C.W. Kan, Review on development and application of 3D printing technology in textile and fashion design. Coatings **12**, 267 (2022)
19. Ultimaker. 2016. *Ultimaker 2+ 3D Printer | Ultimaker* [Online]. Ultimaker.com. Available from: https://ultimaker.com/en/products/ultimaker-2-plu. Accessed 12 Apr 2016