The use of statistical techniques to study the machine parameters affecting the properties of 3D printed cotton/polylactic acid fabrics

Nonsikelelo Sheron Mpofu1,2, Josoph Igadwa Mwasiagi1, Londiwe Cynthia Nkiwane3 and David Njuguna Githinji1,2

Abstract
Textile materials have been combined with polymers using 3D printing technology, thus producing structures with novel properties. The aim of this study was to use statistical methods to determine the effect of 3D printing machine parameters on the mechanical properties of cotton fabrics combined with polylactic acid. Polylactic acid was printed on a cotton fabric using an Athena Fused Deposition Modelling 3D printer. The effect of extrusion temperature, printing speed, fill density and model height on adhesion force before and after washing was investigated. A study of the tensile strength was also undertaken using a central composite rotatable design and regression analysis. The experimental data were used to develop regression models to predict the properties of the cotton/polylactic acid structures. The model for adhesion force before washing yielded a coefficient of determination (R²) value of 0.75 and an optimum adhesion force of 50.06 N/cm. The model for adhesion force had an R² value of 0.84 and an optimum adhesion force of 42.91 N/cm and showed that adhesion force reduced after washing. Adhesion forces before and after washing were both positively correlated to extrusion temperature. However, they reduced with an increase in printing speed and model height. A positive correlation exists between tensile strength and temperature, while a negative correlation exists between tensile strength and printing speed and model height. From the results of this study, it was concluded that 3D printing parameters have an effect on the properties of the structures.

Keywords
Cotton, PLA, 3D printing, adhesion force, extrusion temperature

Date received: 28 February 2020; accepted: 3 May 2020

Introduction
3D printing has found several functions in the textile and clothing industry, which include knitted and woven structures as well as fashion items (shoes and garments).1–4 Although the 3D printed textile-like structures have opened doors for new opportunities, the speed of modern 3D printing is still not fast enough to compete with the conventional textile production methods such as weaving and knitting. Recent studies have also shown that although garments such
as skirts and dresses can be produced using 3D printing, there are still limitations related to the creating process, printing processes, materials, modelling programmes, and wearing the cloth. There is also the challenge of 3D printed textiles having inferior flexibility, comfort and strength when compared to traditional textiles. Research has been done to improve the mechanical properties of fabrics, while maintaining the drape and functionality of the textiles by direct deposition of polymers onto textile fabrics using 3D printing techniques. This method has expanded the possibility of smart textile applications that can be explored in 3D printing such as electroluminescence devices and wearable electronics. However, there is the challenge of the adherence of the polymer to the textile fabric.

Considerable efforts to improve adherence have been done by varying the textile fabric, polymer, as well as the printing parameters and also by polymer coating. Although the effect of these different factors has been studied and observed, there is still need for more research to be able to determine the optimum settings for the best adherence in different polymer–textile combinations. This article will investigate the effect of 3D printing machine parameters on the properties of 3D printed structures.

**Adhesion of polymers to fabric**

Adhesion is the tendency of unlike surfaces to cling to one another due to the intermolecular and interatomic interaction of the two surfaces. There are different theories of adhesion based on the surface characteristics of the materials involved. The theory that is applicable to polymeric adhesion is the diffusion theory which is based on the inter-penetration or diffusion of the polymer across the interface. This is affected by parameters such as the temperature of the polymer, the contact time, the physical form and the weight of the polymer. Studies on polymer to fabric adhesion have highlighted the importance of understanding the binding process of the polymers with the textile fabric as well as factors that influence the flow of the polymer. They determined that for better adhesion, the polymer should be able to penetrate into the fabric. This can be done by reducing the viscosity for high viscosity polymers or by adding pressure for better adhesion.

Adhesion of polymers to fabrics is also affected by cohesion of the macromolecules of the polymer. The difference between adhesion and cohesion is that in adhesion, the adhesive forces cause two different surfaces to cling to one another, whereas in cohesion, the cohesive forces cause similar surfaces to cling to one another. Generally, the strength between the polymer and the fabric is affected by the speed at which the polymer is deposited. If the adhesive forces are less than the cohesive forces, adhesion strength between the polymer and the fabric decreases. It is therefore important to determine the most appropriate speed to achieve a good adhesion strength between the fabrics and polymers.

Researchers have tested 3D printed fabric for adhesion using different methods, with several factors found to be influencing the adhesion force between the polymer and textile substrate. The quality of adhesion between the polymer and the fabric has been examined through visual and surface inspection and by the use of the perpendicular test, the shear test and the peel test.

**Factors affecting the adhesion force between the polymer and textile substrate**

Data from previous research suggest that fabric structure properties such as roughness, areal density, fibre type, weft and warp count as well as fabric thickness have a significant effect on adhesion force. Other studies have emphasised the importance of a lower viscosity of the polymer in achieving a higher adhesion force. These studies have shown that a lower polymer viscosity enables stronger penetration into the pores of the textile substrate and therefore creates a better connection between the polymer and the substrate. Viscosity can be reduced by increasing the nozzle and print bed temperature and also by using flexible filaments. The distance between the nozzle and the printing bed is another important factor in polymer/textile adhesion. Adhesion force has been observed to increase with a decrease in the distance between the nozzle and the printing bed due to the nozzle pressing the polymer into the pores of the fabric with a higher force. Studies have also shown that pretreatment processes carried out on the fabric before printing have an effect on the surface tension and hydrophilicity of the fabric, therefore altering the adhesion force. Processes done in the weaving shed like sizing are important in stabilising warp yarn for weaving but may reduce the wettability of the fabric. Washing and desizing of fabrics before 3D printing has resulted in increased adhesion force due to an improvement in wettability of the fabrics.

The effect of varying different 3D printing parameters on adhesion force has been studied with different combinations of polymers and textile fabrics. An investigation has been done into the adhesion properties of direct 3D printing of polymers and nanocomposites on textiles by varying the printing process parameters. The research concluded that varying different 3D printing parameters like platform temperature, printing speed and extrusion temperature can have a significant effect on the adhesion force of polymers to textile fabrics in direct 3D printing. Another study also showed that 3D printing parameters like printing speed and extrusion temperature have a significant impact on the adhesion force, while nozzle diameter and first layer height had no effect on adhesion force. Optimisation of adhesion of polylactic acid (PLA), combined with polyethylene terephthalate woven fabric, has been done by the use of modelling and has shown that textile structure properties affect adhesion properties.
studies have necessitated more research in optimising adhesion force with different machine parameters and different combinations of the polymer and the fabric. This study investigates the influence of extrusion temperature, printing speed, fill density and model height on the properties of 3D printed PLA/Cotton structures. The purpose of this investigation was to keep the polymer and the fabric parameters constant, while varying the 3D printing machine parameters.

## Methods and materials

### Statistical design of experiments

The statistical design of experiments used in this research work involved the use of a four-factor inscribed central composite design (CCD) to identify the relationship existing between the response functions and the process variables as well as to determine those conditions that optimised the responses. The CCD of experiments is a response surface method that uses a combination of statistical and mathematical methods to choose the best experimental methods to maximally reduce the number of experiments. In CCD, the factors are tested at a minimum of three levels, that is, minimum, middle and maximum and are coded as $-1$, $0$ and $1$. For a rotatable design, each experimental factor must be represented at the five levels of coded units, that is, $-\alpha, -1, 0, 1$ and $\alpha$. This property ensures constant variance at points that are equidistant from the centre point and therefore provides equal precision of response estimation in any direction of the design. In CCD, the factors are tested at a minimum of three levels, that is, minimum, middle and maximum and are coded as $-1$, $0$ and $1$. For a rotatable design, each experimental factor must be represented at the five levels of coded units, that is, $-\alpha, -1, 0, 1$ and $\alpha$. This property ensures constant variance at points that are equidistant from the centre point and therefore provides equal precision of response estimation in any direction of the design. The four factors and levels of variation are given in Table 1.

### Cotton fabric

The fabric used was 100% cotton, and it had the following characteristics: 24 ends/inch, 38 picks/inch, 50 tex warp count, 37 tex weft count, 355.2 grammes per square metre, a thickness of 0.19 mm and white in colour. The fabric was selected based on an earlier study where PLA was 3D printed on 15 randomly selected samples to determine the effect of fabric parameters such as areal density, warp and weft count, fabric thickness and fabric handle on adhesion force. The sample that displayed superior adhesion force was selected for the current study.

### PLA polymer

The PLA polymer used in this experiment was acquired from Hatchbox, United States of America. The filament was purchased from the company’s online shop at http://hatchbox3d.com. The filament was red in colour and had the properties shown in Table 2.

---

**Table 1. Design of experiment runs.**

| Runs | Factors          | Extrusion temperature | Printing speed | Fill density | Model height |
|------|------------------|-----------------------|----------------|--------------|--------------|
| 1    |                  | 210                   | 55.0           | 30.0         | 0.40         |
| 2    |                  | 210                   | 30.0           | 65.0         | 0.40         |
| 3    |                  | 205                   | 42.5           | 47.5         | 0.35         |
| 4    |                  | 205                   | 67.5           | 82.5         | 0.35         |
| 5    |                  | 210                   | 55.0           | 65.0         | 0.30         |
| 6    |                  | 215                   | 42.5           | 82.5         | 0.35         |
| 7    |                  | 215                   | 67.5           | 47.5         | 0.45         |
| 8    |                  | 215                   | 67.5           | 82.5         | 0.35         |
| 9    |                  | 210                   | 55.0           | 65.0         | 0.40         |
| 10   |                  | 200                   | 55.0           | 65.0         | 0.40         |
| 11   |                  | 205                   | 42.5           | 82.5         | 0.45         |
| 12   |                  | 215                   | 42.5           | 82.5         | 0.45         |
| 13   |                  | 210                   | 55.0           | 65.0         | 0.40         |
| 14   |                  | 210                   | 55.0           | 65.0         | 0.40         |
| 15   |                  | 215                   | 67.5           | 65.0         | 0.40         |
| 16   |                  | 215                   | 42.5           | 47.5         | 0.45         |

Optimal data values and sample points were generated, with the predicted response values being closest to the optimal solution. The analysis of variance (ANOVA, P-values) and variance inflation factors (VIFs) were recorded and used to ensure the accuracy as well as the statistical significance of the model. Experimental responses of adhesion force before washing, adhesion force after washing and tensile strength were considered to predict the optimum and interaction effects using regression analysis. The four factors and levels of variation are given in Table 1.
3D printing experiments

The machine used for the 3D printing process was the Athena 3D printer from Michigan State University, USA; it uses the fused deposition modelling 3D printing technique and works with the Franklin Software. The printer had no heated printing bed with a nozzle size of 0.4 mm, and printing was done at a layer height of 0.15 mm. The 3D printer and the fabric were set up according to the method reported in an earlier study.10 The fabric sample was laid on the printer bed and secured with clips to enable the direct deposition of the polymer on the fabric (Figure 1).

The model for 3D printing was designed using Solid Works design software, converted to the STL format and then sliced using the Cura software. The design was a rectangle which had a length of 150 mm and a width of 25 mm (Figure 2(a)). The fabric sample was laid on the printer bed and secured with clips to enable the direct deposition of the polymer on the fabric (Figure 1).

Characterisation of mechanical and physical properties of the printed fabric

Tests were carried out on the printed fabric to determine the tensile strength, adhesion force before washing and adhesion force after washing. The adhesion tests were carried out according to the DIN 53530 standard using the Testometric Micro 500 model tensile tester. The same procedure was used to test the adhesion force of the samples after washing. Washing was done using an M228 Rotawash according to the method outlined in standard ISO 105 C01. The M228 Rotawash machine was operated at a temperature of 40°C for 30 min with the shaft assembly rotating at a speed of 40 ± 2 r/min. Samples were rinsed and air-dried at room temperature before carrying out the adhesion tests. The tensile test was carried out according to standard ASTM D5034 using the Testometric Micro 500 model tensile tester from Rycobel, Belgium. The samples were 150 mm long and 25 mm wide and were gripped evenly by the jaws of the machine with the longitudinal axis in line with the direction of load application. Testing was done at a speed of 100 mm/min.

Results and discussion

Characterisation of the printed fabrics

Characterisation and optimisation of the mechanical properties of the printed fabrics were done by the use of statistical methods. The mechanical properties were the response of the system, while the four process parameters were the input independent variables. The effect of extrusion temperature, fill density, printing speed and model height on the mechanical properties was determined, and these factors were monitored for the optimisation of the mechanical properties.

The regression model for adhesion force \( Y_A \) shown in equation (1) had an \( R^2 \) value of 0.7473. The ANOVA results were done at the alpha (\( \alpha \)) value (\( P < 0.05 \)) and were deemed to be significant. The regression analysis showed that extrusion temperature (\( X_1 \)), extrusion speed (\( X_2 \)) and model height (\( X_3 \)) had an effect on adhesion force, while fill density (\( X_4 \)) had no significant effect on adhesion force

\[
Y_A = -1054 + 4.113X_1 + 14.05X_2 + 864X_4 - 0.01737X_2X_4 - 1048X_3X_4 - 0.0584X_1X_2 \tag{1}
\]

Table 2. Properties of the PLA polymer.

| Property                        | Value  |
|---------------------------------|--------|
| Elongation at break (%)         | 4      |
| Diameter (mm)                   | 1.75   |
| Tensile modulus (MPa)           | 1968   |
| Extruder temperature range (°C) | 180–210|
| Density (g/cm³)                 | 1.27   |
| Melting temperature (°C)        | 155    |
| Solubility in water             | Insoluble |

PLA: polylactic acid.

Figure 1. (a) Preparation of the fabric sample for 3D printing. (b) Fabric sample attached to the 3D print bed with securing clips.

Figure 2. (a) Model designed for 3D printing. (b) 3D printed PLA/cotton structure.
The ANOVA, factor contributions (FC%) and VIFs for the adhesion force are shown in Table 3. The percentage contribution of the factors showed that the extrusion temperature $X_1$ had the highest percentage contribution of 35.62%, while the combined effects of extrusion temperature $X_1$ and printing speed $X_2$ had the second highest contribution of 13.01%. Printing speed contributed 2.28% and model height 1.58%. The P values for the estimated coefficients and curvilinear and interaction effects were less than 0.05 and were therefore significant in the model.

The combined effect of extrusion temperature and printing speed is shown in Figures 3 and 4. The graphs show that as the temperature increased and the printing speed decreased, there was an increase in the adhesion force.

The normal probability plot of residuals for adhesion force (Figure 5) indicated that the data points were normally distributed.

The regression model was used to predict the optimal settings for a maximised adhesion force. The optimal settings obtained were extrusion temperature ($X_1$) of 220°C, printing speed ($X_2$) of 34.55 mm/s, a model height ($X_4$) of 0.41 mm and a predicted adhesion force ($Y_A$) of 50.06 N/cm.

The top five values closest to the predicted optimum settings for adhesion force (Table 4) were also considered in case the optimum settings were not practicable.

It is worth noting that the optimum settings yielded maximum extrusion temperature of 220°C. An increase in extrusion temperature resulted in an increase in adhesion force (Figure 6). This is in line with the general trend in previous studies that showed that an increase in temperature leads to an increase in adhesion force. This is explained by the reduced viscosity of PLA at higher temperatures, which then allows the polymer to penetrate deeper into the woven fabric.11,24

### Table 3. ANOVA, FC% and VIFs for adhesion force.

| Source       | ANOVA (P-value) | FC (%) | VIF |
|--------------|-----------------|--------|-----|
| Regression   | 0.000           | 74.73  |     |
| $X_1$        | 0.000           | 35.62  | 1.00|
| $X_2$        | 0.022           | 2.28   | 1.01|
| $X_4$        | 0.029           | 1.58   | 1.01|
| $X_1^2$      | 0.003           | 10.02  | 1.02|
| $X_2^2$      | 0.004           | 12.21  | 1.02|
| $X_1^2X_2$   | 0.004           | 13.01  | 1.00|
| Error        |                 | 25.27  |     |
| Lack-of-fit  | 0.918           | 12.96  |     |
| Pure error   |                 | 12.31  |     |
| Total        |                 | 100.00 |     |

ANOVA: analysis of variance; FC: factor contribution; VIF: variance inflation factor.

### Figure 3. Combined effect of extrusion temperature and printing speed on adhesion.

### Figure 4. Response surface 3D plot indicating the interaction between printing speed and extrusion temperature on adhesion force.

### Figure 5. The normal probability plot for adhesion force.

### Table 4. Predicted optimum settings.

| $X_1$ | $X_2$ | $X_4$ | Predicted $Y_A$ |
|-------|-------|-------|-----------------|
| 220   | 55    | 0.4   | 42.7830         |
| 215   | 42.5  | 0.45  | 39.3309         |
| 215   | 42.5  | 0.35  | 36.8322         |
| 210   | 55    | 0.4   | 33.7513         |
| 215   | 67.5  | 0.45  | 29.0334         |

$X_1$: temperature; $X_2$: speed; $X_4$: model height.
Another study also showed that PLA adheres better to fabric when extruded at higher temperatures than the normal extrusion temperatures between 180°C and 210°C. Another factor to note is that the optimum settings yielded a value close to the minimum printing speed, that is, 34.5 mm/s. The graphs in Figure 6 show that as the printing speed increased, adhesion force decreased. Previous research has shown that the adhesion force reduces with an increase in printing speed. The penetration of the macromolecules of polymers into the fabric is slow at high printing speeds; as a result, the adhesive forces are less than cohesive forces, hence the decrease in adhesion strength. The adhesion force increased with an increase in model height to an optimal height of 0.411 mm, beyond which the adhesion force reduced. This could be due to the fact that as the height of the model continues to increase, the print becomes easier to peel off the fabric, hence the reduced adhesion force.

**Adhesion force of the printed fabric after washing (Y_{AW})**

The adhesion force regression model (Y_{AW}) shown in equation (2) had a coefficient of determination (R^2) of 0.8337. The ANOVA gave a P value which was 0.000 for the general model and was less than the alpha (α) value (P < 0.05) and was therefore a significant model

\[
Y_{Aw} = -459.7 + 1.233X_1 + 2.023X_2 + 873X_4 - 0.01902X_2X_2 - 1073X_4X_4 \tag{2}
\]

The regression analysis showed that extrusion temperature (X_1), printing speed (X_2) and model height (X_4) had an effect on adhesion force after washing, while fill density (X_3) had no significant effect; thus, it was not captured in the model.

The ANOVA, FC% and VIFs for the adhesion force after washing are shown in Table 5. The percentage contribution of the factors showed that extrusion temperature contributed 57.56% to the regression model for adhesion force after washing, while printing speed and model height contributed 1.07% and 1.04%, respectively. The P values for the estimated coefficients and curvilinear and interaction effects were less than 0.05 and were therefore significant in the model.

The normal probability plot of residuals for adhesion force after washing (Figure 7) showed that the data points were normally distributed.

The regression model was used to predict the optimal settings for a maximised adhesion force after washing. The optimal settings obtained were extrusion temperature (X_1) of 220°C, printing speed (X_2) of 53.23 mm/s and a model height (X_4) of 0.41 mm to achieve a predicted maximum adhesion force after washing of 42.921 N/cm. This is less than the predicted maximum adhesion force before washing, which has a value of 50.06 N/cm. This showed that the adhesion force is expected to reduce slightly after washing the sample.

The top five values closest to the predicted optimum settings for adhesion force after washing (Table 6) were also considered to be used in a situation where the optimum settings proved to be unfeasible.

The optimal settings yielded a maximum temperature of 220°C. Figure 8 shows that as extrusion temperature...
increased, adhesion force increased. The optimum printing speed for adhesion force after washing is 53.23 mm/s. As the printing speed increased, the adhesion force after washing increased until a speed of 53.23 mm/s; thereafter, the adhesion force started to decrease. The optimal settings yielded a maximum model height of 0.41 mm. The adhesion force increased with an increase in model height to an optimal height of 0.41 mm, beyond which the adhesion force reduced.

Results of the study also showed that the adhesion force reduced after washing (Figure 9), as was also observed by researchers in previous studies.25,29

![Figure 7](image)

**Figure 7.** The normal probability plot for adhesion force after washing.

![Table 6](table)

| X₁ | X₂ | X₄ | Predicted Yₐw |
|----|----|----|--------------|
| 220| 55.0| 0.40| 42.8071      |
| 215| 42.5| 0.45| 32.5952      |
| 215| 42.5| 0.35| 31.1052      |
| 210| 55.0| 0.40| 30.4794      |
| 215| 67.5| 0.35| 29.3859      |

X₁: temperature; X₂: speed; X₄: model height.

**Table 6.** Predicted optimum settings for adhesion force after washing.

**Tensile strength (Yₜ) of the printed fabric**

The regression model for tensile strength (Yₜ) is represented in equation (3), which was tested at an alpha (α) value (P < 0.05) and was deemed to be significant

\[
Yₜ = 43148 - 363.8X₁ - 1161X₂ - 77.77X₃ + 8334X₄ + 0.775X₂X₁ + 0.3561X₁X₃ + 28.7X₄X₄ - 0.0426X₂X₃ + 36.27X₂X₄
\]

The regression analysis showed that all factors, that is, extrusion temperature (X₁), printing speed (X₂), fill density (X₃) and model height (X₄) had an effect on tensile strength. The ANOVA, FC% and VIFs for the tensile strength are shown in Table 7. The percentage contribution of the factors showed that extrusion temperature contributed 4% to the model for tensile strength, while printing speed contributed 1.02%, fill density 6.33% and model height 4.70%.

The combined effect of extrusion temperature and fill density had the highest percentage contribution of 36.58%. The combined effect of printing speed and fill density had the second highest percentage of 21.83%. The combined effect of extrusion temperature (X₁) and fill density (X₃) is shown in Figures 10 and 11. The graphs show that as both the extrusion temperature and the fill density increased, there was an increase in tensile strength.

The normal probability plot of residuals for tensile strength (Figure 12) showed that the data points were normally distributed.

The regression model was used to predict the optimal settings for a maximised tensile strength. The optimal settings obtained were extrusion temperature (X₁) 220°C, printing speed (X₂), fill density (X₃) 100% and model height (X₄) 0.35 mm to achieve a tensile strength of 346.22 MPa.

The top five values closest to the predicted optimum settings for tensile strength were also considered and are presented in Table 8 in case the optimum settings were not possible.

The optimum settings produced a maximum extrusion temperature of 220°C. Figure 13 shows that as extrusion
temperature increased, tensile strength increased. Earlier
results have shown that an increase in extrusion tempera-
ture results in an improved tensile strength, with the best
tensile strength achieved at a temperature of 220°C.30,31
This is because at higher temperature, the polymer is less
viscous and there is improved adhesion between the layers.

Table 7. FC% and VIF for the tensile strength.

| Source       | ANOVA (P-values) | FC (%) | VIF |
|--------------|------------------|--------|-----|
| Regression   | 0.000            | 94.06  |     |
| X1           | 0.000            | 4.00   | 1.11|
| X2           | 0.918            | 1.02   | 1.05|
| X3           | 0.052            | 6.33   | 1.04|
| X4           | 0.003            | 4.70   | 1.05|
| X1^2         | 0.000            | 12.93  | 1.10|
| X1^3X3       | 0.000            | 36.58  | 1.06|
| X1^4X4       | 0.047            | 4.68   | 1.06|
| X2^2X3       | 0.014            | 1.99   | 1.05|
| X2^3X4       | 0.000            | 21.83  | 1.05|
| Error        |                  | 5.94   |     |
| Lack-of-fit  | 0.540            | 4.64   |     |
| Pure error   |                  | 1.30   |     |
| Total        |                  | 100    |     |

FC: factor contribution; VIF: variance inflation factor; ANOVA: analysis of variance.

Table 8. Predicted optimum settings for tensile strength.

| X1   | X2   | X3   | X4    | Predicted Y_T |
|------|------|------|-------|---------------|
| 205  | 42.5 | 47.5 | 0.35  | 259.883       |
| 205  | 67.5 | 47.5 | 0.45  | 236.931       |
| 205  | 67.5 | 47.5 | 0.35  | 236.565       |
| 215  | 42.5 | 82.5 | 0.35  | 216.370       |
| 205  | 42.5 | 82.5 | 0.35  | 204.626       |

X1: temperature; X2: speed; X3: fill density; X4: model height.

Figure 9. Boxplot for adhesion force before and after washing.

Figure 10. Combined effect of extrusion temperature and printing speed on tensile strength.

Figure 11. Response surface 3D plot indicating the interaction between fill density and extrusion temperature on tensile strength.

Figure 12. Normal probability plot for tensile strength.

Figure 13. Mean of tensile strength (MPa) vs. extrusion temperature X1 (°C).
Conclusions and recommendations

This study showed that the 3D printing machine parameters have an effect on the properties of the PLA/textile structure. The factors that affected adhesion force both before and after washing were extrusion temperature, printing speed and model height, while fill density had no significant effect. Adhesion force before and after washing were both positively correlated to extrusion temperature and negatively correlated to printing speed and model height. The results also showed that the adhesion force reduced after washing. A positive correlation exists between tensile strength and temperature, while a negative correlation exists between tensile strength and printing speed and model height.

From the results obtained, it can be recommended that research should be done to determine the best washing parameters to maintain a good adhesion force after several washing cycles. Parameters such as washing temperature, washing time, washing detergent and number of washing cycles could be studied.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was financially supported by the European Commission Intra ACP Mobility Program through the project “Mobility to Enhance Training of Engineering Graduates in Africa”.

ORCID iDs

Nonsikelelo Sheron Mpofu https://orcid.org/0000-0001-8419-3388
David Njuguna Githinji https://orcid.org/0000-0002-6009-2248

Data availability

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

References

1. Melnikova R, Ehrmann A and Finsterbusch K. 3D printing of textile-based structures by fused deposition modelling (FDM) with different polymer materials. IOP Conf Ser: Mater Sci Eng 2014; 62: 012018.
2. Beecroft M. 3D Printing of weft knitted textile based structures by selective laser sintering of nylon powder. IOP Conf Ser: Mater Sci Eng 2016; 137: 012017.
3. Pipieri E, Galantucci LM, Kacani J, et al. From 3D foot scans to footwear designing and production. In: Proceedings of the 6th international conference on textiles, Tirana, 20 November 2014.
4. Spahiu T, Grimmelsmann N, Ehrmann A, et al. On the possible use of 3D printing for clothing and shoe manufacture. In: Proceedings of the 7th international conference of textile, Tirana, 10–11 November 2016, pp. 1–7. Tirana: Polytechnic University of Tirana.
5. Kim S, Seong H, Her Y, et al. A study of the development and improvement of fashion products using a FDM type 3D printer. J Fash Text 2019; 6: 9.
6. Körger M, Bergschneider J, Lutz M, et al. Possible applications of 3D printing technology on textile substrates. IOP Conf Ser: Mater Sci Eng 2016; 141: 012011.
7. Grimmelsmann N, Martens Y, Schläf P, et al. Mechanical and electrical contacting of electronic components on textiles by 3D printing. Procedia Technol 2016; 26: 66–71.
8. Tadesse MG, Dumitrescu D, Loghin C, et al. 3D printing of NinjaFlex filament onto PEDOT:PSS-coated textile fabrics for electroluminescence applications. J Electron Mater 2018; 47: 2082–2092.
9. He H, Chen X, Ukkonen L, et al. Textile-integrated three-dimensional printed and embroidered structures for wearable wireless platforms. Text Res J 2019; 89: 541–550.
10. Pei E, Shen J and Watling J. Direct 3D printing of polymers onto textiles. Rapid Prototyping J 2015; 21(5): 556–571.
11. Sanatgar RH, Campagne C and Nierstrasz V. Investigation of the adhesion properties of direct 3D printing of polymers and nanocomposites on textiles: effect of FDM printing process parameters. Appl Surf Sci 2017; 403: 551–563.
13. Meyer P, Dopke C and Ehrmann A. Improving adhesion of three-dimensional printed objects on textile fabrics by polymer coating. *J Eng Fibres Fabr* 2019; 14: 1558925019895257.

14. Mittal KL. The role of the interface in adhesion phenomena. *Polym Eng Sci* 1977; 17(7): 467–473.

15. Lee I and Wool RP. Polymer adhesion vs substrate receptor group density. *Macromolecules* 2000; 33: 2680–2687.

16. Awaja F, Gilbert M, Kelly G, et al. Adhesion of polymers. *Prog Polym Sci* 2009; 34: 948–968.

17. Brinks G, Warmoeskerken GM, Akkerman R, et al. The added value of 3D polymer deposition on textiles. In: *Proceedings of the 13th AUTEX world textile conference*, Dresden, 22–24 May 2013.

18. Malengier B, Hertleer C, Cardon L, et al. 3D printing on textiles: testing of adhesion. In: *Proceedings of the international conference on intelligent textiles and mass customisation (ITMC 2017)*, Ghent, 16–18 October 2017.

19. Sabantina L, Kinzel F, Ehrmann A, et al. Combining 3D printed forms with textile structures – mechanical and geometrical properties of multi-material systems. *IOP Conf Ser: Mater Sci Eng* 2015; 87: 012005.

20. Grimmelmann N, Kreuziger M, Korger M, et al. Adhesion of 3D printed material on textile substrates. *Rapid Prototyping J* 2019; 24(1): 166–170.

21. Spahiu T, Al-Araboyat M, Martens Y, et al. Adhesion of 3D printing polymers on textile fabrics for garment production. *IOP Conf Ser: Mater Sci Eng* 2019; 459: 012065.

22. Holme I. Adhesion to textile fibres and fabrics. *Int J Adhes Adhes* 1999; 19: 455–463.

23. Kozier T, Dopke C, Grimmelmann N, et al. Influence of fabric pretreatment on adhesion of three-dimensional printed material on textile substrates. *Adv Mech Eng* 2018; 10(8): 1687814018792316.

24. Spahiu T, Fafenrot S, Grimmelmann N, et al. Varying fabric drape by 3D imprinted patterns for garment design. *IOP Conf Ser: Mater Sci Eng* 2017; 254: 172023.

25. Eutionnat-Diffo PA, Chen Y, Jinping G, et al. Optimization of adhesion of poly lactic acid 3D printed onto polyethylene terephthalate woven fabrics through modelling using textile properties. *Rapid Prototyping J* 2019; 26: 390–401.

26. Cavazzuti M. Optimization methods: from theory to design scientific and technological aspects in mechanics. Berlin; Heidelberg: Springer, 2013.

27. Montgomery DC. *Design and analysis of experiments*. 8th ed. Hoboken, NJ: John Wiley & Sons, Inc., 2013.

28. Rivera ML, Moukperian M, Ashbrook D, et al. Stretching the bounds of 3D printing with embedded textiles. In: *Proceedings of the 2017 CHI conference on human factors in computing systems*, Denver, CO, 6–11 May 2017, pp. 497–508. New York: ACM.

29. Martens Y and Ehrmann A. Composites of 3D-printed polymers and textile fabrics. *IOP Conf Ser: Mater Sci Eng* 2017; 225: 012292.

30. Sood AK, Ohdar RK and Mahapatra SS. Experimental investigation and empirical modelling of FDM process for compressive strength improvement. *J Adv Res* 2012; 3: 81–90.

31. Sun Q, Rizvi GM, Bellehameur GT, et al. Effect of processing conditions on the bonding quality of FDM polymer filaments. *Rapid Prototyping J* 2008; 14(3): 72–80.

32. Fernandez-Vicente M, Calle W, Ferrandiz S, et al. Effect of infill parameters on tensile mechanical behavior in desktop 3D printing. *3D Print Addit Manuf* 2016; 3(3): 183–192.