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Use of regression to study the effect of fabric parameters on the adhesion of 3D printed PLA polymer onto woven fabrics

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Abstract
The use of the three-dimensional (3D) printing technique is gaining popularity due to its ability to produce products with minimum waste. 3D printing can be used to add polymers onto woven fabrics to produce novel structures. This research work concentrated on the study of the fabric properties affecting the adhesion of Polylactic Acid (PLA) polymer onto selected fabrics. Different fabrics made from cotton, polyester and acrylic, were selected and using 3D printing, PLA polymer was printed onto the fabric surface. Regression models were used to study the effect of selected fabric properties on the adhesion of PLA polymer onto the woven fabrics. The results obtained in this research work indicated that fabric areal density, warp count (Tex), weft count (Tex), fabric thickness and fabric handle indicated a positive correlation with adhesion of PLA onto woven fabrics. On the other hand, warp ends/inch and weft picks/inch showed a negative correlation with the adhesion of PLA polymer onto woven fabrics.

Keywords: 3D printing, PLA, Fabric thickness, Fabric handle, Regression

Introduction

One method of reducing costs during manufacturing is to decrease the amount of waste generated in the manufacturing process; a strategy exhibited by the 3D printing technique where polymers are deposited layer by layer to form objects (Gibson et al. 2010; Canessa et al. 2013). This method can also be referred to as additive manufacturing. According to the American Society for Testing and Materials (ASTM) group F42- Additive Manufacturing; the processes can be described in 7 categories as follows: Material Extrusion, Material Jetting, Binder Jetting, Vat Photopolymerisation, Powder Bed Fusion, Sheet Lamination and Directed Energy Deposition. The most common technique used in textiles is Fused Deposition Modelling (FDM) (Korger et al. 2016; Gurcum et al. 2018). FDM is a common material extrusion process used on many low-cost domestic 3D printers. In this technique, the material is selectively dispensed through a nozzle or orifice. The extruded material is heated and then deposited in layers until the 3D object is formed. The quality of the final model is influenced by several factors which when controlled successfully can lead to the production of quality prints (Melnikova et al. 2014; Christiyan et al. 2016).

The use of FDM in textiles has facilitated the direct depositing of polymers onto fabrics to create fabric-polymer structures. This method has however posed challenges in the adherence of the polymer to the fabric. Several studies have been carried out in an effort to overcome the adherence challenge. The studies have shown that the roughness of the surface has an effect on adhesion force. Adhesion of the polymers to rough surfaces is based on the mechanical interlocking theory. This is based on the polymer keying into the rough surface (Awaja et al. 2009). Adhesion to textile fabrics has also been shown to depend on the nature of the fibre surface and is affected by the presence of additional treatments on the fabric as well as impurities (Korger et al. 2016; Narula et al. 2018). These observations necessitate the study of fabric structures and how they can be modified for improved adhesion force. Studies have shown that adhesion force reduces with continued use of fabrics. Textile fabrics undergo a lot of chemical and physical treatments during use and this in turn leads to failure of the adhesive joint (Holme 1999). It is therefore important to improve the adhesion forces so that they can withstand any form of chemical and physical treatments. Research has been done to determine the fabric to polymer combinations with the highest adhesion force (Sabantina et al. 2015; Pei et al. 2015; Malengier et al. 2017). However, these studies looked at the use of different polymer types on different fabric types and have not explored the deposition of one polymer type onto different fabric types. Although research has been carried out to study the adhesion properties of different fabric to polymer combinations, no detailed statistical study has been done on the effect of the different fabric properties on adhesion force. The purpose of this research work was to study the effect of selected fabric properties on the adhesion of 3D printed PLA polymer to fifteen fabric samples. The polymer (PLA) and the 3D printing parameters were kept constant while the fabrics were varied. Statistical analysis was used to study the effect of the different fabric properties on adhesion force.

Methods

The design for 3D printing was customized using SolidWorks software and then sliced using the Cura software. The polymer used for the 3D printing process was PLA filament with an elongation at break of 4%, a tensile modulus of 1968 MPa, a diameter of 1.75 mm, an extruder temperature range of 180 °C to 210 °C and was red in colour. The 3D printer and the fabric were set up according to the method used by Pei et al. (2015). The fabric samples were laid on the printer bed and secured with clips to enable the direct deposition of the polymer onto the fabric. For all 3D printing experiments, the settings were maintained as indicated in Table 1, and fifteen (15) samples fabric samples were used (Fig. 1).

The selection was done to try and vary the fibre types and different fabric structure properties. The fabric samples were tested for:

- Fabric areal density according to ASTM D3776.
- Fabric ends/inch according to ASTM D3775.
- Fabric picks/inch according to ASTM D3775.
- Warp and weft count according to ASTM D1059-01.
- Fabric thickness according ASTM D1777.

Table 1 3D printing parameters

Printing parameter	Value
Fill density	65%
Printing speed	50 mm/s
Printing temperature	200 °C
Nozzle size	0.4 mm
Layer height	0.15 mm
Filament diameter	1.75 mm

- Fibre type according to American Association of Textile Chemists and Colourists (AATCC) 20.

The fabric handle was measured using the subjective assessment of fabric handle as described by Kawabata and Niwa (1989). This method was also used by Tuigong and Xin (2005) in the assessment of commercial fabrics. In their research their panelists had some background textile knowledge and were first trained prior to testing. Tomovska et al. (2016) used the same method to determine the perception of different assessors on the contributions of different texture properties of knitted fabrics to their aesthetic properties.

In this research work a total of 6 male and 6 female postgraduate students were trained for the subjective testing method. The panellists were selected from individuals who use textile fabrics on a day to day basis. They were experts in different non-textile fields and were from different countries (Table 2).

In the subjective assessment of fabric handle, the assessor usually strokes the fabric with one or several fingers and then squashes the fabric gently in the hand. The assessments are based on the sensations of smoothness or roughness, hardness or softness as well as stiffness or limpness (Hu 2008). The terms smoothness and roughness were explained to the panellists in detail before they began the assessment. They were also trained on how to handle and stroke the fabric. The panellists were then able to judge the fabrics based on the sensations of smoothness or roughness. Their eyes were covered to ensure that judgement was not based on visual observation but entirely on the feel of the fabric on the hand. They each had to grade the fabric on a scale of 1–5 where 1 was for a smooth fabric and 5 for a rough fabric. The average readings of the different fabrics were recorded.

The fabric samples were preconditioned to standard atmospheric conditions. 3D printing of the PLA onto the fabrics was then done resulting in a textile/PLA structure as shown in Fig. 2a. The structures were then prepared for adhesion tests by cutting off the fabric parts around the 3D printed polymer and ensuring that the only parts that remained were those of the composite as illustrated in Fig. 2b.

After the 3D printing process adhesion tests were carried out according to the standard DIN 53530. At one end of the composite the fabric and the PLA were separated to allow for clamping on the Testometric Micro 500 model tensile tester as illustrated in Fig. 3.

Once the adhesion of PLA polymer onto the fabrics had been determined regression models between fabric properties and adhesion force were designed and used to study the

Fig. 1 Woven fabric samples for 3D printing

Table 2 Details of Subjective Assessment Panellists

Gender	Nationality	Area of specialization	Current level of study
Female	Kenya	Publishing	Masters
Female	Uganda	Library and Info Science	Masters
Female	Kenya	Media Studies	Masters
Female	Kenya	Publishing	Masters
Female	Tanzania	Sociology	Ph.D.
Female	Tanzania	Linguistics	Ph.D.
Male	Burundi	Economics	Masters
Male	Bangladesh	Information Technology	Masters
Male	Burundi	Linguistics	Ph.D.
Male	Rwanda	Technology Education	Ph.D.
Male	Burundi	Information Technology	Masters
Male	Zambia	Energy Studies	Masters

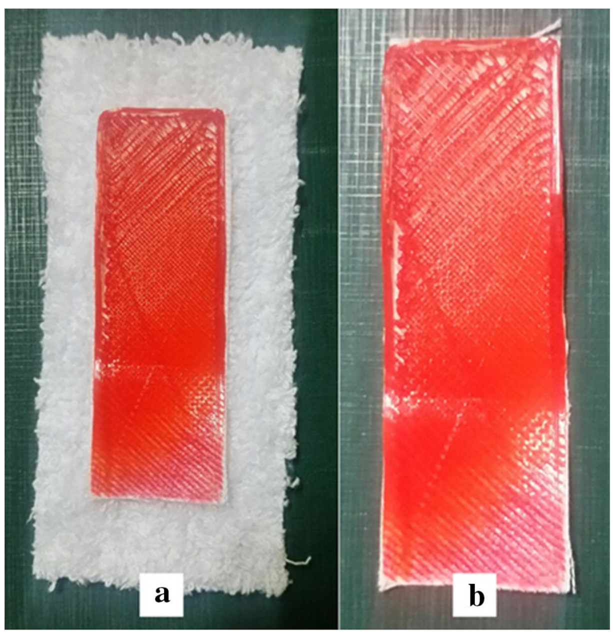

Fig. 2 PLA/cotton structure, **a** before cutting out the fabric parts around the composite and **b** prepared for loading on the tensile tester for adhesion tests

effect of the fabric properties on the adhesion of PLA polymer onto the fabric. In this study the most significant regression models were discussed.

Results and discussions

The properties of the studied fabric samples

The fifteen fabric samples were characterized in terms of fabric areal density, warp density, weft density, warp count (Tex), weft count (Tex), fibre type, and fabric thickness. A summary of the measured properties of the fabric samples is given in Table 3.

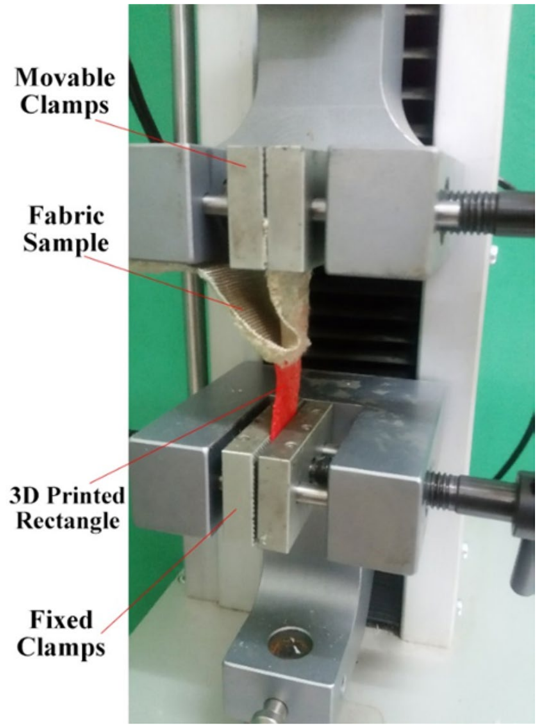

Fig. 3 Adhesion test on the Testometric Micro 500 model tensile tester

Table 3 Properties of the studied fabric samples

SN	Areal density (Gsm) X_a	Ends/inch X_b	Picks/inch X_c	Warp tex X_d	Weft tex X_e	Fabric thickness (mm) X_f	Fabric handle X_g	Fibre type X_h
1	210.4	46	52	73	17	0.04	3.2	Polyester
2	218.4	32	111	50	10	0.003	1.7	Polyester
3	227.6	69	80	19	59	0.002	2.7	Cotton
4	126.0	48	68	26	31	0.002	2.7	Cotton
5	146.0	60	68	28	32	0.002	2.2	Cotton
6	246.8	75	54	20	72	0.04	3.0	Polyester
7	137.6	50	64	33	30	0.002	3.3	Cotton
8	132.4	22	25	75	72	0.03	4.5	Cotton
9	224.8	49	55	63	59	0.004	2.7	Polyester/ cotton
10	332.4	17	15	288	276	0.1	5.0	Acrylic
11	451.2	20	20	277	280	0.09	5.0	Acrylic
12	536.0	28	77	336	29	0.18	4.3	Acrylic
13	128.8	59	22	25	71	0.08	1.0	Cotton
14	282.3	42	32	60	42	0.12	2.5	Acrylic
15	355.2	24	38	50	37	0.19	3.3	Cotton

Effect of areal density on adhesion force

A second order model was formulated to predict the effect of fabric areal density on adhesion force. Equation 1 gives the fitted regression model that described the relationship

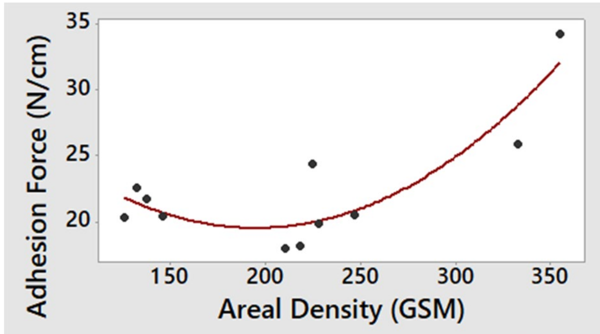

Fig. 4 Effect of areal density on adhesion force

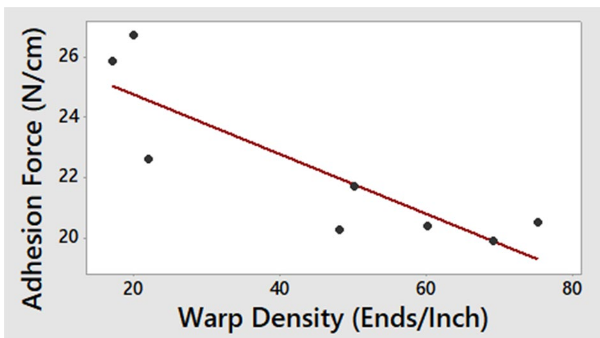

Fig. 5 Effect of ends/inch on adhesion force

between adhesion force (Y_A) and areal density (X_a).

$$Y_A = 38.13 - 0.1914X_a + 0.000491(X_a)^2 \quad (1)$$

The effect of areal density on adhesion force of PLA onto fabrics was also represented graphically in Fig. 4. The coefficient of determination (R^2) was 0.7997 and the P value of 0.002 was less than 0.05 hence the model was significant. The relationship between adhesion force and areal density was therefore statistically significant and can be used to study the effect of areal density on the adhesion force. From the regression equation, the higher the areal density the higher the adhesion between the fabric and the PLA polymer. This may be due to the large contact area for bonding.

Effect of ends/inch and picks/inch on adhesion force

The effects of ends/inch (X_b) and picks/inch (X_c) on adhesion exhibited similar trends (Figs. 5 and 6), where the adhesion force decreased as the ends and picks increased as shown in Eqs. 2 and 3.

$$Y_A = 26.74 - 0.09985X_b \quad (2)$$

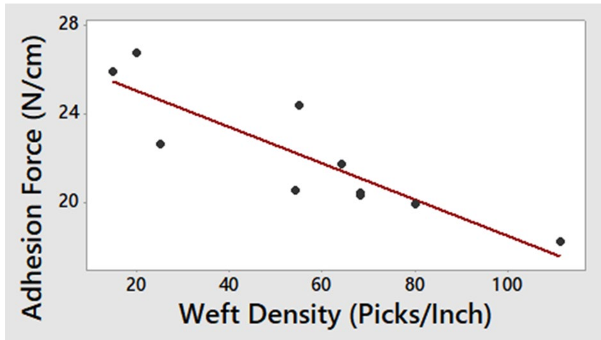

Fig. 6 Effect of picks/inch on adhesion force

$$Y_A = 26.65 - 0.08240X_c \quad (3)$$

The R^2 values for the ends/inch and picks/inch were 0.7303 and 0.7655 respectively.

The two regression models also reported negative correlation with adhesion force of −0.86, which indicated that ends/inch and picks/inch are negatively correlated to adhesion force. This could be due to the fact that as the warp and weft density increased the fabric cover factor reduced. An increase in cloth cover factor reduced fabric pores and there was less diffusion of the polymer into the fabric. This reduced adhesion forces. On the other hand, as the warp and weft density decreased there were more pores which allowed the polymer to diffuse into the fabric. In their study Sabantina et al. (2015) concluded that fabrics with a lower warp and weft density had higher adhesion forces as observed in the adhesion force of PLA and open textile structures. This could be because of the increased mechanical connection generated by the PLA surrounding the single yarns. The results were also in line with those from other studies that revealed that an increase in ends and picks per inch reduced the adhesion force between the polymer and the textile fabric (Rivera et al. 2017; Malengier et al. 2017).

Effect of warp and weft count on adhesion force

The effect of warp count (X_d) and weft count (X_e) measured using the Tex system, on adhesion force is given in Eqs. 4 and 5.

$$Y_A = 19.64 + 0.02373X_d \quad (4)$$

$$Y_A = 17.50 + 0.09087X_e \quad (5)$$

The effect of warp and weft count on adhesion force was also presented using graphs in Figs. 7 and 8. The value of R^2 for warp and weft count were 0.7284 and 0.765 respectively, with both properties recording a positive correlation of over 0.8 with adhesion force. This could be an indication that an increase of warp and weft count increased yarn diameter hence increasing the surface area where the polymer attached to the fabric. These results were similar to those deduced by Sanatgar et al. (2017).

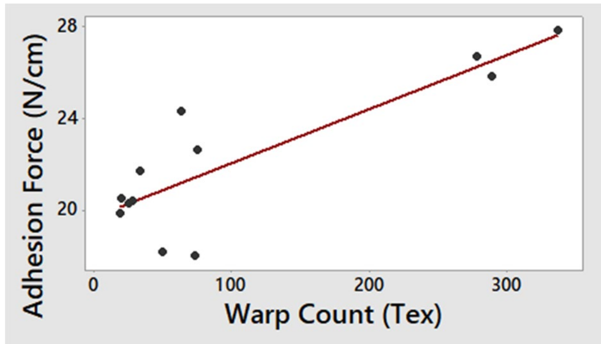

Fig. 7 Effect of warp count on adhesion force

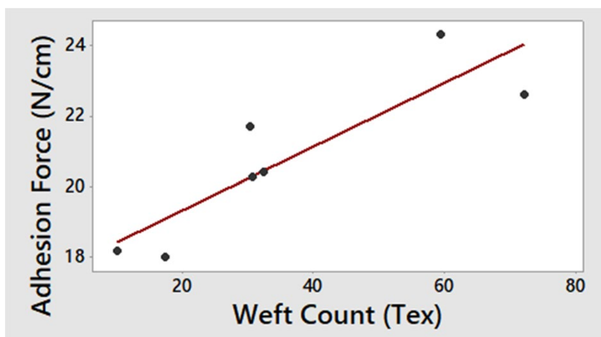

Fig. 8 Effect of weft count on adhesion force

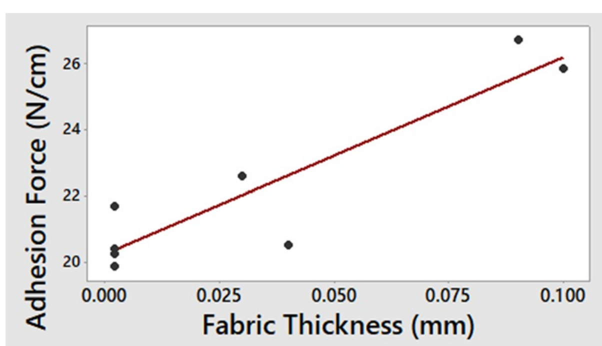

Fig. 9 Effect of fabric thickness on adhesion force

Effect of fabric thickness on adhesion force

A linear regression model was formulated to predict the effect of fabric thickness on adhesion force. Equation 6 describes the relationship between adhesion force (Y_A) and fabric thickness (X_f) as follows:

$$Y_A = 20.24 + 59.61X_f \tag{6}$$

The value of R^2 was 0.8349 and the P value of 0.002 was less than 0.05 therefore the relationship between adhesion force and fabric thickness was statistically significant. The positive correlation indicated in Fig. 9 showed that when fabric thickness increased, adhesion force also tended to increase. Several studies have shown that adhesion force increases with an increase in fabric thickness (Korger et al. 2016; Grimmelsmann et al. 2017; Martens and Ehrmann 2017). A thicker fabric allows for deeper penetration hence leading to an increase of adhesion force as the fabric thickness increases. This also increased the connections inside the textile structure offering sufficient areas for the polymer to penetrate inside the fabric.

Effect of fabric handle on adhesion force

A linear regression model was formulated to predict the effect of fabric handle on adhesion force. Equation 7 gives the linear model that described the relationship between adhesion force (Y_A) and fabric handle (X_g).

$$Y_A = 14.43 + 2.315X_g \tag{7}$$

The value of R^2 was 0.602 and the P value of 0.003 was less than 0.05 therefore the relationship between adhesion force and fabric handle was statistically significant. The positive correlation of 0.78 indicated that when fabric roughness increased, adhesion force also tended to increase as shown in Fig. 10. Rougher fabrics have higher adhesion force due to the free-standing fibres that allow for an increase in mechanical interlocking between the polymer and the fabric. Researchers have also shown in their studies that rougher fabrics have higher adhesion force to polymers which agrees with these results (Pei et al. 2015; Korger et al. 2016).

Effect of fibre type on adhesion force

The results of the fibre tests showed that the fabrics had the following fibre types: Polyester (PET), Cotton, Acrylic and Polyester/Cotton blend. The average adhesion force for each fibre type was calculated, recorded and represented graphically in Fig. 11. The graph showed that acrylic exhibited the highest adhesion force to PLA while

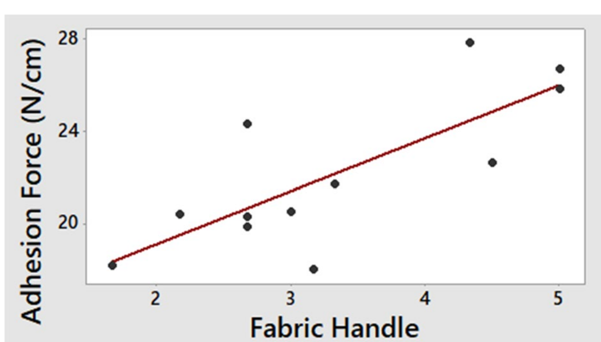

Fig. 10 Effect of fabric handle on adhesion force

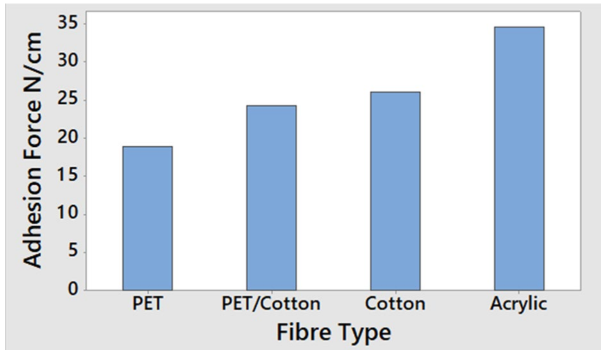

Fig. 11 Effect of fibre type on adhesion force

polyester had the lowest adhesion force to PLA. Adhesion force has been observed to be affected by fibre type. In previous studies there have been no tests on acrylic but the adhesion force of polymers to polyester has been shown to be less than that of polymers to cotton (Martens and Ehrmann 2017; Rivera et al. 2017).

Conclusions

PLA was deposited onto 15 woven fabric samples using 3D printing techniques. The polymer and the 3D printing parameters were kept constant to be able to determine the effect of the different fabric properties on adhesion force.

The tests showed that the different fabric properties did have an effect on adhesion force. Using regression models; fabric areal density, warp and weft count, fabric thickness and fabric roughness were positively correlated to adhesion force. As each of these properties increased, the adhesion force also increased. The opposite was true for the ends/inch and picks/inch which were negatively correlated to adhesion force. Considering the fibre types used to manufacture the fabrics (acrylic, cotton, polyester/cotton blend and polyester), tests showed that the acrylic based fabrics displayed the highest adhesion force to PLA with polyester based fabrics showing the lowest adhesion force.

Abbreviations

PLA: Polylactic Acid; 3D: three dimensional; ASTM: American Society for Testing and Materials; AATCC: American Association of Textile Chemists and Colourists; DIN: Deutsches Institut fur Normung (German Institute for Standardization); FDM: Fused Deposition Modelling; PET: Polyester.

Authors' contributions

All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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

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References

Awaja, F., Gilbert, M., Kelly, G., Fox, B., & Pigram, P. J. (2009). Adhesion of polymers. *Progress in Polymer Science, 34,* 948–968.
Canessa, E., Fonda, C., & Zennari, M. (2013). *Low-Cost 3D Printing for Science, Education and Sustainable Development.* Trieste: ICTP—The Abdus Salam International Centre for Theoretical Physics.
Christiyan, K. J., Chandrasekhar, U., & Venkateswarlu, K. (2016). A Study of the Influence of Process Parameters on the Mechanical Properties of 3D Printed ABS Composite. *IOP Conf. Series: Materials Science and Engineering, 114*, 012109. IOP Publishing. https://doi.org/10.1088/1757-899x/114/1/012109
Gibson, I., Rosen, D. W., & Stucker, B. (2010). *Additive Manufacturing Technologies*. New York: Springer.
Grimmelsmann, N., Kreuziger, M., Korger, M., Meissner, H., & Ehrmann, A. (2017). Adhesion of 3D printed material on textile substrates. *Rapid Prototyping Journal, 24*(1), 166–170.
Gurcum, B. H., Borklu, H. R., Sezer, K., & Eren, O. (2018). Implementing 3D printed structures as the newest textile form. *Journal of Fashion Technology & Textile Engineering.*. https://doi.org/10.4172/2329-9568.s4-019.
Holme, I. (1999). Adhesion to textile fibres and fabrics. *International Journal of Adhesion, 19,* 455–463.
Hu, J. (2008). *Fabric Testing*. Cambridge: Woodhead Publishing. **in Textiles**.
Kawabata, S., & Niwa, M. (1989). Fabric performance in clothing and clothing manufacture. *The Journal of the Textile Institute, 80*(1), 19–50.
Korger, M., Bergschneider, J., Lutz, M., Mahltig, B., Finsterbusch, K., & Rabe, M. (2016). Possible Applications of 3D Printing Technology on Textile Substrates. *IOP Conf. Series: Materials Science and Engineering, 141,* 012011. Cologne: IOP Publishing. https://doi.org/10.1088/1757-899x/141/1/012011
Malengier, B., Hertleer, C., Cardon, L., & Van Langenhove, L. (2017). 3D Printing on Textiles: Testing of Adhesion. *ITMC2017-International Conference on Intelligent Textiles and Mass Customisation.* https://doi.org/10.4172/2329-9568.s4-013
Martens, Y., & Ehrmann, A. (2017). Composites of 3D-Printed Polymers and Textile Fabrics. *IOP Conf. Series: Materials Science and Engineering. 225*, 012292. India: IOP Publishing. https://doi.org/10.1088/1757-899x/225/1/012292
Melnikova, R., Ehrmann, A., & Finsterbusch, K. (2014). 3D Printing of Textile-Based Structures by Fused Deposition Modelling (FDM) with Different Polymer Materials. *2014 IOP Conf. Series: Materials Science and Engineering. 62*, 012018. IOP Publishing. https://doi.org/10.1088/1757-899x/62/1/012018
Narula, A., Pastore, C. M., Schmelzersen, D., Basri, S. E., Schenk, J., & Shajoo, S. (2018). Effect of Knit and Print Parameters on Peel Strength of Hybrid 3-D Printed Textiles. *Journal of Textiles and Fibrous Materials*. 1, 2515221117749251.
Pei, E., Shen, J., & Watling, J. (2015). Direct 3D Printing of Polymers onto Textiles. *Rapid Prototyping Journal, 21*(5), 556–571.
Rivera, M. L., Moukperian, M., Ashbrook, D., Mankoff, J., & Hudson, S. E. (2017). Stretching the bounds of 3D printing with embedded textiles. *CHI 2017*, 497-551. Denver: ACM
Sabantina, L., Kinzel, F., Ehrmann, A., & Finsterbusch, K. (2015). Combining 3D printed forms with textile structures—Mechanical and geometrical properties of multi-material systems. *IOP Conf. Series.: Materials Science and Engineering, 87,* 012005. Beijing: IOP Publishing. https://doi.org/10.1088/1757-899x/87/1/012005
Sanatgar, R. H., Campaigne, C., & Nierstrasz, V. (2017). Investigation of the Adhesion Properties of 3D Printing of Polymers and Nanocomposites on Textiles: effect of FDM Printing Process Parameters. *Applied Surface Science, 403,* 551–563.
Tomovska, E., Jordera, S., & Zafirova, K. (2016). Contribution of Texture to Aesthetic Properties. *Book of Proceedings of the 7th International Conference*, 225-230. Tirana.
Tuigong, D. R., & Xin, D. (2005). The use of fabric surface and mechanical properties to predict fabric hand stiffness. *Research Journal of Textile and Apparel, 9*(2), 39–46.