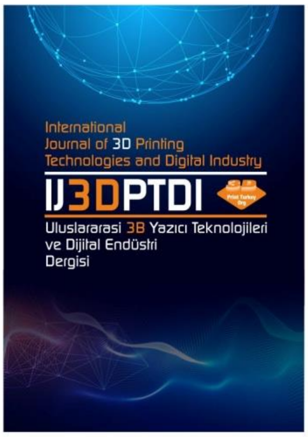

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FUNCTIONALIZATION OF WOVEN FABRICS BY 3D PRINTED STRUCTURES IN FUSED FILAMENT FABRICATION (FFF): EFFECTS OF INFILL PATTERNS ON TENSILE STRENGTH

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ABSTRACT

Three-dimensional (3D) printing has an increasing popularity in recent years with easy availability and the wide range of applications in many fields. While producing textile-like structures with 3D technology is still a challenging problem, combining textiles with 3D printed structures enables the manufacture of many alternative structures in the field of textile applications. This study investigates the effect of 3D parts with different infill patterns printed onto the cotton woven fabric for tensile strength. For this purpose, 3D parts with concentric, grid and triangle infill patterns were printed onto plain and twill woven fabrics with polylactic acid (PLA) filaments in the Fused Filament Fabrication technique. Adhesion between fabric and 3D parts and tensile strengths of produced structures were measured to assess the effectiveness of 3D printing. Results showed that greater adhesion between 3D parts and fabrics were obtained for plain-woven fabrics. The infill patterns were also found effective for the tensile strength performance.

Keywords: 3D Printing, Woven Fabrics, Additive Manufacturing, FFF.

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1. INTRODUCTION

Additive manufacturing (AM), in the well-known name of three-dimensional (3D) printing, relies on the layer-by-layer production technique. The flexibility in the production, enables to produce of complex structures and ease of use increased the popularity of AM in many fields. After the first introduction of AM in the 1970s [1], many different techniques were developed and the American Society of Testing and Materials (ASTM) [2], reported in [3], are grouped available AM processes into 7 categories as VAT photopolymerization, material jetting, binder jetting, powder bed fusion, sheet lamination, direct energy deposition, material extrusion. The meet of AM with the textile industry is not totally new but has an increasing popularity in recent years [1,4]. Utilization of the flexible and simple production technique of AM with textile structures, reducing the waste production and sustainability in 3D printing technology lead to the development of many new products from the fashion industry to technical textiles [1,3,4]. The main types of 3D printed technologies that are used in the textile context are grouped as fused deposition modeling (FDM) under the material extrusion category, selective laser sintering (SLS) under the powder bed fusion category, and stereolithography (SLA) under the VAT polymerization category [3,4]. Between these technologies, FDM, also known as Fused Filament Fabrication (FFF), is the most widely used technology and produces 3D printed structures as deposition of the heated thermoplastic polymer through the nozzle that moves horizontally to heated printing bed [1, 3, 5]. In the other 3D printing technology with the textile application, SLA, is used for fabric-like stiffness structures and comprises components as photopolymer resin tank, the moving platform into the resin tank, the UV light, and computer-controlled laser [1,4]. 3D parts are produced in SLA technology by evaporating resin with UV light for each layer. SLS technology is used for textile-like structures and [1] powder form materials are bonded together with the heat in this method [4].

In the literature, the use of 3D printer technology in the textile industry has been the scope of many researches such as development of multimaterial textiles, the production of fabric-like structures, the development of medical and smart textile structures [6,7,8]. Ahrendt et al. [8], converted textile structures to orthopadeic devices with AM (Figure 1a). Spahiu et al. [9], produced a garment with 3D printers (Figure 1b). Korger et al. [10], showed to produce flexible 3D structures onto the fabrics with FDM for functional garment and technical textiles (Figure 1c, Figure 1d). Melnikova et al. [11] manufactured fabric like structures in SLS and FDM 3D printing technologies and compared the results of both produced parts. Grothe et al. [12], printed low profile cylinder structurues on different textile substrates with SLA technology to combine both features which may use for microelectromechanical systems. Muthukumurana et al. [13], showed different applications of 3D structures onto the fabrics. Rivera et al. [14], also studied different application of combining textile and 3D printed structures.

Figure 1. Illustration the 3D printing technology in textile context [8,9,10].

In the development of multi-component structures by combining textile and 3D parts in FFF technology, molten polymers are deposited onto the textile surface and adhesion between both structures is a critical factor that affects the usability and properties of end products. The adhesion between the 3D part and the fabric as well as the effective parameters on the adhesion have also been the subjects of many studies. Malengier et al. [15], defined three different methods to measure adhesion between 3D structures and fabrics as perpendicular tensile, shear and peel tests. They also printed 3D structures with polylactic acid (PLA) filament on different woven fabrics and tested the adhesion. They concluded that fabric structures and weave patterns are effective on adhesion. Narula et al. [16], studied the knit fabric structure on the adhesion 3D printed textiles in terms of fabric width, the ratio of the fabric width to print width, and fabric construction. Results showed that increasing fabric width resulted in greater peel strength. On the contrary, increasing print width decreases the peel strength. Mpofu et al. [17], studied the relation between fabric properties and adhesion of 3D structures and concluded that fabric areal density, fabric thickness, warp, and weft yarn counts show a positive correlation with PLA filament adhesion onto woven fabrics. Korger et al. [18] also pointed out that fabric properties are effective on the adhesion of 3D structures and stated that rougher fabric surfaces or porous fabric structures display better adhesion of 3D structures. There are also some studies that aimed to improve adhesion between the fabric and 3D structures by changing fabric surface properties with pre-treatment [19,20]. Print settings such as nozzle and bed temperatures also affect the adhesion [21]. There are also some studies that use different polymers for combining 3D printed parts with textile structures. Goncu-Berk et al. [3], printed 3D structures using flexible thermoplastic polyurethane (TPU), thermoplastic elastomer, and PLA on polyester and polyamide knitted fabrics and on laminated neoprene textiles. The study concluded that TPU filament is the most compatible with all fabrics and the greatest adhesion was observed for laminated neoprene fabrics. Pei et al. [22], studied the performance of 3D parts printed on different structures and raw materials of fabrics for three different filaments. In the study, acrylonitrile butadiene styrene (ABS), PLA, and nylon filaments were used. Results indicated that PLA filaments displayed overall better results comparing to the ABS and nylon filaments.

In the related literature summary, it is determined that the use of AM in the textile industry has become increasingly popular in recent years. Although the production of garments with a 3D printer is seen as a challenging problem due to the drawbacks such as poor wearability or cover factor of 3D structures [1,3,6,10], combining textiles with 3D structures can be used in the development of composite materials with novel properties for many different applications such as fashion, technical textiles, agricultural textiles, and orthoses [8,9,10,13,23]. Despite the increasing number of studies examining the printing of 3D parts onto textiles in the literature, most of the studies investigate the parameters that affect the adhesion between components of end products, limited studies that focus on mechanical properties are available. Therefore this study aimed to investigate the effect of 3D printing on tensile strength of the woven fabrics which can be counted as a composite material. For this purpose, 3D parts were printed onto the plain and twill woven fabrics in Fused Filament Fabrication (FFF) technology. Besides, in order to investigate the effect of infill patterns, three different infill patterns as concentric, grid, and triangle were selected for the production of 3D parts. Polylactic acid (PLA) filament was used for the production of 3D parts which is the most widely used filament in 3D printing technology with a wide application range, applicability, and sustainability in different techniques [24]. Tensile strength of fabrics, pure 3D parts, 3D parts printed onto fabrics were measured. Besides, adhesion between both structures was also measured.

2. MATERIALS AND METHODS

2.1. Materials

In this study, plain and twill woven fabrics were used and 3D parts were printed on the warp directions. Thickness, weight, linear density of warp yarns and roughness of the fabrics are given in Table 1. In addition, fabric images acquired with a stereomicroscope and processed with MATLAB software are presented in Figure 2. Figure 2a, 2b and 2c show the original, grayscale and binary images for plain-woven fabrics, respectively. A calculated threshold value (0.49) was used for converting grayscale images to binary images and the pixel value greater than the threshold value is converted to the black pixel while pixel value lower than the threshold value is converted to the white pixels. In the binary image of a plain-woven fabric, white pixels represent the pores and black pixels represent the fabric (Figure 2c). Figures 2d, 2e, and 2f show the original, grayscale and binary images for twill-woven fabrics. There is no pore in the structure of the twill-woven fabric. However, twill patterns on the structure cause depth change on the fabric surfaces and cause lower threshold values in the grayscale images. For this reason, the threshold value was used as 0.50 rather than the calculated threshold value (0.25) while converting grayscale images to binary images (Figure 2f). Mitutoyo SJ 301 surface roughness tester was used for roughness properties of fabrics and mean values of the peaks from fabric surfaces were used as roughness parameters as reported [26]. PLA filaments (ABG brand from TURKEY) in 1.75 mm diameter were used for 3D part production.

Table 1. Fabric properties.

Properties	Plain Woven	Twill Woven
Thickness (mm)	0.31	0.29
Weight (g/m^2)	179.96	123.30
Roughness	28.09	17.61
Warp density (yarns/cm)	34	90
Warp yarn count (Tex)	18.5	11.2

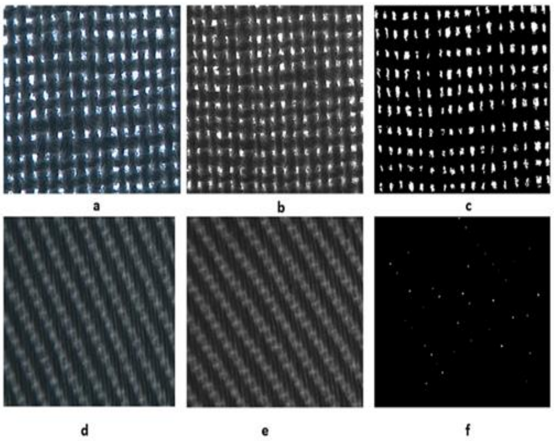

Figure 2. Plain and twill woven fabric images.

2.2. Methods

2.2.1 Production of 3D part

All 3D parts printed onto the fabrics were produced with a low-cost model of FFF 3D printer (Ender 3 V2). In the FFF technique, the production process starts with designing part in computer-aided design (CAD) software. After designing the part, the next step, named creating G-code, involves slicing the part into layers and defining each layer in X and Y dimensions. In the last step, created G-code is transferred to the 3D printer for production, and molten polymers through the heated nozzle are deposited onto the printing bed [7,11,12]. In the study, 3D parts for the tensile strength tests were designed in SolidWorks software as 150 mm length, 25 mm width, and 3 mm thickness. G-code for each part was obtained with CURA software and each part contains 15 printing layers with 0.2 mm thickness. Three different infill patterns were selected as concentric, grid, and triangles in CURA software (Figure 3) and in order to investigate the effects of infill patterns on the tensile strength each part contains 3 bottoms, 3 top and 9 infill layers. For printing 3D parts onto the fabrics, fabrics were fixed on the print bed as illustrated in Figure 4 and 3D parts were printed on warp direction. Z-offset, the distance between the heated nozzle and the printing bed, was set after fixing for each of the fabrics. Detailed print settings were given in Table 2.

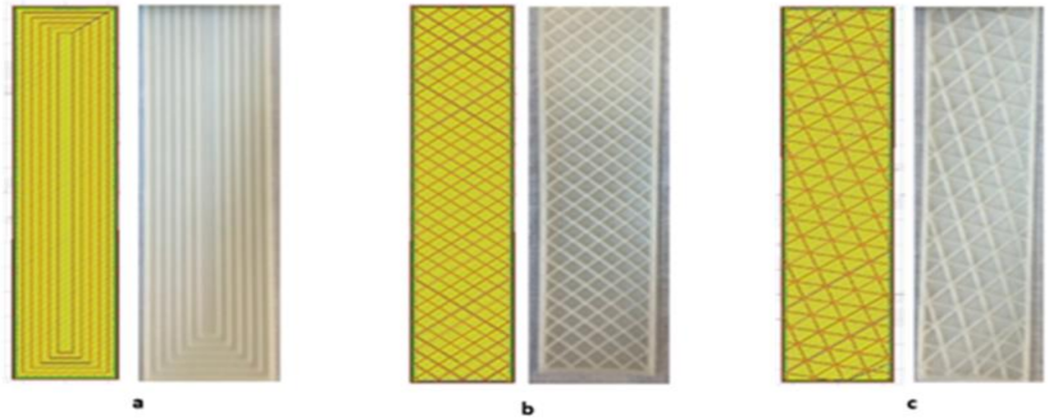

Figure 3. Illustration of infill patterns a) concentric b) grid c) triangle.

Table 2. 3D printer settings.

Properties	Unit	Value
Print Speed	*mm/s*	50
Nozzle Heat	*˚C*	200
Print Bed Heat	*˚C*	50
Layer Thickness	*mm*	0.2
Polymer Flow	*%*	100
Extrusion Width	*mm*	0.4
Infill Density	*%*	20

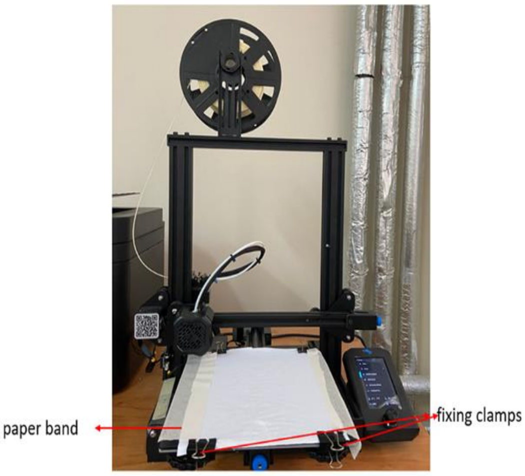

Figure 4. Illustration of fabric fixage on the printing bed.

2.2.2 Tensile strength and adhesion test

The tensile strength test was carried out by clamping 25 mm sections of the sample with a total length of 150 mm to the upper and lower jaws. (Figure 5a). The tensile strength test was performed according to the ASTM D 5034 standard. The gauge length was 100 mm and the test speed was 100 mm/min. In order to compare the effects of printed 3D structures on the tensile strength results, plain woven fabrics and pure 3D structures were tested in the same procedure. Adhesion between 3D structures and fabrics was measured with the shear test that was developed based on EN 1373 standard and described in [15]. According to the shear test 60 mm length, 50 mm width, and 4 mm thickness of 3D parts are printed onto the fabrics. However, during the performing of the shear test, fabric breakage was observed before the separation due to the greater tensile behaviours of 3D parts than plain woven fabrics. For this reason, the dimensions of 3D parts were changed to 60 mm length, 25 mm width, and 0.6 mm thickness, and shear tests were performed as described in [15] (Figure 5b). Both of the tests were performed by using Instron 4411 tensile strength tester.

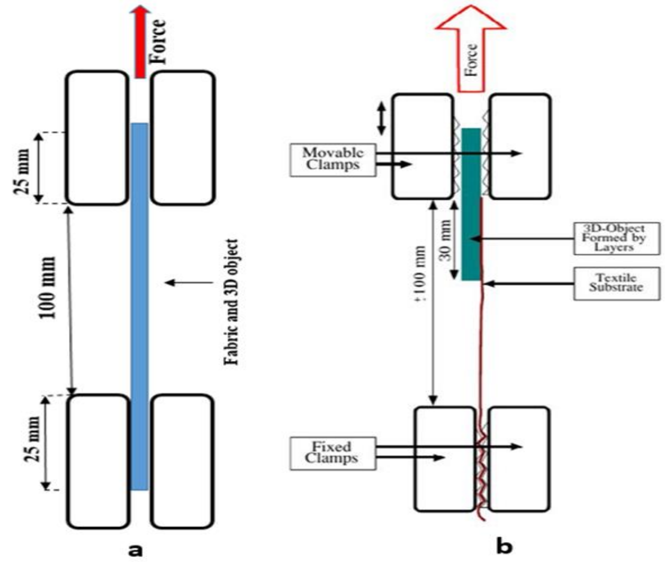

Figure 5. a) Tensile strength test b) shear test for the adhesion [15].

3. RESULTS AND DISCUSSIONS

The adhesion test results for 3D parts printed onto the twill and plain woven fabrics with the 95% confidence interval are given in Figure 6. It is seen from Figure 6 that, greater adhesion results were obtained for the plain-woven fabrics than twill-woven fabrics. In the literature, it was pointed out that fabric properties affect the adhesion between the 3D parts and the fabric and, fabric with greater porosity, rougher structures, and greater thickness provides better adhesion of 3D structures [3, 11, 18, 22, 23]. Among the selected fabrics, plain woven fabrics have a more porous and rougher structure and provide a form-locking structure by keeping the molten polymer in the fabric [24]. Thus, greater adhesion forces were obtained for plain woven fabrics.

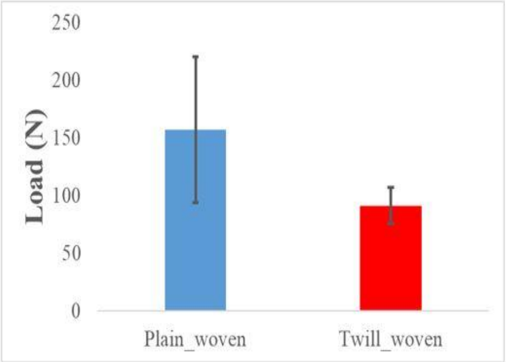

Figure 6. Adhesion test results.

Figure 7 shows the tensile strength test results for plain fabrics, pure 3D parts, and 3D parts printed onto the fabric. It is seen from figure 7 that, plain-woven fabric has the lowest tensile strength value, followed by pure 3D structures, and the twill-woven fabric has the greatest tensile strength value. It is also seen from figure 7 that infill patterns are effective in mechanical properties of the pure 3D parts [25,27,28]. Concentric infill patterns display greater tensile strength values followed by triangle and grid infill patterns and differences between tensile strength values are statistically significant at 95% confidence level (α_e<0.05). It could be related to the same direction of concentric infill patterns with the moving clamp during the tensile strength test.

Comparing the tensile strength test results showed that printing 3D structures onto the fabrics increase the tensile strength values for plain woven fabrics. The tensile strength of the fabrics with 3D printed structures differs for different infill patterns of 3D parts. The greatest difference in the tensile strength value was observed for grid infill structures 3D part printed onto the plain fabric, approximately 20% greater than pure 3D part with grid infill patterns. For the concentric infill structures, 5% of improvement was obtained for tensile strength value than the pure 3D part. On the other hand, for the 3D structures that were printed onto the twill-woven fabrics, lower tensile strength results were obtained than pure 3D structures and also twill-woven fabrics.

Lower adhesion between twill-woven fabrics and 3D parts and the non-porous surface that prevents the molten polymer from penetrating into the fabric structure may cause disorientation of initial layers and lower the tensile strength resulting in final structure [21].

Besides the adhesion between fabrics and 3D parts, tensile strength and elongation behaviours of individual parts may explain the different performances of the end product. In Figure 8a, load (N) and elongation values for plain-woven fabrics, pure 3D parts for different infill patterns, and 3D parts printed onto the fabrics were presented. It is seen from figure 8a that, plain-woven fabric has lower elongation and tensile strength values than pure 3D parts. Combining both structures resulted in greater tensile strength results and could be assumed to display novel properties as a composite material. On the other hand, as it is shown in Figure 8b, twill-woven fabric has the greatest tensile strength and elongation values, and printing 3D parts onto the twill-woven fabrics did not positively improve the properties.

Different behaviours of the final structures produced by printing 3D parts onto the fabric were also observed during the tensile strength test and illustrated in Figure 9. Figure 9a shows the tensile strength test performed in Instron tensile strength tester. 3D parts printed onto the plain-woven fabrics were shown in Figure 9b for the concentric, triangle, and grid infill patterns, from left to right. 3D printed parts printed onto the twill-woven fabrics were also shown in Figure 9c for the concentric, triangle, and grid infill patterns, respectively. While performing the tensile strength test, it was observed that concentric and grid infill structures of 3D parts printed onto the plain-woven fabrics were broken simultaneously with the fabrics. In other samples, only 3D parts were broken (Figure 9b, 9c). Although combining 3D parts and fabric was introduced as a new method for the production of composite or multi-material structures, it is important to optimize production parameters or to choose the material with similar elongation behaviours to produce final structures having better properties [10,11,29].

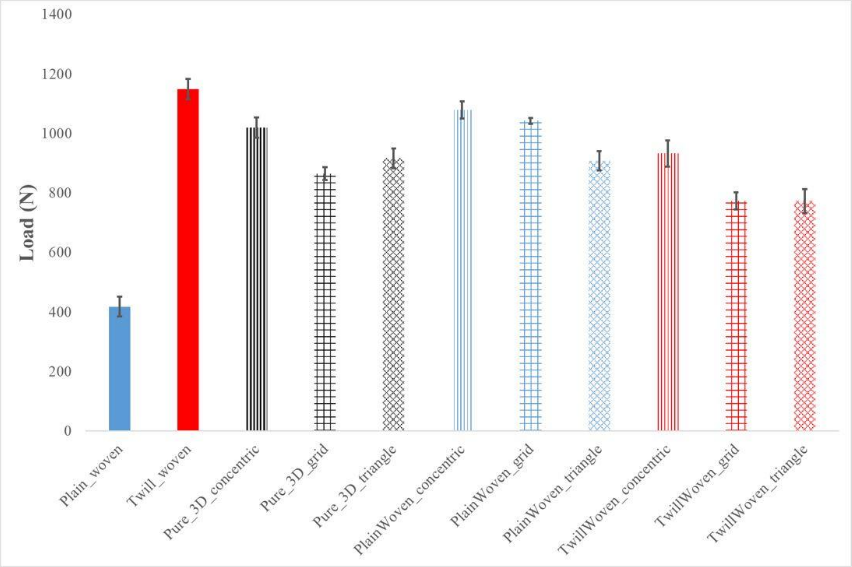

Figure 7. Tensile strength of the pure 3D parts and 3D parts printed onto the fabrics.

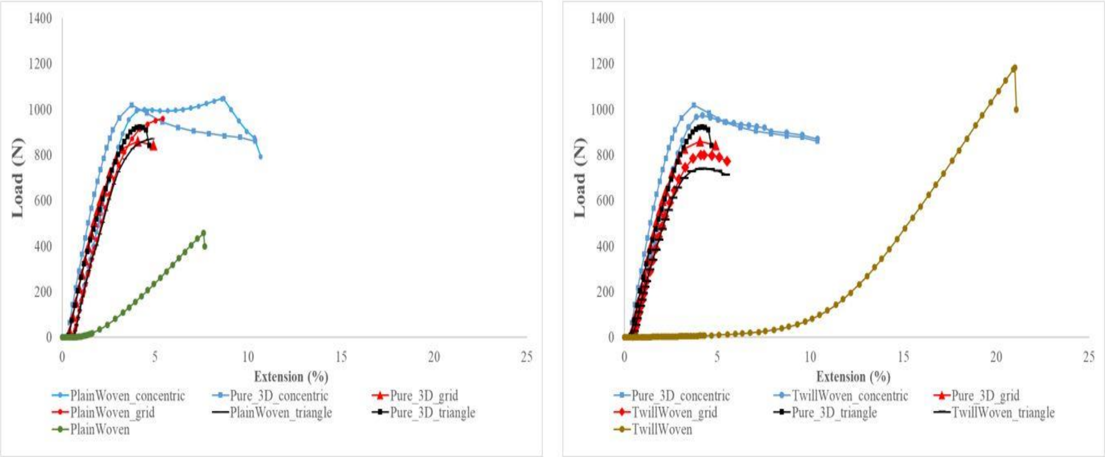

Figure 8. Load and elongation values a) plain-woven fabrics, pure 3D parts, 3D parts printed onto the plain-woven fabrics b) twill-woven fabrics, pure 3D parts, 3D parts printed onto the twill-woven fabrics.

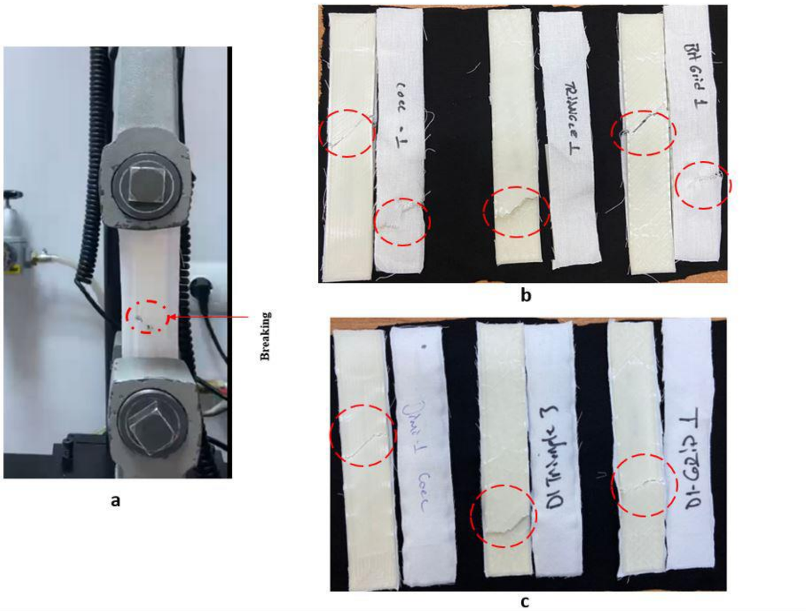

Figure 9. a) Tensile strength test, b) 3D parts printed onto the plain-woven fabrics after tensile strength test c) 3D parts printed onto the twill-woven fabrics after tensile strength test.

4. CONCLUSION

Additive manufacturing, known as 3D printing technologies, has increasing popularity utilizing the advantages such as producing complex geometry, a wide range of applications, and customized production. Producing 3D parts onto the textile subtracts also has shown a dramatic increase for the application field from the fashion industry to technical textiles. In this study, tensile strength was measured for 3D parts with different infilled patterns printed onto the woven fabrics. Two different woven fabrics and three different infill patterns for 3D parts were selected for the production. Adhesion between the fabrics and 3D parts, tensile strength for fabrics, pure 3D parts, and 3D parts printed onto the fabrics were tested. Results showed that greater adhesion was obtained for the plain-woven fabrics with greater porosity and rougher surfaces. For the tensile strength values, it was found that the infill patterns of the 3D parts are effective. Comparing the tensile strength values of 3D parts printed onto the fabrics also showed that, mechanical characteristics of fabrics are important for the properties of the final structure. Combining plain-woven fabrics with lower tensile strength values than pure 3D parts resulted in greater tensile strength values than individual structures and could be counted as a composite material with novel properties. Using elastic polymers, optimizing printing parameters, and increasing the adhesion between fabrics and 3D parts may lead produce structures with novel characteristics for specific purposes.

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