THE MANUFACTURING TECHNOLOGY OF 3D PRINTED MODELS ON VARIOUS MATERIALS USING THE FUSED DEPOSITION MODELING PROCESS

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The joining of thermoplastic and textile materials is gaining more and more importance today. New combinations of materials and new structures that change fashion trends are obtained. The paper presents the technology of joining thermoplastic materials with different fabrics. For example, the realization of a button on textiles and the description of 3D printing were taken. This pioneering venture describes the technology, fabric model-making process, and materials melting bond analysis. Unfortunately, available thermoplastic materials have many limitations regarding durability, aging, and service life according to the defined requirements. The idea of this paper is the application of 3D printing in the fashion industry as an emerging topic for discussion. The experimental part of this investigation will provide a new guideline for designers of PLA/ABS printing elements on textile substrates and possibility for application in modern textile design.

Keywords: additive technology, thermoplastic polymer, textile, 3D printing, model

Introduction

The accumulation of worn and used textiles today represents a significant environmental threat. In this direction, the textile industry is seen as a major polluter of the environment. Reducing textile waste during the production process and choosing ecological, biodegradable, and recyclable materials in the new era of technological development is becoming an imperative. Today, the development of the textile industry is focused on new technologies and materials to save natural resources.

In the textile industry, 3D printing develops prototypes and various inserts/details for high fashion. Combining textiles with 3D printing tends to obtain new structures that should improve mechanical characteristics, reliability, and durability to exploitation requirements. Unfortunately, in most cases, 3D fashions details on clothing generally result in stiff clothing.

The following 3D printing technologies are used in the textile industry: 1) SLA‒(Stereolithography), 2) SLS‒(Selective Laser Sintering), and 3) FDM‒(Fused Deposition Modeling) [1]. There are different types of 3D printers in use. Some printers can produce a complete garment or can print individual parts. Various methods later join those parts into one whole [2]. These printers use mostly thermoplastic polymer materials. This way of printing (on fabric) enables the creation of various structures with a specific function (for example: the installation of sensors and miniature electronics) [3].

The main obstacles to the realized models include printing time, the price of the model, as well as the mechanical properties (stiffness) of the plastic. The advantages are reflected in the direct printing of the material, the garment's lifespan is extended, and the product design is improved [4]. In the example of the realization of footwear [5], athletic footwear, and sports equipment [6], bags, jewelry [7], and printed accessories have found their complete application. For the successful application of a 3D printer, it is necessary to know the properties of the thermoplastic material and set the heating and melting temperature of the material, that is, set the ideal printing speed of the molten material on the textile.

This study presents the development of the technological process of making 3D-printed elements from thermoplastic materials. During printing, a big problem is the printed print's inhomogeneity, the surface's large roughness due to the different widths of the melted print lines between the layers and at the ends of the printed element (model). The present problem is caused by the roughness of the printed element and the deviation from the given dimensions of the print. The inhomogeneity of the printed elements due to the air gaps between the print lines leads to deviations in the material's mechanical properties.

The goal of this paper is to present a methodology for the formation of a connection between textiles and thermoplastic material. FDM is the process of directly applying

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the material to the textile with the help of a 3D printer. The method of forming the joint and preparing the parameters is important from the aspect of the quality of adhesion of the plastic material to the contact surface of another material. The set task, on the button example, is to examine the direct bonding of layers of polymer material to various fabrics using the FDM process.

Material and methods

CAD model

Realization of 3D CAD models is done using one of the CAD software packages. Here is an example of drawing a button and later its realization on a 3D printer. Also, using a CAD software package makes it possible to make changes before the model goes to print, see Figure 1.

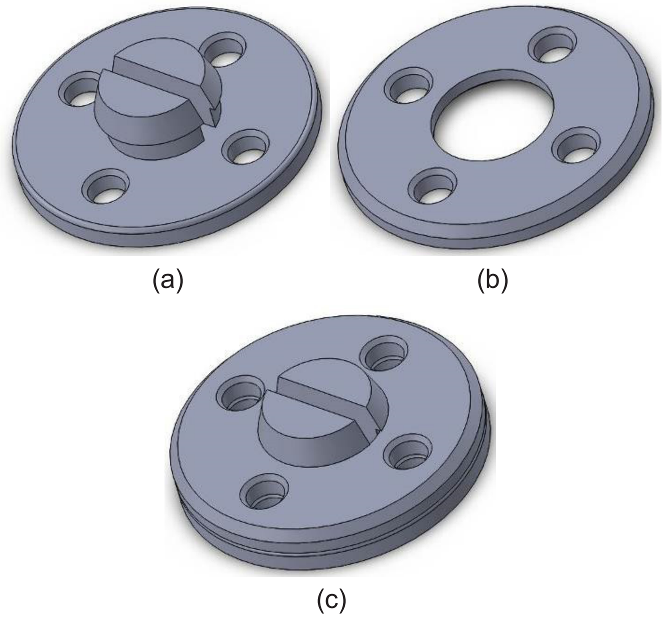


Figure 1. The CAD model layout: a) base, b) cover, c) assembly

The virtual into a physical model transformation

The process of rapid model creation using 3D printing takes place in the following steps [8]:

- A 3D CAD model is drawn on one of the CAD software packages;
- The CAD model is translated as an STL file into the specialized Prusa Slicer program, which adjusts the system's operational parameters. Prusa Slicer mostly manipulates *3mf, *stl, and *obj files;
- With the help of the Prusa Slicer program, based on the STL file, the G code in the *gcod extension is generated, which the 3D printer recognizes, and thus the model is ready for realization. Most conventional 3D printers use a layer-by-layer printing technique;
- In the end, the model is realized and subsequently processed and cleaned.

The 3D printing technology

Using the FDM process (Fused Deposition Modeling), a thermoplastic filament in a wire is melted through an extruder nozzle and applied in layers to the work surface. Combining FDM printing (or 3D printing) of thermoplastic polymers with textiles creates new possibilities in the production process and realizing new products. Printing on plastic and glass network structures is attractive because it creates a new reinforced structure or "functional textile" [9].

3D printing on textile substrates is also considered a new type of functional textile that offers new possibilities in realizing individual or customized products with freedom of form and design. In addition to the production of buttons on textiles and various accessories, there is integration and the appearance of local reinforcement on various clothing items [10].

The 3D printer Original Prusa i3 MK3S+ was used to make the button. The printer has a working volume of 250×210×210 mm, with a minimum layer print resolution of 0.05 - 0.30 mm and a print speed of 10-100 mm/s, see Figure 2.

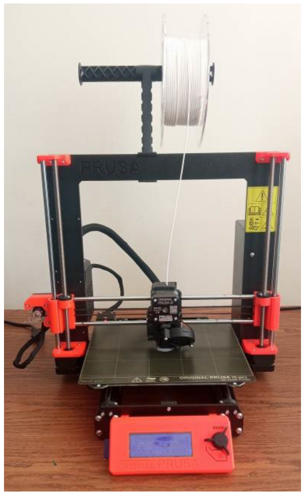


Figure 2. Original Prusa i3 MK3S+

White PLA filament with a diameter of 1.75 mm (manufacturer Devil Design) was used to make the model. The first distance between the nozzle and the heat plate was adjusted for a thickness of 0.15 mm, but the other layers were also printed with the same thickness. The realized button model on the Prusa Slicer interface is given in Figure 3. After the model analysis and the nozzle movement trajectory, the STL file is transformed into a recognizable *gcod for the operation of the 3D printer.

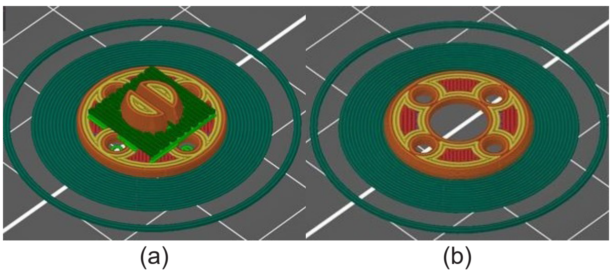


Figure 3. The nozzle virtual movement: a) base, b) cover

In model printing, the following parameters are considered: infill density, number of wall line contours, infill orientation, raster angle, and number of shells. Selected printing parameters are shown in Table 1.

Table 1. 3D printing parameters

Parameter	Value
Layer Height	0.15
Wall Line Contour	2
Printing Temperature	210°C
Build Plate Temperature	60°C
Printing Speed	50 mm/s
Infill Density	100%
Infill Orientation	-45°/+45°

Various techniques were used to support the combination of textiles with 3D-printed models. Therefore, an attempt was made to provide further guidelines for improving printing technology on textiles. For printing on textiles to reach the required performance, ensuring a good connection between the thermoplastic polymer and the substrate is necessary. Printing parameters, polymer characteristics, and textile types greatly influence the adhesive force of the plastic on the material. PLA shows the best bonding/gluing characteristics at high printing temperatures and with as small a diameter as the potential of the molten layer.

Button manufacturing process

Combining 3D printed models with fabric and other materials is an innovative process that offers many possibilities. The example of a button shows the methodology and technology of 3D printing on several types of textile materials and plastic structures (silk, viscose, polyester, and polyvinyl mesh). The process of printing the model on the mentioned materials was carried out with the help of:

- 3D printer, model: Original Prusa i3 MK3S+,
- Device for laser cutting and engraving, model: FL-350i
- An additional tools and accessories.

Filament and fabric

Different polymer materials are used in 3D printing technology: thermoplastic (PLA, ABS, TPU, PVA, PP, PVC), elastomers (PA, PU), and epoxy resins [11]. Only a couple that are often in use will be mentioned.

PLA (polylactic acid) filament was used in the paper. PLA is a thermoplastic biodegradable material that has good strength [12]. Unfortunately, it emits more CO_2 when in use [7]. When it hardens, it is not flexible, hydrophobic, and not resistant to high temperatures [13]. The technology of printing PLA over fabric is applying molten material and its adhesion to the fabric. However, to achieve better structural and mechanical properties of printed samples, PLA is of great importance in developing prototiping elements used for research purposes and in industry.

ABS (Acrylonitrile Butadiene Styrene) is a petroleum derivative and a toxic material [14]. It emits unpleasant fumes during printing that are dangerous for the environment [15]. The extruder's temperature ranges from 220-240 °C, while the temperature of the heat plate is around 100 °C. The ABS material has excellent mechanical properties (the styrene component provides strength; butadiene component provides impact resistance) and resistance to elevated temperatures and external influences (acrylonitrile component) [16].

TPU (Thermoplastic Polyurethane) is ideal for creating complex and flexible grid structures. TPU gives good mechanical characteristics on printed parts [17]. In general, TPU is a flexible elastomer that can behave like rubber; that is, it can bend and compress. TPU has high strength, high elongation at break, and retains its elasticity even at low temperatures [18].

The following textile materials as substrates for 3D printing were selected: silk, viscose, polyamide, and polyvinyl plastic mesh. The selected fabrics were cut in a square, with dimensions of 10×10 cm^2, see Figure 4. These dimensions were taken due to quick material manipulation and possible reaction if there were unwanted effects of the fabric burning. Next, we started making the net on the textile.

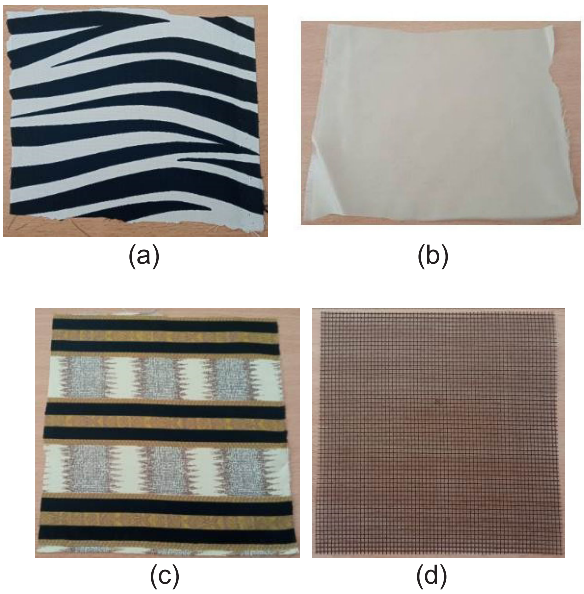
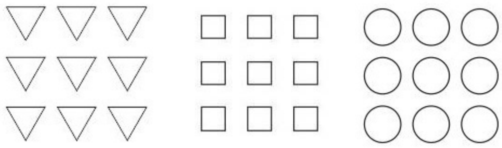


Figure 4. Fabric preparation for 3D printing: a) silk, b) viscose, c) polyamide, d) polyvinyl mesh

Result and discusion

Network structures realization on fabric

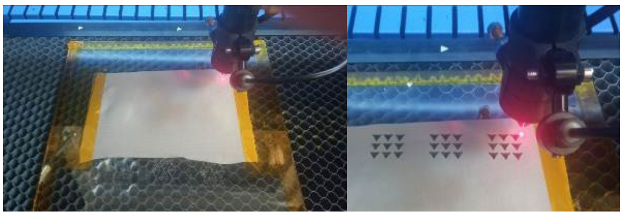
The CAD software was used to draw network structures of different geometric shapes, while the *dwg output file was later used to cut fabrics according to selected geometries. The layout of network structures, a 3×3 matrix with triangles, squares, and circles, is shown in Figure 5.



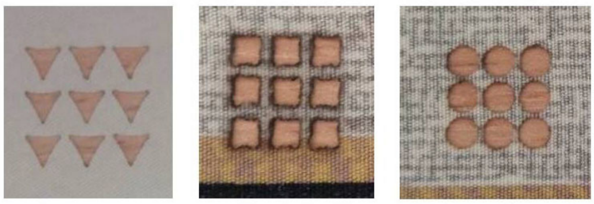
(a) (b) (c)

Figure 5. Display of 3x3 matrix structure: a) triangle, b) square, c) circle

The laser engraving and cutting machine (model-FL-350, Slovenia) with a working surface of 300×500 mm and a laser power of 60 W, was used to produce the mentioned nets on the fabric. In realizing the geometries, the following laser parameters were used: a) speed of movement of the laser head: 90 mm/s, b) laser power: 15 W, and c) laser frequency: 500 ppi. Figure 6 shows the fabric preparation and engraving of various geometric matrices on the FL-350 machine.



(a) (b)



(c)

Figure 6. Realization of 3x3 matrices: a) preparation, b) laser engraving, c) fabric appearance

Printing and joining

The FDM process (or 3D printing process) involves melting thermoplastic material through a heated nozzle. The filament is fed to the extruder head (1) and transported to the guide (2) via a pair of gears driven by a stepper motor (3). The filament passes through the heater/liquifier (4) and exits in a molten state through the nozzle (5) in the form of a string (6). The molten material touches the active (heated) plate (7) and sticks to it. Later, the material is cooled and solidified as a finished model on build platform (8). Figure 7 shows the key elements that participate in the realization of the model [19].

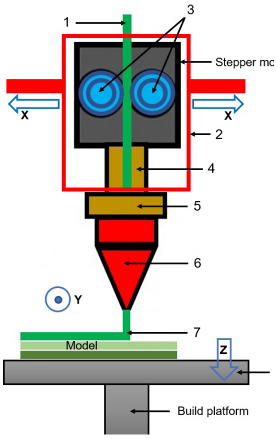


Figure 7. Extruder elements

Printing time depends on model size and technology. Smaller models take a few minutes, but larger specimens take several hours [20]. The formed first layer in the XY plane allows the extruder to be raised by the layer's height along the Z-axis. The process is repeated until the specimen is printed. According to the described procedure, a button specimen was realized, see Figure 8.

(a) (b) (c)

Figure 8. Standard button model realization: a) base, b) cover, c) assembly

After realizing the standard button on the 3D printer, the button manufacturing was started directly on the fabric. The first step involves printing one (or more) layers of molten filament on the printer's heating plate, see Figure 10. After the first layer is formed, the 3D printer pauses. After that, the fabric is placed over the press; see Figures 9, 10, and 11. An auxiliary self-adhesive paper tape is used to straighten the fabric and lay it on the formed layer with its entire surface; that is, it is stiffened with its entire surface to the printer's heating plate. The fabric is positioned so that the mesh structure, or 3x3 matrix, of the desired geometry is centered precisely above the printed/fused layer, see Figures 9, 10, and 11. Finally, the 3D printer is restarted, prints directly over the fabric, and joins to the previously melted layer of PLA filament.

(a) (b) (c)

Figure 9. Button on silk realization: a) first layer creation, b) placement of fabric placement with a circle-shaped matrix, c) realized button from the upper side, c) button lower part appearance

Figure 10 shows the process of making a button on viscose material with a triangular matrix, while Figure 11 shows the same process repeated on polyamide with a square matrix. An interesting detail indicates that the melted filament has separated from the fabric (see Figure 10c). The melted thread on the fabric itself must be extracted with quality because it is of great importance when the sample is tested for mechanical (tension and pressure) or temperature (heating) stability [21]. The reason for separation is probably that the melting temperature of the filament is not high enough, and thus, better adhesion with the viscous material did not occur. On the other hand, the material was not treated (e.g., with glue) or prepared (matrix formation) for better adhesion of the molten filament.

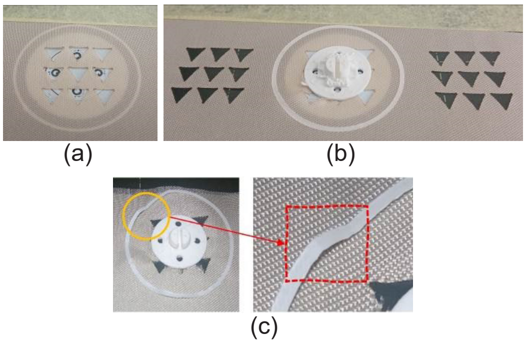


Figure 10. Button on viscose: a) first layer formation, b) making button from the upper side, c) appearance of separation of the molten filament

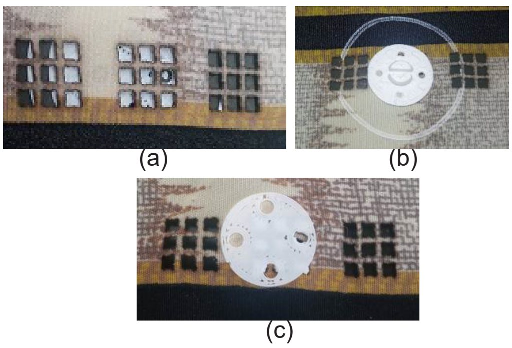


Figure 11. Button on polyamide: a) first layer formation, b) realized button from the upper side, c) appearance of the lower part of the button

Figure 12 shows the connection of polyvinyl mesh and filament. Unlike the previous examples, here we are talking about a regular grid of square shape (2×2 mm^2), and at the same time, the larger area of the grid merges with the molten filament.

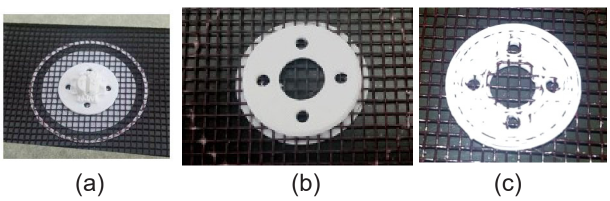


Figure 12. Button on the polyvinyl mesh: a) realized base, b) realized cover, c) realized connection

When the button is printed, there is a visual control of the complete print and a check of the joining between the filament and the fabric during and after 3D printing. Therefore, the connection between polymer and textile describes the quality of the joint. The joining of melted layers (or "plastic to textile welding") primarily depends on the printing temperature [22]. At higher temperatures, there is a greater diffusion of the polymer through the fabric, that is, the so-called "welding" layers [23].

Since most 3D printers have a limited printing temperature level of up to 320 °C, only those fabrics and raw materials with this melting temperature are suitable. Also, the quality of plastic welding is tested by the ability to withstand a more significant number of washing and drying cycles at elevated temperatures.

Microstructural analysis

Figure 13 shows the appearance of the bond between the polymer matrix based on PLA and textile fibers (silk). The sample was observed using scanning electron microscope (SEM), model MIRA 3 TESCAN, with a magnification of ×100 and view field of 1.9 mm. The width of the silk fiber is about 5 μm. When cutting the silk-PLA material, the silk threads are pulled out, but no delamination was observed between the two materials. Furthermore, this structural analysis is coupled to an adhesion quality assessment criterion between PLA termoplastic polymers and textile fibers. The bond quality between all adjacent PLA filament segments was exelent without delamination.

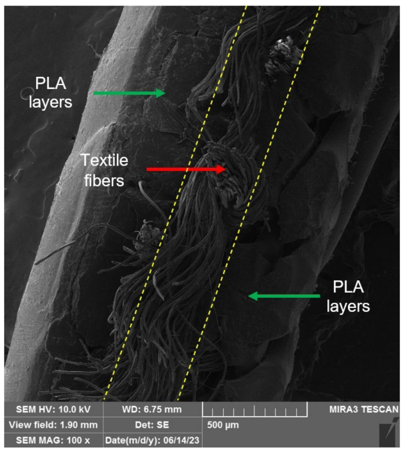


Figure 13. Microscopic structure of the bond between PLA filament and textile

Conclusion

In this paper, the method of applying the FDM procedure in order to print quality specimens using thermoplastic polymers is presented. It has been shown that the thermal treatment of PLA affects the reduction of the plasticity of the material, which leads to an increase in the brittleness of the sample. The paper was created as a pioneering attempt to respond to new trends in the textile industry. To improve the process of 3D printing on various types and fabrics thicknesses, the following must be done:

- Before the printing process, a mesh should be designed on the fabric that includes the entire model with its contour;
- Examine the degree of solubility and disintegration of the material in water after several washing cycles in a washing and dryer machine at higher temperatures;
- For the best bonding of the melted filament to the fabric, the parameters should be defined according to the fabric type and the layer on which the extruder headrests, i.e., for which particular Z coordinate the extruder is raised (mostly it is a function of the thickness of the fabric/material) and to allow everything to keep the temperature value of the nozzle constant.
- After the specimen realization, a detailed specimen mechanical analysis for stretching, bending, and pressure should be performed.

Future research will be focused on the investigation of laminated form of materials with combination textile/polymer filament. The influence of printing orientation, infil, type of filaments, natural/sinthetic textile, and weaving orientation on the mechanical properties of laminates composite will be studied.

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Izvod

TEHNOLOGIJA PROIZVODNJE 3D ŠTAMPANIH MODELA NA RAZLIČITIM MATERIJALIMA KORIŠĆENJEM PROCESA FUZIONOG TALOŽENJA MATERIJALA

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Spajanje termoplastičnih i tekstilnih materijala danas dobija sve veći značaj. Dobijaju se nove kombinacije materijala i nove strukture koje menjaju modne trendove. U radu je prikazana tehnologija spajanja termoplastičnih materijala sa različitim tkaninama. Na primer, uzeta je realizacija dugmeta na tekstilu i opis 3D štampe. Ovaj pionirski poduhvat opisuje tehnologiju, proces izrade modela tkanine i analizu veze topljenja materijala. Nažalost, dostupni termoplastični materijali imaju mnoga ograničenja u pogledu izdržljivosti, starenja i veka trajanja prema definisanim zahtevima. Ideja ovog rada je primena 3D štampe u modnoj industriji kao tema za diskusiju u nastajanju. Eksperimentalni deo ovog istraživanja će dati novu smernicu za dizajnere PLA/ABS štampanih elemenata na tekstilnim podlogama i mogućnost primene u modernom dizajnu tekstila.

Ključne reči: aditivna tehnologija, termoplastični polimer, tekstil, 3D štampa, model