3D printing of textile-based structures by Fused Deposition Modelling (FDM) with different polymer materials

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Abstract. 3D printing is a form of additive manufacturing, i.e. creating objects by sequential layering, for pre-production or production. After creating a 3D model with a CAD program, a printable file is used to create a layer design which is printed afterwards. While often more expensive than traditional techniques like injection moulding, 3D printing can significantly enhance production times of small parts produced in small numbers, additionally allowing for large flexibility and the possibility to create parts that would be impossible to produce with conventional techniques. The Fused Deposition Modelling technique uses a plastic filament which is pushed through a heated extrusion nozzle melting the material. Depending on the material, different challenges occur in the production process, and the produced part shows different mechanical properties. The article describes some standard and novel materials and their influence on the resulting parts.

1. Introduction
Rapid prototyping and rapid manufacturing systems are often based on solids, e.g. in the form of thin laser-cut layers sequentially bonded to each other, inkjet-like 3D printing with thermoplastics, selective laser sintering (SLS) from a powder, or the fused deposition modelling (FDM) process firstly established by Stratasys [1]. Most inexpensive 3D printers, developed for private use or small companies trying their first steps in the area of 3D printing, use the FDM process.
As a preparation for 3D printing, a geometric model created by CAD software is exported as STL (Surface Tessellation Language), OBJ (Wavefront) or – depending on the CAD program and the printer – other interchange formats and sliced afterwards (i.e. split into a number of layers). During the construction, care must be taken that the 3D model is “watertight” (i.e. contains no holes), manifold (i.e. edges must not be shared between more than two faces), and that the surface normals point outwards [2]. Corrections of the respective errors can be performed, e.g., by “netfabb” [3].
Depending on the printing process, such as SLS or FDM, additional requirements have to be fulfilled. For FDM models, it is important to take into account the position of the model in the printer – with the largest and necessarily most exact plane at the bottom –, the problem of strongly tilted faces (> 45°) necessitating support material, or the infill pattern inside a closed object. For SLS printing, instead, large volume models should contain so-called escape holes through which the polyamide powder can be removed after printing. Additionally, spaces between moving parts must be large enough to allow for the powder to flow away when the design is taken out of the 3D printer. In both processes, care must be taken that wall thicknesses are large enough, especially if the model is planned to be polished afterwards.
2. Experimental

While 3D printers are already used in several fields by companies and individuals, printing of textile-like patterns is still rare. In technical textiles, 3D printing has already been used to create applications such as flexible heating systems or wearable technology [4,5]. In design, garments such as bikinis [6], complete dresses [7] or shoes [8] are 3D printed. These garments, however, are clearly produced for show, not for everyday wearing. Thus, the project described here concentrates on more textile-like patterns which can be combined with traditional textiles or even replace them.

After designing different textile or textile-based structures in the free 3D graphics software Blender™, the models have been checked and – if necessary – repaired using netfabb. Afterwards, the repaired STL file has been imported in the “repetier host” and sliced into a layer model before the resulting file is sent to the 3D printer.

Most experiments depicted in this article have been performed using the FDM printer X400 produced by German RepRap with PLA (polylactic acid, elongation at break ~ 4 %, tensile modulus 1968 MPa [9,10]) or soft PLA (PLA + softener, elongation at break up to ~ 200 % [9]), BendLay (butadiene; harder than soft PLA, but not as brittle as ABS; impact strength 3kJ/m², tensile modulus 1550 MPa [11]) and other traditional and experimental materials. ABS (Acrylonitrile butadiene styrene) has been excluded after first tests showed the insufficient mechanical properties of the resulting textile-based models [12].

For comparison with the FDM process, an SLS printer employed by Shapeways [2] has been used with the material “White Strong & Flexible” (nylon).

3. Results

First experiments aimed at reproducing textile structures, especially weft knitted single face structures, before the experiments concentrated on developing lace patterns and finally multi-material models. All structures were printed without using a base substrate, although 3D printing on flexible textile materials is principally possible, depending on material combinations and printer settings.

3.1. 3D printing of weft knitted structures

Creation of 3D printed weft knitted structures is based on the development of a CAD model (figure 1, upper left panel). For this, Blender™ has been used to import a model of a knitted stitch created in Adobe Illustrator, to duplicate the stitch and to add the 3D form by deforming the Beziér curve depicting the stitch. It must be taken into account that the material thickness, as well as the distance between neighbouring stitches, are large enough for the SLS or the FDM technology, respectively. With the program “netfabb”, the printability of the design has been verified.

The developed CAD model has been used for 3D printing by SLS process (figure 1, upper right panel) with 0.8 mm material thickness and a minimum distance between the different stitches of 0.4 mm. The resulting model reproduces in principle the look of a single face weft knitted fabric; however, it should be mentioned that the lack of flexibility of the material itself leads to distinctly different mechanical properties of the model, compared with knitted structures created from traditional textile yarns. Additionally, the SLS process can normally only use one material per model; multi-material models have to be printed separately and joined afterwards.

For the FDM process, it is principally needed to use support structures – from a different or the same material as used for the model itself – to achieve the short distances between the stitches as depicted in figure 1 (upper left panel). As figure 1 (lower left panel) shows, however, small support structures from the same material are hard to realize. Additionally, the design had to be magnified to reach the minimum material thickness (here 1.88 mm) necessary to avoid breakage of the structures. Nevertheless, the support structures were still too fine to be produced by the printer as desired; instead undesirable clots were created which partly destroyed the model. In this way, it is not possible to build such a relatively fine model by FDM.

The same structure has been realized using soft PLA without support structures. Unexpectedly, this experiment gave a significantly better result (figure 1, lower right panel). While there are still fine
undesirable connections between the stitches, following the trace of the printing nozzle which sometimes extrudes material when this process should be stopped, the basic structure is clearly visible. The stitches are mostly separated, and the flexibility of the material itself leads to significantly more similar properties compared to a textile knitted structure than for the design produced by SLS.

![Figure 1](image.png)

**Figure 1.** CAD model of a single-face weft knitted fabric produced with Blender™ (upper left panel), 3D printed with SLS (upper right panel), FDM with BendLay and support structures (lower left panel), and FDM with soft PLA without support structures (lower right panel). Dimensions depicted by ruler.

Nevertheless, it should be mentioned that the surface of the soft PLA model still exhibits roughness on a macroscopic scale, contrary to the microscopic roughness of man-made or natural textile fibres. Nevertheless, these experiments already show that simple replication of common textile structures may not be the ideal way to produce 3D printed textile materials. Due to the layer-by-layer construction of the FDM technique, models that are built up from layers can be expected to be printed more successfully and with fewer problems occurring. Thus, the next sub-chapters deal with such thin layered structures.

### 3.2. 3D printing of layered structures

Several layered structures have been realized by FDM technology. Figure 2 shows a test structure, used to examine whether single strings can be deposited on top of relatively open structures without any support structures.
Figure 2. Test pattern for a layered structure, composed of three stacked layers.

The resulting FDM print (figure 3) shows that while this approach is mostly successful, the strings may sometimes break, even if a minimum diameter of 0.4 mm is maintained. Thus, as the next approach to create textile-based 3D-printed patterns, lace-like structures have been created which start with a partly open base layer, too, but do not include free-floating areas.

Figure 3. Resulting FDM printed 3-layer structure (dimension 8 cm x 8 cm).

3.3. 3D printing of lace patterns
Lace patterns have been created, inspired by the well-known Plauen lace, containing mostly floral and round elements on a base layer connecting these parts. Such a design is depicted in figure 4 (left panel). Due to the absence of free-floating areas, printing by the FDM process is unproblematic, if all connection lines have large enough diameters (figure 4, right panel).

Figure 4. Multi-layer lace pattern, depicted in “netfabb” (left panel), and the resulting 3D print (right panel). Detail dimension ~ 4 cm x 7 cm.
Additional to soft PLA, which has been used for most lace patterns to avoid possible mechanical problems with harder material resulting in breaks of the base connections, an experimental polymer has been used: Lay Tekkks, one of four different types of porous filament from the line PORO-Lay. Lay Tekkks is a hard filament, produced by Kai Parthy from CC-Products (Cologne), which is transported to the nozzle without the transport problems that too soft filaments may generate in several FDM printers. After finishing the printing process, however, it can be put into warm water for a period of minutes to hours, leading to the hard part of the material being dissolved and thus softening the resulting sample more and more, the longer it is immersed in water (figure 5).

Figure 5. Lace pattern created from Lay Tekkks before (left panel) and after dissolving the hard material fraction in warm water for three hours (right panel). The dimension of the design is 8 cm x 8 cm.

3.4. 3D printing of multi-material models
FDM printers with two or more nozzles offer the possibility to mix different materials in one printed part. Since garments often contain harder parts, such as eyelets, buttons or other reinforcements, such material mixes have also been developed and printed.

Figure 6. Multi-layer multi-material structure, depicted in Blender™ as three separate layers plus separate ring from different material marked red (left panel), and the resulting two-material print with hard BendLay ring in soft PLA layer construction (right panel). The dimension of the design is 8 cm x 8 cm.

Figure 6 (left panel) shows exemplary the construction of a three-layer base, planned to be printed with soft PLA, and a harder ring (depicted red) which fits in the gap of the soft middle layer, thus
being partly fixed by the top and the bottom layer after finishing the design. In this way, it is indeed possible to create such a multi-material model (figure 6, right panel). Similarly, lace models with three or more layers of soft PLA can contain reinforced parts constructed from hard PLA or BendLay.

4. Conclusion
In a recent project, textile-based structures have been 3D printed using SLS and FDM technology. While ABS has turned out to be often too brittle for the desired fine structures, and hard PLA, as well as the nylon used in SLS printing, can be too hard to be used in typical textile applications such as garments, soft PLA – also in combination with less flexible materials such as BendLay – has proven to be able to reproduce some textile-based structures.

These materials enable the development of novel patterns and construction methods for clothing and related areas, allowing for new designs as well as new functionalities that cannot be achieved by conventional textile fabrics.

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