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ADVANCES IN TEXTILE MANUFACTURING WITH 3D PRINTING TECHNOLOGY

BRAD Raluca

Lucian Blaga University of Sibiu, Faculty of Engineering, Computer Science and Electrical Engineering Department, B-dul Victoriei 10, 550024 Sibiu, Romania, E-Mail: raluca.brad@ulbsibiu.ro

Abstract: *This paper explores the most used technologies and materials in 3D printing for textiles. It presents an overview of additive manufacturing techniques such as Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS), highlighting their applications in textile manufacturing. Various materials, including PLA, ABS, PETG, TPU, and specialized resins, are examined for their mechanical properties, flexibility, and suitability for textile integration. The study also reviews recent advancements in 3D-printed textiles, emphasizing innovations in material composition, structural designs, and process optimization. Research findings on chain structures, auxetic materials, and bio-compatible resins demonstrate the potential of 3D printing in producing functional, wearable textiles with enhanced comfort and durability. Furthermore, the integration of smart materials, such as shape memory polymers, elastic liquid crystals, and hydrogels, opens the way for 4D printed intelligent textiles that adapt to environmental stimuli like temperature, humidity, and mechanical stress. Sustainability and customization are key drivers in the adoption of 3D printing in the fashion industry, as the technology reduces material waste, enables on demand production, and offers new possibilities for personalized garments. Despite significant progress, challenges remain in scalability, material limitations, and adherence to traditional textile properties. Future research will focus on enhancing material performance, refining printing techniques, and exploring hybrid manufacturing approaches.*

Key words: *Additive Manufacturing, Fused Deposition Modelling (FDM), PLA, flexibility*

1. MATERIALS AND TECHNOLOGIES USED IN TEXTILE 3D PRINTING

3D printing, also known as additive manufacturing, involves creating three-dimensional objects from digital models by laying down successive layers of material until the object is complete. There are several technologies employed for this process [1], [2]:

- Fused Deposition Modeling (FDM), the most common for home or semi-industrial use, where a plastic filament is melted and extruded layer by layer
- Stereolithography (SLA), that uses a laser to cure liquid resin into a solid object, which is also recognized for its high accuracy
- Selective Laser Sintering (SLS), where a powder made from plastic, ceramic, or a metal is fused by a laser, commonly used in industrial applications.

The FDM technology applied to textile printing utilizes the following materials, each one with properties benefits and drawbacks:

- PLA (Polylactic Acid), a biodegradable plastic made from renewable resources like corn starch or sugar cane, easy to print with and available in many colors. Otherwise, it is not as robust or heat-resistant as other materials and can be easily breakable. Nowadays, it is widely used for prototyping, in various educational projects and the production of simple household items. PLA composites can be combined with natural fibres such as jute, cotton and hemp and are biodegradable.

- ABS (Acrylonitrile Butadiene Styrene), known for its strength and durability, making it suitable for functional parts, with higher heat resistance than PLA. As a disadvantage, it requires higher temperatures to print, can emit toxins and could deform, especially in cold air. This material is suitable for prototyping and short series production of automotive parts, toys, or other casings.
- PETG (Polyethylene Terephthalate Glycol), combines the benefits of PLA and ABS, being strong, flexible, less prone to warping and with good layer adhesion. Further, it is more expensive than PLA, can be challenging to print with for beginners. General applications range from containers, drone parts or medical equipment.
- Nylon (Polyamide - PA6, PA11, PA12 in 3D printing contexts) is a versatile material used across various 3D printing technologies, particularly known for its strength, durability, flexibility and excellent abrasion resistance. Among cons properties are hygroscopic, difficult to print because it requires a heated bed. It can be used for printing gears, hinges and wear-resistant parts.
- TPU (Thermoplastic Polyurethane), is a versatile and flexible material used in 3D printing, known for its rubber-like elasticity, making it ideal for applications that require flexibility and durability. TPU is used in various industries, including automotive, healthcare, and consumer goods like flexible hoses, footwear components, and even prosthetics. Printing can be challenging due to its elastic properties, that requires careful handling to avoid issues like clogging and stringing.

In the case of SLA, where materials are resin-based and cured using UV light, for textile applications, the following resins are commonly used [1], [2]:

- Photopolymer Resins, that allows high detail and resolution, smooth surface finish, suitable for jewelry, dental models, miniatures. Often requires post-processing (like curing), can be toxic if not handled properly and it is more expensive.
- Tough or Engineering Resins, which are strong, durable, with properties imitating traditional engineering plastics. Tey are more costly, might need additional curing or post-processing and might be used for functional prototypes, tools or connectors.
- Bio-Compatible and Conductive Resins. These resins are used for skin-safe, medical-grade, and wearable applications in textiles and soft prosthetics. Among the existing products, BioMed Clear Resin is an ISO 10993 certified, used for medical and skin-contact applications; BioMed Amber Resin which is rigid but biocompatible, suitable for semi-flexible textile components; Silicone-Based SLA Resins used for soft, flexible, and skin-safe applications, mimicking textile properties.
- Conductive Resins utilized for E-Textiles and Smart Wearables, are infused with conductive additives, allowing electricity flow for sensors and circuits in textiles. It can use Graphene-Infused Resin, that provides electrical conductivity while maintaining flexibility, Carbon-Nanotube Resins used in flexible circuits for wearable tech or Silver-Based Conductive Resins employed in flexible and stretchable e-textiles for smart garments.

2. THE LATEST DEVELOPPEMENTS IN ADDITIVE MANUFACTURING

However, additive manufacturing in the textile and garment industry is still highly specialized and has only recently started to show its potential for broader adoption. The paper of [3] provides a comprehensive analysis of the advancements and challenges in 3D and 4D textiles using Additive Manufacturing (AM). The authors are claiming that even if significant scientific progress has been made, the field remains in its early stages due to technological limitations in scalability. The study highlights the diverse applications of AM in textiles, including functional filament fibers, direct 3D printing on fabrics, fully 3D-printed garments, and dynamic 4D textiles.

In the case of FDM, a more cost-effective alternative to other 3D printing methods, the authors of [4] are employing FilaFlex, a material providing enhanced wearability. The paper explores the growing role of 3D printing in the fashion industry, emphasizing its potential for garment production. Statistics presented in [5] have shown a strong interest in 3D printed fashion, due to its potential to reduce waste and enable customized or home-based production, responding to the growing demand for sustainable and personalized manufacturing solutions in the fashion sector.

The authors of paper [6] studied the properties of PLA, ABS and TPU in FDM. To create flexible structures with textile-like behavior, TPU, a flexible filament, is preferred over PLA and ABS, which, despite the printing of chain-like structures, did not meet the requirements for a garment collection inspired by Vivaldi's Four Seasons. Paper [7] provides an overview of the key performance parameters of materials commonly used in FDM printing for textiles and apparel. The authors conclude that ABS and PC require higher printing temperatures than PLA, with PC offering the highest heat resistance and PLA the lowest. As a result, PLA-based garments are unsuitable for high-temperature environments. Additionally, PLA experiences minimal shrinkage compared to ABS and PA. In terms of tensile strength, PLA, PC, and PA perform well, whereas TPU has the lowest tensile strength. Other authors [8] had innovated new chainmail-like structures that blend creativity with wearability, that are enhancing softness, comfort and flexibility in 3D printed fabrics made from polymers. The structures are inspired by ancient chain mail armor, composed of interlocking hollow nylon polymer octahedrons. These fabrics can transition from a flexible, fluid-like state to a rigid, load-bearing structure under pressure, offering potential applications in wearable technologies and motorcycle gear, exoskeletons, and even military-grade apparel.

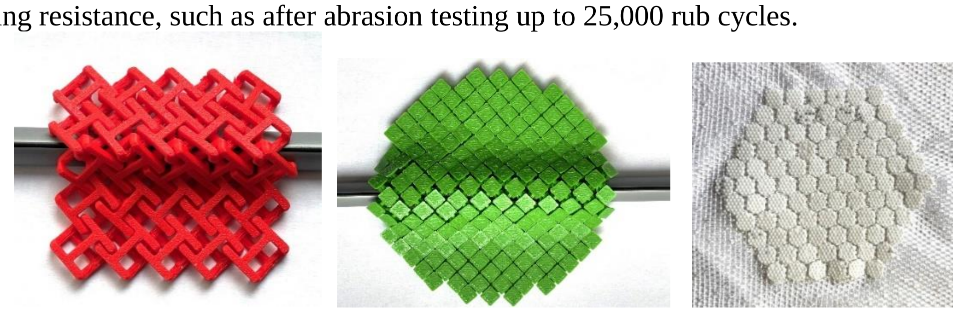
Fig. 1*: Printed parts assembled in a dress with stitches and belts [4]*

Paper [9] resume design methods for auxetic mechanical metamaterials, which exhibit a negative Poisson's ratio and unique deformation properties. Traditional auxetic materials have lower mechanical stiffness, but recent advancements have led to high-stiffness designs suitable for energy absorption, load-bearing, and thermal-mechanical applications. It also explores multifunctional applications, including textiles and apparels, aiming to provide guidelines for developing auxetic materials with tailored mechanical properties.

The relationship between design parameters and the mechanical properties of 3D printed wearable interfaces made from soft materials like TPU are described in [10]. It focuses on how factors such as strand thickness, strand distance, rotation angle, and layer height influence tensile strength, elongation at break, and Young's modulus. The research introduces a modeling technique for flexible mesh structures and provides experimental analysis to understand these effects. A regression model is developed to guide future design considerations for 3D printed flexible structures in wearable applications. The paper of Wirth et al. [11] explores the mechanical characterization of 3D printed biaxial weaves, enabling complex yarn structures and enhanced manufacturing flexibility. A generative model is developed to analyze the relationship between design parameters and mechanical properties using a two-stage Design-of-Experiments approach. Samples are made by material jetting and tested under tension, revealing a bilinear stress–strain behavior influenced by load direction, weave pattern, yarn diameter, and spacing. The study also highlights reduced layer-wise delamination, demonstrating the potential of material printing for creating quasi-continuous textile structures with tunable mechanical properties.

Paper [12] proposes a parameter optimization method combining the Kriging model and Cuckoo Search (CS) algorithm for enhancing the tensile strength in FDM for 3D printed PLA parts. Printing speed and temperature were analyzed, with optimal values determined as 31 mm/s and 225°C, respectively. The Kriging model demonstrated high accuracy, with a prediction error of only 0.62%, validating its effectiveness in optimizing FDM process parameters. In the paper of Lekeckas et al. [13], the adhesion strength between 3D printed materials and chiffon fabrics are investigated in order to enhance garment functionality. By testing different fabric and material combinations using uniaxial tensile tests, the research demonstrates that 3D printed TPU elements can improve the comfort and durability of low-elasticity chiffon garments. The proposed system enables garment renewal, repair, and customization, extending the functional and aesthetic possibilities of clothing within a sustainable framework.

Two fabric types, weft knitted and braided, obtained by 3D printing methods with PLA filaments, were tested for mechanical properties in [14]. The research includes one yarn knitted structure and diamond, Hercules, and triaxial braids. Results showed that the weft knitted fabrics exhibited good ductility, with a tensile displacement ranging from 12-15 mm and a peak force of approximately 250 N. The braided structures were able to bear significant compressive loads, with displacement at failure exceeding 25 mm. Optical microscope analysis revealed that the yarns contained voids and cracks, contributing to sample failure. The additively manufactured weft knitted fabrics are suitable for wearable, filtration, and geotextile applications, while braided structures are ideal for shock absorption applications. However, challenges remain, particularly in material development, as current 3D printed materials do not yet fully replicate textile properties and often exhibit stiffness. The authors of [15] explore the role of 3D printing, in extending the lifecycle of textiles within a circular economy, by integrating bacterial cellulose and PETG as a printed medium onto fabrics. The method is tested using 3D printed woven samples and standard equipment for determining resistance, such as after abrasion testing up to 25,000 rub cycles.



a. b. c.

Fig. 2*: FDM printed structures using PLA. a) and b) chain structure; c) hexagonal elements on nylon fabric. Models downloaded from [24] and printed using PLA*

The use of cotton fibers as a raw material for 3D printed textiles to overcome the flexibility and comfort limitations of current 3D printing materials in presented is [16]. By dissolving cotton fibers in a LiCl/DMAc solvent and incorporating hydroxyethyl cellulose, a printable ink was developed and processed using material extrusion. The research optimized dissolution, ink viscosity, and post-processing methods, leading to improved flexibility, breathability, and moisture absorption in 3D printed cellulose fabrics compared to conventional 3D printed textiles. Additionally, these fabrics exhibited superior abrasion resistance over traditional cotton fabrics. As a proof of concept, garments and gloves were successfully produced, demonstrating the potential of this approach for producing flexible, wearable 3D printed textiles. Other authors have enhanced flexible materials by incorporating reinforcing fibers or infill particles, improving performance while also giving printed textiles and garments unique qualities [17], [18], [19], [20]. 3D printing also has applications in footwear, both for uppers and soles. According to tests conducted in paper [7], functional footwear, such as 3D printed upper of the FDM sports shoes incorporating layers of TPU fibers, offers advantages like lightweight (aprox. only 197 g), good moisture absorption, and enhanced comfort. The design not only minimizes weight but also reduces energy consumption during long-distance runs. Beyond the upper, the FDM process is also widely used for 3D printing soles using TPU material, as Latiz technology [7], and also by Nike, Adidas, and New Balance [21].

Many studies position 3D printed garments as a complementary innovation rather than a replacement for traditional fashion. With its benefits of low cost, considerable creative freedom, and a variety of material options, 3D printing has been advocated in the textile industry [22]. This type of technology combined with smart materials with shape memory opens a new avenue for exploring 4D printed smart textiles. The essential elements of 4D printed smart textiles, therefore, include the development and synthesis of new materials with different responsive forms using equipment and the ability to print complex shapes using advanced additive manufacturing techniques [23], [7].

3. CONCLUSIONS

Combining 3D printing with smart materials (shape memory, elastic liquid crystals, hydrogels), it enables the development of 4D printed intelligent textiles with environmental adaptability. The key to 4D printed textiles lies in creating new materials that respond to external stimuli (humidity, temperature, light, pressure, electric and magnetic forces) and have the ability to print complex shapes and new colors using advanced techniques.

The 3D printing sector is projected to experience substantial growth, offering considerable advancements for the textile industry. Recent innovations in manufacturing, such as the introduction of precision alignment stations have significantly enhanced the capabilities of high-end fashion printing. In terms of sustainability, 3D printing techniques are instrumental in reducing waste and fostering sustainable manufacturing practices through precise production methods. This technological evolution also supports customization, enabling the creation of personalized garments and unique designs, thereby transforming conventional manufacturing paradigms. A shift towards localized manufacturing is evident, promoting faster and more cost-efficient production processes. Optimal results in 3D printing are achieved with the use of open-weave fabrics such as tulle, which allow for superior adhesion between printed layers. 3D printing can reinforce and repair materials, constituting an alternative to traditional assembly technologies while extending product lifespan and conserving raw materials. The most inspiring part of these advancements is their transformation of our perspective on textile and fashion production. Rather than relying on conventional manufacturing techniques, the industry is shifting toward a digital, adaptable, and eco-friendly approach that not only meets market demands but also minimizes environmental impact.

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