THE INFLUENCE OF ADDITIVE MANUFACTURING IN THE TEXTILE INDUSTRY

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Currently, the textile industry represents a big threat to the environment and human health, through the large resource consumption, through the harmful chemicals eliminated in the environment, and through the enormous amounts of waste resulted from both the pre-consumption and post-consumption phases. Moreover, it is a continuous need to bring digitalization in this industry to promote sustainability and resource efficiency. Additive manufacturing or 3D Printing is proposed lately as a solution to all these issues created by the textile industry, thus an emphasis has been placed on this technology to replace traditional textile production technologies. Although it has not yet had considerable success in practice, manufacturing of textiles via 3D printing is still a promising effort, due to the benefits it brings, and thus the research continues. This technology has the ability to build remarkable structures with limitless shapes and size, it can functionally optimize the products right from the start, and most important, the production steps can be skipped, thus allowing to reduce the production time and to bring digitisation closer to this sector. Furthermore, the resource consumption can be reduced, the transport routes can be eliminated as well as the textile waste generated during production. In conclusion, this technology is a totally different way to design which diminishes the effort and can conduct to a strong change in the industry. This paper discusses the advantages of the 3D Printing process for the textile field, the encountered difficulties, and recent developments in terms of materials, technologies, and applications.

Keywords: 3D printing, sustainability, advanced materials

INTRODUCTION

The process of Additive Manufacturing (AM) or in other words 3D Printing (3DP) or Rapid Prototyping enables to use different kinds of materials to create unique 3D structures with controlled shapes and sizes by depositing material layer-by-layer, instead of subtracting material or redistributing material as in the classical technologies of manufacturing (forging, milling, drilling, casting, plastic deformation, etc.). A special printing machine is used to convert the virtually created geometry of an object (a 3-dimensional computer-aided-design (CAD) model), which is sliced in discrete layers, into the physical object (Lussenburg *et al*., 2014).

The first AM process was invented by Charles Hull in 1986, namely, stereolithography, currently existing various other additive manufacturing processes differentiated by the specific method of forming the layers and materials used. The diversity of materials that can be used confirms the continuous evolution of the AM field (metals, polymers, photopolymers, ceramics, sand, paper, food and even organic tissues).

In the field of 3D printed textiles, Selective Laser Sintering (SLS) (Beecroft, 2019) and Fused Deposition Modelling (FDM) (Takahashi and Kim, 2019; Partsch *et al*., 2015) are two commonly used processes. Also, Polyjet technology was introduced recently to the list of technologies that can be used to print directly to textiles and create clothing items that unlock a limitless colour palette, limitless creativity and unparalleled flexibility through a wide range of rigid and flexible materials (Molitch-Hou, 2022). Table 1 describes these three different types of additive manufacturing technologies.

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Table 1. Description of some of the existing AM technologies (DelVecchio, 2021)

	Resin-based	Powder-based	Filament
Method	Material Jetting	Powder Bed Fusion	Material Extrusion
Alternative name	Polyjet	Selective laser sintering (SLS)	Fused Deposition Modelling (FDM)
Key Materials	Photopolymers, polymers, waxes	Plastic, metal, and ceramic powders, sand	Thermoplastic filaments, liquids, and slurries (syringe types)
Bonding principle	Cured with UV light	Fused with laser	Fused with heat
Strengths	Low surface roughness; Enables multiple materials in a single part; High level of accuracy; Full-colour printing.	Medium surface roughness; High mechanical properties; Powder acts as material support.	Low build cost; Good mechanical properties; Allows for multiple colour printing.
Weaknesses	Limited material options; Overexposure to outdoor UV light can weaken parts; Costly and time-consuming.	High build cost; Cool-down time of 50% of print time, leading to longer production time.	High surface roughness; Slow build speed.

Some frequently used materials for 3D printing with FDM technology (Table 2), for example, are filaments of polylactic acid (PLA), the most commonly used material, acrylonitrile butadiene styrene (ABS), Nylon, thermoplastic polyurethane (TPU), polycarbonate (PC), blends of PC and ABS and others, and also composites made of plastic filaments that contain a certain fraction of fibres or particles (e.g., wood fibres, ceramic particles, brass particles, short carbon fibres, electrically conductive carbon black) which can give special properties to the printed structure (e.g., electrical conductivity).

Table 2. Properties of the most common used materials in FDM technology (Bates-Green and Howie, 2017)

PLA	A biodegradable polymer, it creates no toxic gases while melting (no ventilation system needed), low glass transition temperature ~60-65°C (PLA parts can often be printed in unheated atmosphere with no build plate heat and no special adhesives), flows and is extruded around 215°C, is susceptible to water degradation.
ABS	Has good rheological properties which make relatively smooth surfaces, it has stiffness, resistance to heat and environmental degradation, needs a well-ventilated space when printed, extruded around 220°C needs an elevated build plate temperature and/or atmospheric temperature and use of chemical adhesives on the build plate because of high glass transition temperature (~ 105°C).
Nylon	Has high toughness, flexibility in bending and stiffness in tension, resistance to fatigue, heat and wear resistance, and strong adhesion between layers, absorbs water from the atmosphere quickly (needs to be desiccated), more expensive than other materials, extruded at temperatures from 240°C to 270°C, which can harm some printers.
TPU	An elastomeric, rubbery material with very good flexibility, melts at easy FDM temperatures around 230°C, resistant to abrasion and solvents like petroleum chemicals.
PC	Has high strength, high layer adhesion, high impact resistance and toughness, ability to plastically deform greatly before it breaks, high-temperature stability, a smooth printed texture and optical clarity, extruded at 315°C, a temperature that many printers can't reach with difficulty adhering it to the build plate, and it's easily scratched.

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THE POSITIVE IMPACT OF 3DP ON THE TEXTILE SECTOR

- Sustainable process of manufacturing - the additive process reduces material waste during production, reduces the use of materials that are intensive water consuming such as cotton, as well as the need for extensive human labour.
- Offers an easier recycling potential for the 3DP apparel than current materials, thus helping reduce the amount of clothing thrown into landfills.
- Production can be local and on-demand -this means that there is no need for stock products, and no overproduction occurs.
- At-home printers can help reduce the impact of large factories.
- Faster manufacturing cycles - allowing the manufacturers to speed up the market and supply chain.
- High accuracy and efficiency.
- In fashion it is important to introduce new design forms that keep up with consumer requirements, thus 3D printing allows designers to innovate faster and can contribute to design freedom and personalization (customized design).
- 3D models for fashion accessories, such as buttons, cufflinks, and bag clips, can also be printed.
- Prototyping, or getting a sample made, is also cheap and time-efficient with 3D printing (Flynt, 2019).

DIFFICULTIES ENCOUNTERED BY 3DP TECHNOLOGY

The use of 3D printers in the production of textiles is still extremely complex. When 3D printed fabrics are used to create wearable garments, strength, flexibility and comfort are the main requirements. But this technology still struggles to achieve them.

Moreover, 3DP is still an expensive technology in most cases or the quality of objects is not high enough, to which is added limited expertise and limited materials choice, so the development of the technology approach in different fields is hampered by these aspects (Everett, 2021).

With the increasing introduction of digitalization in the industrial sectors, people are not yet very open to embrace this concept, because it is associated with the loss of manufacturing jobs, but still, it seems like they are beginning to understand the practical aspects of 3D printing.

Also, with the download-and-print-yourself option, controlling the originality of products produced as well as their quality can become a problem if people print their personal items (Flynt, 2019).

To overcome the problem of flexibility and strength multiple approaches, based on shape complexity and material behaviour, were addressed by researchers and manufacturers to create products with appropriate properties, as follows:

a. printing fibre-shaped structures ultra-long and flexible that can be woven/knitted into fabrics - mostly developed to be used in the sector of energy storage, as batteries or supercapacitors, that can be further utilized in wearable and smart products (Praveen *et al.*, 2021);

b. printing of flexible structures based on rigid materials (Čuk *et al.*, 2020), but with discrete bodies that make up multiple assemblies (the so-called “chain-mail-like structure”);

c. printing using materials that are capable to be flexible (e.g., TPU) and creating common textile structures like knit or woven, or other complex geometries (Čuk *et al.*, 2020);

d. printing rigid plastic on top of the existing traditional fabric (direct-to-textile 3DP), which is the most used process at the moment (Čuk *et al.*, 2020).

Figure 1 exemplifies some types of the mentioned structures.

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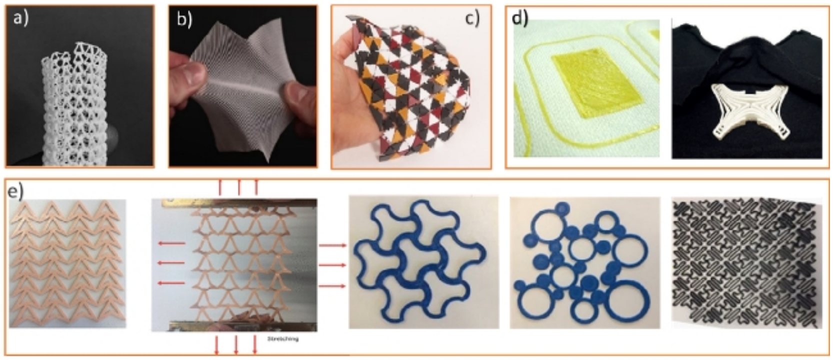

Figure 1. Types of textile structures created by 3D Printing: a) tubular weft-knit (Beecroft, 2019); b) quasi-woven fabric ("DefeXtiles") (Forman *et al*., 2020); c) chain-mail-like model (Mings, 2017); d) direct to-textile printing (Martens and Ehrmann, 2017; Korger *et al*., 2020); e) other flexible structures (Spahiu *et al*., 2020)

In addition to the performance of the material itself and the design, also the printing technology of the fabric has a critical impact. It is necessary to be used flexible-material specialized 3D printers, like for example, the INTAMSYS FLEX 510 printer and Raise3D E2 printer, two printers developed recently by INTAMSYS, Raise 3D, Covestro and Polymaker, which are highly adapted for printing flexible materials which match the characteristics required for a 3D printed fabric (Stevenson, 2020).

APPLICATIONS

Fashion Sector

The fashion industry is now turning to 3D technologies to create innovative products such as 3D printed shoes, garments, accessories, ties and bags designed by many prominent brands and designers (Čuk *et al*., 2020).

Most of the 3D printed clothing is printed using the selective laser sintering process. This method of 3D printing offers the ability to make intricate designs and achieve a high level of detail which is a requirement in fashion and clothing (Flynt, 2019).

Recently created by a Dutch designer, a 3D printed impressive dress made entirely from a vegan organic material based on cocoa bean shells brought together nature, fashion, and technology. Also, Kornit Digital, a sustainable fashion brand adopted additive manufacturing (direct-to-yarn printing technology) to produce knit-like garments that can contribute to sustainable and waste-reducing fashion (Alexandrea, 2022).

Homemade clothes represent an alternative to the expensive designer creations and can also sustain the friendliness with the environment. People are now able to print personal items with an at-home printer. However, the quality control aspect remains a challenge.

Besides the haute couture creations, 3D printing is now useful to create smart clothes that can respond to stimuli and offer new functionalities, in addition to beautification and comfort. For example, some high-tech 3D printed dresses with interesting sensing functions were created: releases smoke to alert when someone is invading the personal space of the wearer (the Smoke dress - the first fully-flexible 3D printing material) (Materialise, 2021), tracks the wearer's attention level and alerts other people around the wearer (through lighting) to not disturb the wearer from activities that require a lot of

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attention (the Synapse dress) (Boorman, 2014) or captures the breathing intensity of the wearer and when breathing becomes heavy, some robotic arms attached on the dress extend out like the legs of a spider to "defend" the wearer (the Spider Dress) (Starr, 2014).

Technical Textiles Sector

3D printed textiles were explored lately in different areas of the technical textiles sector. In this field the main focus is on functional properties.

The so-called "DefeXtiles", a technique that can produce thinner and flexible fabric-like structures with a fused deposition modelling (FDM) printer and PLA, TPU, ABS, PA etc. as extrusion materials has demonstrated its efficiency in the creation of different interesting objects, like a lampshade that can be turned on and off by pinching her pleats, tough and deformable badminton shuttlecocks and a fabric-like tendon actuator for a dancing person toy which has the necessary flexibility to curve during actuation (Forman *et al*., 2020).

As wearable devices are gaining more interest from the general population, a group of scientists developed a 3D printed fibre-based sensitive strain sensor that can be used as a skin-attached wearable device for the real-time detection of human activities (Cao *et al*., 2019).

A newly developed chain-mail-like fabric shows good potential for use in many technical applications. This fabric has advanced properties. When encased in a plastic envelope and vacuum-packed, it can become more than twenty-five times as hard as its original state under pressure and can hold up over 50 times its weight, it is lightweight, adaptable to the shape of the body and can retain a fairly flat shape under load. Selective laser sintering printing of nylon material was used to obtain the structure (Wang *et al*., 2021). It can be used for stab- and bullet-proof vests, for wearable exoskeletons and reconfigurable medical supports, or for protective vests for high-contact sports.

A decorative (panel) curtain that aims to improve room acoustics using functional 3D prints is another example of an application of 3DP in the field of technical textiles. The combination of TPU material printed on a PES-weave demonstrated that can suit requirements regarding both material properties like flexibility and feel as well as performance characteristics of adhesion and abrasion (Korger *et al*., 2020).

Scientists in the field of space also integrated 3D Printed fabrics as materials for astronaut spacesuits or as shields and insulation for spacecraft. They used additive manufacturing with metallic materials to create a chain-mail-like fabric that possesses four essential functions: reflectivity, passive heat management, foldability, and tensile strength (Jet Propulsion Laboratory-Caltech, 2017).

CONCLUSIONS

The possibility of using 3DP on a large scale in the textile sector is getting closer. Despite some disadvantages, the technology offers a multitude of advantages that combat the weaknesses. The innovative part of the fashion designers, engineers, and manufacturers of 3D printers will bring us step by step closer to this technology. It is up to us and our openness to accept it as a technology that can change our future in a good way, in order to influence the market of 3D printed products and contribute to the health of the environment and future generations.

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