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3D Printing on Textiles – Overview of Research on Adhesion to Woven Fabrics

3-D tisk na tekstil - pregled raziskav o adheziji na tkane tekstilije

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Abstract

3D printing on textiles has great potential to influence developments in various industries. It enables the production of new, potentially personalised products in areas such as technical textiles, protective clothing, medical products, fashion, textile and interior design. 3D printing can also contribute to waste-free production processes. In the method of 3D printing on textiles, the material is applied directly to the textile substrate to create 3D objects, patterns or designs on the surface. The fused deposition modelling (FDM) technology, where thermoplastic filaments are extruded and deposited in thin layers based on a 3D model, is widely used for this purpose. A precise control of factors such as temperature and speed is essential in FDM to regulate the flow of polymer material during the printing process. The most commonly used polymer for 3D printing on textiles using FDM is polylactic acid (PLA). Acrylonitrile butadiene styrene (ABS) is another widely used material, known for its low shrinkage rate and high printing accuracy, while thermoplastic polyurethane (TPU) is used due to its exceptional mechanical properties, e.g. tensile strength, flexibility, durability and corrosion resistance. Good adhesion between 3D printed objects and the textile surface is essential for the production of quality products. Adhesion depends on various factors, e.g. textile properties, printing parameters and the type of polymer used. The composition of the woven fabric, including the areal density, warp and weft density, yarn count, fabric thickness and weave pattern, significantly affects the adhesion strength of the 3D printed polymer. When considering double weaves, which allow different materials in the upper and lower layers, better adhesion properties are found than at single weaves. A cross-sectional analysis revealed that the polymer penetrates deeper into a double-woven fabric, resulting in improved adhesion. In general, the study highlights the advantages of double weaves for 3D printing applications on textiles.
Keywords: 3D printing, adhesion, woven fabric, double fabric

Izvleček

3-D tisk na tekstil vpliva na razvoj različnih industrij. Omogoča izdelavo novih, potencialno personaliziranih izdelkov na področjih, kot so tehnične tekstilije, zaščitna oblačila, medicinski pripomočki, moda, oblikovanje tekstilij in

interierja. 3-D tisk pripomore tudi k proizvodnim procesom brez odpadkov. Pri 3-D tisku na tekstil se material nanaša neposredno na tekstilno podlago, da se na površini tekstila ustvarijo različni 3-D objekti ali vzorci. V ta namen se pogosto uporablja tehnologija modeliranja s spajanjem slojev (FDM), pri kateri se termoplastični filamenti ekstrudirajo in nalagajo v tankih plasteh glede na oblikovani 3-D model. Natančen nadzor dejavnikov, kot sta temperatura in hitrost, je pri tehnologiji FDM bistvenega pomena za uravnavanje pretoka polimernega materiala med tiskanjem. Najpogosteje uporabljeni polimer za 3-D tiskanje na tekstil s tehnologijo FDM je polimlečna kislina (PLA). Akrilonitril butadien stiren (ABS) se prav tako pogosto uporablja, ker ima nizko stopnjo krčenja in omogoča visoko natančnost tiskanja, medtem ko se termoplastični poliuretan (TPU) uporablja zaradi izjemnih mehanskih lastnosti, kot so natezna trdnost, prožnost, trpežnost in odpornost proti koroziji. Dobra adhezija med 3-D natisnjenimi predmeti in tekstilno površino je bistvenega pomena za izdelavo kakovostnih izdelkov. Adhezija je odvisna od različnih dejavnikov, kot so lastnosti tekstila, parametri tiskanja in vrsta uporabljenega polimera. Konstrukcija tkanin, vključno s ploskovno maso, gostoto osnove in votka, finostjo preje, debelino tkanine in vezavo, pomembno vpliva na adhezijo 3-D natisnjenega polimera. Pri dvojnih tkaninah, ki omogočajo uporabo različnih materialov v zgornjem in spodnjem sloju, je bila ugotovljena večja adhezija kot pri enojnih tkaninah. Analiza prečnega prereza je pokazala, da polimer prodre globlje v dvojno tkanino, zaradi česar je adhezija boljša. Na splošno so raziskave pokazale prednost uporabe dvojnih tkanin za aplikacijo 3-D tiska na tekstil.
Ključne besede: 3-D tisk, adhezija, tkanina, dvojna tkanina

1 Introduction

Three-dimensional (3D) printing is an additive manufacturing (AM) technology that produces objects by depositing material in thin layers. The deposited layers of material are bonded together in different ways depending on the 3D printing technology and the material used [1]. The technology has great potential to influence developments in many areas of the textile and fashion industry. In addition to the production of new, possibly personalised products in the fields of technical textiles, protective clothing, medical products, fashion, textiles, interior design etc., it can influence the modernisation of processes with a view to waste-free production [2, 3]. In textile and apparel design, 3D printing is used in three different forms, i.e. direct printing on textiles, printing of rigid elements that can be assembled into flexible textile-like structures and printing of elastic materials that resemble textiles. Each of these forms can be realised with different printing technologies [4]. In 3D printing on textiles, the material is applied directly to the textile substrate and the desired 3D objects, patterns or designs are created on its surface. The fused deposition modelling (FDM) technology is usually used for this purpose. In addition, stereolithography (SLA) [5] and PolyJet technology, where aesthetic, detail and surface finishes are the most important, can be used [6]. In FDM, a 3D printer uses the process in which thermoplastic filaments are extruded and deposited in thin layers based on a previously designed 3D model [7]. During this process, the printer ensures precise control over factors such as temperature and speed to regulate the flow of the polymer material [8].

In the workflow of 3D printing on textiles, 3D models should first be created in a 3D computer application and exported as stl files for slicing in a suitable software where the parameters for the 3D printing process are defined. Fixing a textile substrate to the printer bed to achieve stability and precise alignment of the threads is an important step in the workflow, as it affects the accuracy of the print. Some researchers mentioned fixing textiles with tape on the print bed [9] or using lacquer [10]. In addition, special mounting frames [11] can be prepared for precise positioning of a textile and clamps [12, 13] can be used for fastening to prevent the textile from slipping during the printing process.

The most common polymer for 3D printing on textiles using the FDM technology is polylactic acid (PLA). This polymer is predominantly used for all applications on a textile substrate. One of the notable advantages of PLA is its low extrusion temperature, which is typically around 210 °C. In addition, PLA is a biopolymer; thus, its biodegradability and renewability make it an environmentally friendly choice for 3D printing [14, 15].

Acrylonitrile butadiene styrene (ABS) is, along with PLA, one of the most widely used materials in FDM. It has a relatively low glass transition temperature and very good processing properties. While the shrinkage rate during the cooling process is low, the printing accuracy and dimensional stability are high [16]. ABS is also frequently used and tested in 3D printing on textiles [17–19].

Another material used for 3D printing is thermoplastic polyurethane (TPU). It has exceptional mechanical properties, e.g. tensile strength, abrasion resistance, hydrolytic stability, flexibility, durability and corrosion resistance. The polymer is composed of various soft and hard segments. These segments contribute to the unique properties and behaviour of TPU [20]. Tests have also shown that synthetic fabrics such as polyester, polyamide and laminated neoprene are compatible with TPU filaments. Direct 3D printing of TPU filaments onto neoprene can therefore offer many potential functional applications, e.g. protective clothing and other aesthetic 3D decorations [21, 22].

Polyethylene terephthalate (PET) copolymer is a modified version of polyethylene terephthalate in which additional monomers or additives are incorporated into the polymer chain. This modification can introduce specific properties and characteristics that make it suitable for 3D printing applications on textiles. It requires slightly higher temperature for 3D printing than PLA (240 °C). It has better mechanical properties than PLA and is also recyclable. Polyethylene terephthalate copolymer with glycol modification (PETG) was tested by Ercegović et al. for use in car interiors [23]. In the study, three different polymers were printed on the composite with a porous knit of polyester fibres (PET) on the front side. TPU polymers were found to have better adhesion properties than PLA and PETG, while TPU has a more polar character among the polymers and is hence suitable for printing on most textile substrates.

As the field of 3D printing continues to evolve, researchers and manufacturers are constantly exploring novel materials that expand the range of possibilities and enhance the capabilities of printed objects. These new materials bring forth diverse properties such as increased strength, improved flexibility, enhanced heat resistance, and even specialised functionalities like conductivity or bio-compatibility [24]. New thermoplastic filaments used in recent research for 3D printed polymer adhesion to textiles include polyamide combined with percentage of carbon fibres or glass fibres and high-performance polyolefin with percentage of glass fibres, which have strong mechanical properties and can withstand much higher temperatures than PLA, for example [25]. Furthermore, the adhesive forces between these new materials and textile substrates can vary significantly. Different materials may exhibit stronger or weaker bonding properties with specific types of fabrics or textile constructions. This allows for customisation and optimisation of the bonding process to achieve desired levels of adhesion and durability between the 3D printed objects and textile substrates.

2 Use of 3D printing on textiles

3D printing on textiles has become an important technology for manufacturing new products in recent years, at a time when new 3D technologies are on the rise and proving useful in many fields. One important area is medicine, particularly prosthetics, where customised products such as orthopaedic devices can be made [2], combining soft and flexible textile material with 3D printed material that provides a firm support. In these cases, knitted materials are usually used for the textile substrate. 3D printing on textiles can also be used for protective clothing [22]. Other area is textile for garment production, considerably textile design. Spahiu et al. made some experiments where 3D printed patterns were printed on a textile substrate for modifying the drape of a fabric [26]. 3D printing is also used for fabric surface decoration [27]. An open-pore fabric can be used as a substrate where adhesion is not a problem as the printed polymer can tightly bound into the open pores of the textile. The textile decorated by 3D printing can then be used to make garments [28], as shown in Figure 1.

Figure 1: Detail of fabric decorated with 3D printing (photo: Manca Drusany)

Many other 3D printing on textiles design projects are featured on the website of the company STRARASYS, which collaborates with numerous fashion and textile designers [29]. A breakthrough technique involves additive manufacturing on stretched fabrics that, once released, undergo a remarkable metamorphosis from a flat 2D pattern to a dynamic 3D geometry [30]. The literature review shows that 3D printing on textiles enables the versatility of new aesthetic and functional properties that will further expand the scope of applications; moreover, various textiles substrates can be enriched with some additional visual and physical properties through 3D printing [31, 32]. Recently, 4D printing (4DP), an advanced technology that combines functional materials and 3D printing, has been developing. It introduces time as the fourth dimension and enables the development of smart materials with versatile properties. By combining the 3D printing technology with textiles, dynamic and adaptable structures can be created that can change shape or properties based on external stimuli or environmental conditions. This integration of 3D printing with textiles expands the capabilities of 4D printing by incorporating the inherent properties and behaviour of the textile material into the final printed object. The key feature of 4DP is the shape memory effect (SME), which allows printed objects to respond to external stimuli, e.g. heat, moisture, electricity, magnetic fields. By leveraging SME, the 4DP technology eliminates the inherent rigidity of 3D printed prototypes and opens possibilities for complex smart textiles and fashion items in various industries [33].

3 Adhesion of 3D printed polymer on textile substrate

For the versatile use of polymer-textile composites, it is important that the 3D printed polymer bonds to the textile with sufficient force. A prerequisite for the production of quality products is therefore good adhesion of the 3D printed objects to the textile surface [11]. Adhesion between the polymer and the substrate is enabled by three primary mechanisms, i.e. mechanical coupling, molecular bonding and thermodynamic adhesion. These mechanisms play a critical role in establishing a strong and durable bond between the polymer material and substrate surface. Mechanical coupling or interlocking considers the mechanical penetration of the adhesive into the pores and voids of the solid surface, and is based on the penetration of the adhesive into the surface of the substrate. Molecular bonding is the predominant mechanism generally accepted as an explanation for adhesion between two closely spaced surfaces. In this process, intermolecular forces occur between the adhesive and the substrate, including dipole-dipole interactions, van der Waals forces and various forms of chemical interactions, e.g. ionic, covalent and metallic bonds. While the thermodynamic theory assumes that the adhesive adheres to the substrate at the interface due to interatomic and intermolecular forces, if close contact is achieved, only an equilibrium process is required at the interface [34]. In studies, it was found that when some polymers are printed on various textile substrates, physical interlocking bonds are formed without any chemical bonding between the polymer and the substrate material [17, 22]. The intensity of adhesion depends on factors from three different categories in the printing process, i.e. textile properties, printing parameters and the type of polymer printed [35]. These are also the main areas of interest for research in the field of adhesion of 3D printed objects to the textile substrate. The research is mainly conducted on woven and knitted fabrics; however, our focus in the article is on the adhesion of 3D printed polymer to woven fabrics.

3.1 Methods for testing adhesion

In the revised literature, three methods are used to quantify the adhesion of 3D printed parts to a textile substrate, i.e. a perpendicular tensile test, a shear test and a T-peel test. It was found that these tests are all suitable for evaluating the adhesion properties [37]. T-peel is the most used adhesion test which is usually performed according to the standard DIN 53530 [13, 17, 36–41]. Sometimes, the adhesion test was also conducted visually and experientially, as in the case of a study in which different textile substrates were 3D printed with different polymers in the form of snap and zip fasteners, and the composites were observed to see how they behaved when the functionalised fabric was washed [18].

3.2 Observing morphology

The morphology of 3D printed objects on textile substrates also provides information about possible physical bonding. The surface of the fabric has a significant effect on the adhesion properties; thus, observing the surface of the printed textiles plays an important role in the study of adhesion. The morphology of the fabric is closely related to the adhesion of the 3D printed polymer, as it allows the molten polymer to penetrate the pores of the fabric

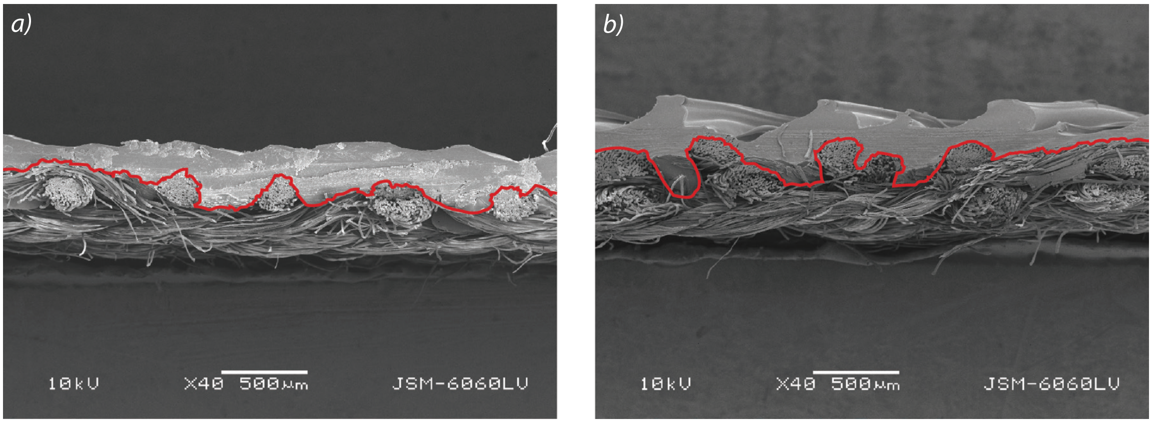

Figure 2: Cross-section of 3D printed fabrics: a) simple fabric, b) double fabric, both fabrics are cut in warp direction and printed at z-distance z = 0.25 mm, 40· magnification [11]

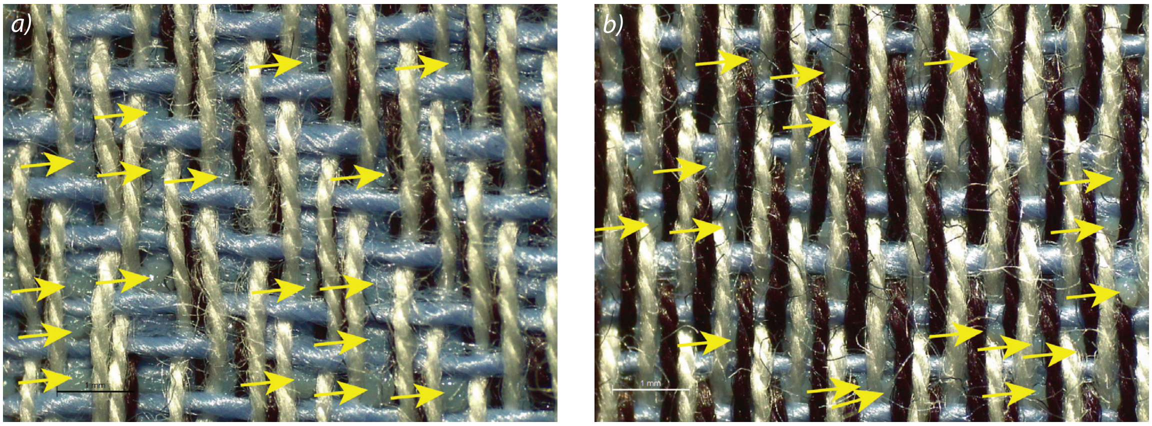

Figure 3: Images acquired with optical microscope, 20· magnification, of back of fabrics 3D printed with constant z-distance (z = 0.25 mm): a) double fabric, b) simple fabric, where deposits of penetrated molten polymer are marked [11]

structures [17, 40]. The images show how the printed polymer coats the threads in a fabric or protrudes through the textile substrate. Optical microscopes, confocal laser scanning microscopes or scanning electron microscopes are generally used to optically evaluate the composites, surfaces and their cross-sections [37–39, 41]. Figures 2 and 3 show the images taken with the scanning electron microscope and the optical microscope for the adhesion study.

3.3 Influence of 3D printing parameters on adhesion

Among the parameters of 3D printing, according to the research of most authors, the distance of the print head from the print bed or the textile substrate, i.e. the so-called z-distance, is the most important [17]. Other parameters, e.g. printing speed and temperature, print bed temperature and nozzle size, different infill orientations of the first printed layer [40] etc., also influence adhesion between the textile substrate and 3D printing polymer. Printing at a lower nozzle position is clearly advantageous for the adhesion [9]. Nevertheless, as the distance decreases, the adhesion force increases until reaching a minimum distance where the nozzle gets clogged by the filament [38]. Göksal et al. [25] suggest the necessary optimisation of the z-distance to achieve sufficient adhesion between the two materials, while the importance of this printing parameter proposes further research to optimise this value without first performing a series of tests, such as measuring the force the textile fabric exerts against the nozzle or polymer flow.

3.4 Influence of woven fabric composition on adhesion

The most influential parameters affecting the properties of woven fabrics are the warp and weft raw materials, warp and weft count, warp and weft density, and the type of weave. These parameters have a significant effect on the structure and appearance of the woven fabric [42]. All the revised research has clearly confirmed that the adhesion strength of the 3D printed polymer depends on the fabric structure. Subsequently, much research has been conducted on how specific construction parameters of the textile substrate itself affect the adhesion of the 3D printed polymer.

The following influencing factors were analysed on woven fabrics in relation to the adhesion strength of 3D printed polymer to the textile substrate: areal density [13], warp and weft density [13, 43, 44], yarn count [13], fabric thickness [9, 13, 45], weave patterns, e.g. plain weave, twill, broken twill, satin and hopsack [43, 44, 46, 47].

Yarn count

Yarn count is a numerical expression that defines yarn fineness. The count is a number indicating the mass per unit length in the direct system (e.g. Tex system) or the length per unit mass of yarn in the indirect system (e.g. metric count system – Nm). Yarn count can be tested using the ASTM D1059-01 or ISO 7211-5 standard. Few studies have been conducted examining only yarn count for its effects on adhesion. Mpofu et al. [13] concluded in their research that the adhesion force increases with increasing yarn count or yarn diameter. Silvestre et al. [10] also led a study in which the conductive material (PLA graphene) was printed on various woven textile substrates. It was found that the adhesion of the printed polymer to the textile substrate was greater at higher thread count. This could indicate that increasing the warp and weft thread count increases the yarn diameter and consequently the surface area to which the polymer adheres on the fabric.

Warp and weft density

Warp and weft density refers to the number of threads per unit length in warp and weft direction. The testing of warp and weft density (ends/cm, wefts/cm) is performed in accordance with the ISO 7211-2 standard. When considering the influence of warp and weft density on adhesion, it was generally found that higher warp and weft density results in a lower adhesion force [13, 47, 49]. In one of the research projects [44], weft densities (weft/cm) were predefined in the weaving process, which enabled a precise and systematic observation of the adhesion force. The findings were the same as at other studies, i.e. the highest adhesion force was found at the lowest weft density and the lowest adhesion was found at the highest weft density.

The observed phenomenon can be attributed to the relationship between warp and weft density and fabric cover factor. As the warp and weft density increased, the fabric cover factor decreased. This reduction in the fabric cover factor led to a decrease in fabric pores, limiting the diffusion of the polymer into the fabric. Consequently, the reduced diffusion resulted in lower adhesion force [13]. This can be explained by the fact that as the density of weft yarns increases, the polymer can hardly enclose individual yarns. As a result, the polymer has less surface area available to adhere to the fabric, which reduces the adhesion force [44].

Fabric thickness

Multiple studies have consistently demonstrated a direct association between fabric thickness and adhesion force, indicating that an increase in fabric thickness corresponds to a subsequent increase in adhesion force. These findings emphasise a positive relationship between these two variables, suggesting that thicker fabrics generally exhibit higher adhesion forces [13, 44, 45, 48, 50]. These good adhesion results may be due to the bonds of the printed polymer with the fibres on the top of the textile as well as inside the textile structure, which should provide enough open areas for the molten polymer to penetrate inside [17, 18, 45]. However, in a study performed by Störmer et al. [9], the results of the adhesion test regarding the fabric thickness unexpectedly showed the highest adhesion force for a thin fabric.

Fabric material, type of yarn

The studies of adhesion properties were conducted on textile substrates with different raw material compositions. Most frequently, investigations were implemented on cotton and polyester (PES), other materials were tested as well. In general, it was found that better adhesion can be achieved if the textile surface is roughened or hairy as shown for the polyester (PES), cotton (CO) and wool (WO) sample [22]. In some cases, it has been established that certain combinations of materials do not produce high adhesion force, e.g. PLA polymers on polyamide (PA) fabric, since the two polymers are not compatible [47].

In later research, Demir at al. [51] compared jute, flax and cotton fabrics regarding adhesion between 3D printed PLA and textile substrate. The aim of the research was to investigate the influence of fabric treatments on adhesion, untreated samples also being tested and compared. Untreated flax fabrics woven in plain weave were found to adhere better than cotton twill fabrics, which have no notable pores on the fabric surface. On the other hand, lower adhesion strength was measured on more porous jute fabrics than on flax fabrics.

Weave pattern

Several studies have been conducted on the effects of weave pattern on the adhesion of 3D printed polymer to a textile substrate. Mainly plain weave, twill and satin were tested, next to broken twill weave, hopsack and satin. In most cases, adhesion was found to be higher with twill compared to plain weave [43]. In a study by Malengier et al. [36], it was also established that a plain weave fabric reaches the least adhesion compared to twill and satin. In that study, they showed that the twill fabric was the best textile substrate for the 3D printing of PLA filament, regarding the adhesion. In a study by Silvestre et al. [10], better adhesion was achieved in the satin fabric than in twill and plain weave.

Comparison of simple and double fabrics

A recent study by Čuk et al. investigated the adhesion of 3D printed polymers to textile substrates, specifically comparing double-weave structures with simple fabrics. Simple weave fabrics consist of a single set of warp and weft threads interwoven in a weave pattern, creating a single-layer fabric, while double weave fabrics consist of two sets of warp and weft threads, creating a double layer or double fabric [11]. Double fabrics are namely an extremely suitable textile substrate for 3D printing applications, as the materials for the top and bottom layers of the fabric can be different, thus creating different fabric functionalities [52]. In addition, a special thread can be inserted into the space between the layers to achieve specific characteristics of a fabric, e.g. temperature sensing [53]. The results of the research [11] showed remarkable differences between the two types of fabrics and emphasised the significant influence of the z-distance parameter on the adhesion force. This study highlights the complicated relationship between fabric structure, z-distance and adhesion strength in 3D printing applications on textiles. The study was performed on samples printed with two different z-distance settings. One part of the samples was printed with a constant z-distance (z1), which means that the height of the print head remained the same regardless of the thickness of the fabric, and was 0.2 mm. In this way, the nozzle was always positioned relatively deep into the fabric when printing the first layer. The other part was printed with a constant z-distance offset (z2) from the fabric surface, which means that the height of the nozzle varied and was adjusted to the fabric thickness. For each fabric sample, the nozzle was 0.1 mm below the surface when the first layer was printed. At constant z-distance, all samples showed higher adhesion strength than the samples printed at constant z-distance offset. When printing with a constant z-distance (z1), simple fabrics had weaker adhesion compared to thicker, double-layer fabrics, as print nozzle penetrates deeper into thicker fabric. Figure 2 above shows the cross-section of the (a) printed simple fabric and the (b) printed double fabric cut in warp direction. Both fabrics were printed with a z-distance of 0.25 mm. The images were taken with a scanning electron microscope. Figure 3 above shows the backs of the printed simple and double fabric samples. Both samples were printed with a z-distance of 0.25 mm. Numerous deposits of molten polymer can be seen on both samples, which penetrated through the pores of the fabric.

The printer nozzle penetrates deeper into a double weave fabric and the polymer penetrates through the pores of the upper layer into the lower layer, where it adheres to the yarns or fibres. In addition, double weaves have higher thread density; however, the threads are arranged in two layers and grouped according to the weave. As a result, the structure of the fabric is less compact, the specific surface area is larger, and thus, the adhesion is better.

Conclusion about textile properties influencing adhesive strength

The adhesion of materials to a textile in the context of 3D printing has been predominantly explained using the mechanical adhesion theory. This theory suggests that the adhesion strength is improved due to the roughness and porosity of textile surfaces. However, a comprehensive understanding of the adhesion properties of thermoplastic polymer layers deposited on textiles through 3D printing requires the integration of both diffusion and mechanical theories. By combining these two theories, a more complete understanding of adhesion mechanisms can be achieved, considering the interplay between surface roughness, porosity and molecular diffusion processes [43].

A review of research results revealed that the fabric construction parameter thickness appears to have a huge impact on the adhesion strength of the 3D printed polymer to the woven fabric.

Fabric thickness is determined by various factors, including yarn diameter, the degree of compression between interlaced threads and the presence of float sections within the weave repeat [54].

In other words, fabrics with different weaves, yarn count, thread density and raw material have different thickness; therefore, different adhesion forces can be expected. Consequently, the z-distance parameter must be optimised for each fabric regarding its thickness to print inside the substrate and to enhance the adhesion strength. It is important to note that some fabrics are more compressible that others [55]. Fabric thickness should hence be precisely measured before the printing process. In the research, fabric thickness was measured using textile thickness testers and the measurements were performed according to the standards [9, 11, 40]. Furthermore, a micrometre calliper was used to measure the thickness of a fabric with higher pressure, which can be compared to the nozzle pressure during 3D printing [9, 22].

Similarly, fabric roughness is influenced by the particular weave structure, the number of individual pores formed within the weave, as well as the densities of threads and any irregularities in the yarn [54]. Moreover, in the literature, fabric roughness was determined as a factor that positively correlates with the adhesion strength [13, 43]. The mean pore size also has a substantial influence on adhesion as found in the research by Eutionnat-Diffo et al. [43]. A higher mean flow pore size of the textile material could substantially enhance the adhesion strength.

Fabric parameters exert a significant influence on the maximum achievable adhesion forces between 3D printed polymers and textiles. However, the above presented parameters may not be adequate for accurately predicting adhesion forces for a particular fabric. In some cases, only a general trend can be discerned, highlighting the complexity and multifactorial nature of the adhesion process [17].

3.5 Improvement of adhesion with pre-treatment and after-treatment

The adhesion of 3D printing to a textile substrate can be increased by various pre- and after-treatment processes, as studies have shown. Polymer coatings on textiles can lead to a significant increase in adhesion [17]; various chemical pre-treatments can be successfully applied as well [51]. Kozior et al. [40] found that a glue stick in particular increased adhesion between cotton and PLA. Furthermore, other textile surface treatments to adjust the textile surface properties, e.g. hairiness or hydrophobicity, can improve adhesion. For example, washing the textile substrate [35] can result in a more hydrophilic surface, which confirms the statement of Korger et al. [45] that a hydrophilic surface of the textile substrate means a higher adhesion strength. A thermal treatment was researched as a possible after-treatment and in most cases confirmed to have a positive effect on adhesion strength, e.g. the research by Görmer et al., where ironing was performed [56].

4 Conclusion

Compared to knitted textile substrates, which are stretchable in several directions, and thus very flexible and more elastic than woven fabrics, the latter offer greater dimensional stability as well as the possibility of using stiffer yarns, which is advantageous in achieving certain properties in the production of protective clothing, technical textiles, decorative and apparel textiles etc., making them an ideal textile substrate for many different applications of 3D printing.

The literature review confirmed the fact that the influence of fabric construction on the adhesion of 3D printed polymers to a fabric is significant and must be constantly monitored and evaluated in the context of other parameters of 3D printing on textiles, e.g. the printing material used and the printing process itself. It was also found that the influence of the 3D printing process has been studied more, as changes can be made in a very controlled and systematic way, while this is usually difficult with fabric construction parameters. Therefore, the ability to produce fabrics for research, which was found only in few research papers, is of great value as the fabric construction parameters can be more precisely controlled in this way.

To achieve higher adhesion, it is necessary to design the textile substrate to have sufficient open area on which the molten polymer can adhere. In general, the improvement of adhesion is possible by increasing the roughness and porosity of a textile material. According to the research reviewed, such conditions can be achieved by increasing fabric thickness, double weave, lower thread density etc. Among other parameters which have a strong influence on adhesion and are not related to the construction of the fabric, the distance between the print head (nozzle) and the fabric is certainly the most important. Of course, more and more researchers are focusing on pre- and post-treatment, which also has a major impact on the adhesion of 3D printing to textiles; however, this was not the main focus of the review presented in this article.

In general, the adhesion force in 3D printing on textiles is primarily influenced by the properties of the textile substrate rather than the properties of the printing material; hence, the choice of a textile plays a crucial role in determining the adhesion force between the printed object and the fabric surface.

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