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THE INFLUENCE OF FDM TECHNOLOGY PARAMETERS UPON PRINTING ONTO TEXTILE SUBSTRATES

BY

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Abstract. The integration of additive manufacturing into textile and fashion engineering has enabled the development of hybrid material systems and novel fabrication strategies. Among the various 3D printing technologies, Fused Deposition Modeling (FDM) is widely utilized due to its accessibility, material compatibility, and the extensive control it offers over process parameters. While prior research has primarily focused on optimizing interlayer bonding and structural performance in conventional FDM applications, the direct deposition of polymers onto textile substrates introduces a distinct set of challenges, particularly in achieving reliable adhesion to flexible, porous surfaces. Existing literature has predominantly examined this issue from the perspective of textile properties–such as weave structure, fiber composition, and surface topography–while considerably fewer studies have addressed the role of printing parameters. This review consolidates and critically evaluates current research that investigates the influence of FDM process settings–including nozzle and bed temperature, nozzle-to-substrate distance, print speed, flow rate, and cooling conditions–on the adhesion performance of polymer–textile interfaces. The review aims to identify recurring trends, highlight unresolved challenges, and outline promising directions for future investigations in this rapidly evolving area.

Keywords: 3D printing; settings; parameters; adhesion; textiles; fabric.

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1. Introduction

Over the past decade, Fused Deposition Modeling (FDM) 3D printing has evolved from a prototyping tool into a widely used method for manufacturing, driven by advancements in materials, hardware, and slicing software. Standard parameters for materials like PLA–such as nozzle temperatures between 190°C and 215°C, bed temperatures around 60°C, and print speeds of 30–50 mm/s–have proven effective for achieving good interlayer bonding and surface quality in conventional applications. However, in the emerging field of 3D printing directly onto textiles, these default settings require reconsideration.

The integration of 3D printing onto textile substrates offers significant opportunities for innovation in fashion, functional apparel, and technical textiles, enabling the creation of hybrid materials with enhanced properties and custom functionalities. This integration facilitates advanced applications including sensor integration and the use of conductive polymers, enabling garments to sense environmental stimuli, monitor physiological conditions, and transmit data. Additionally, mechanical functionalities such as articulated joints, flexible structures, and adaptive support elements can be integrated directly onto textiles, significantly enhancing their practical utility and ergonomic performance. Successfully addressing adhesion challenges between polymers and textiles is critical to harnessing these opportunities. Improved adhesion ensures greater durability, wash resistance, and performance consistency of printed structures, thereby expanding their practical applications. Achieving reliable polymer-textile bonding not only enhances the mechanical and aesthetic qualities of composite materials but also fosters sustainability by enabling the creation of more durable and versatile products.

Extended research in this area has primarily focused on how textile-related factors–such as yarn composition, weave density, thickness, and porosity–affect adhesion (Sheron *et al.*, 2018; Čuk *et al.*, 2020; Kočevar, 2023). While this has generated valuable insights, printer-side parameters that can be directly controlled during the manufacturing process have received comparatively less attention. As polymer–textile adhesion is a complex phenomenon involving mechanical interlocking, thermal dynamics, and surface compatibility, printer settings may play a critical role in achieving reliable and durable bonding.

This review aims to synthesize recent studies that deliberately varied FDM printing parameters to improve adhesion between polymer and textile substrates. The focus is placed on parameters such as nozzle temperature, bed temperature, Z-distance, flow rate, and first-layer print settings. Additionally, the review highlights underexplored variables–including cooling fan control and print speed modulation–that may significantly impact first-layer behavior. By mapping the current landscape of research and identifying consistent findings, contradictions, and methodological gaps, this work seeks to provide a foundation for further innovation in textile-integrated 3D printing.

1.1. Methodology of Literature Selection

This review focuses on identifying and analyzing studies that investigate the influence of Fused Deposition Modeling (FDM) printing parameters on adhesion to textile substrates. The literature selection was conducted based on a targeted search of publications from the period 2016 to 2023. Three primary sources were used to retrieve relevant articles: ScienceDirect, ResearchGate, and reference tracing from highly cited and thematically related publications.

Keyword combinations such as "*3D printing fabric*", "*3D printing textiles*", and "*FDM adhesion*" were used to locate studies specifically addressing the interaction between polymer deposition and textile surfaces. Studies that focused on other additive manufacturing technologies (e.g., SLA, SLS) or on textile property analysis without reference to printer settings were excluded from the core review.

In total, approximately 48 papers related to 3D printing on textiles were screened. Of these, 18 studies that explicitly investigated the effect of printer-side parameters–such as extrusion temperature, bed temperature, Z-offset, print speed, and flow rate–on polymer–textile adhesion were selected for in-depth analysis. Additional references focused on textile characterization are mentioned briefly in the introduction to provide context but are not central to the technical synthesis.

2. FDM Printing Parameters and Methods Influencing Adhesion

A standard slicer such as Cura or Orca Slicer allows adjustment of dozens of parameters related to material extrusion, movement, and thermal control. Despite the wide range of adjustable variables, only a limited number have been specifically identified as having a direct impact on adhesion to textile substrates. Most studies have focused on a few key parameters–such as speed, nozzle temperature, bed temperature, Z-distance, and first layer orientation–while many others remain unexplored in this context.

Due to the wide variation in experimental designs, material combinations, and adhesion test methods across the reviewed studies, direct quantitative comparisons between parameter effects are not feasible. For this reason, no unified table summarizing numerical outcomes is included, as such a synthesis would risk misrepresenting the underlying methodological inconsistencies. Instead, qualitative patterns and parameter sensitivities are discussed contextually within each subsection.

2.1. Main parameters (Z-distance, printing speed, nozzle and build plate temperature)

Döpke *et al.* (2016) investigated the adhesion of PLA to knitted textile substrates, representing one of the earliest studies to vary printer settings to improve adhesion. The study found that z-distance–the nozzle-to-surface gap–directly influenced adhesion, likely due to the pressure exerted by the molten polymer as it infiltrates the textile structure. Nozzle diameter was also varied between 0.4 mm and 1 mm, with larger diameters showing a positive correlation with adhesion strength. In contrast, flow rate and bed temperature were reported to have minimal influence on adhesion in the tested conditions. As depicted in Fig. 1 adhesion forces were measured for PLA prints produced with varying nozzle diameters.

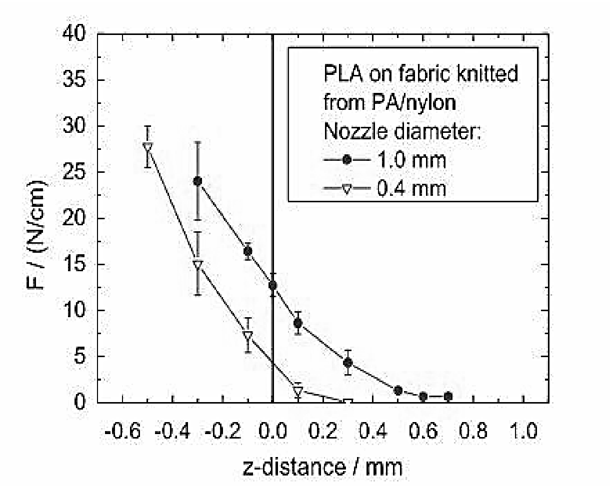

Fig. 1 – Adhesion forces, measured between PLA prints with different nozzle diameters at different z-distances (source: Döpke *et al.*, 2016).

Spahiu *et al*. (2017) examined the influence of various printer settings on polymer–textile adhesion. Reducing the print speed from 37.5 mm/s to 22.5 mm/s led to a slight improvement in adhesion. Increasing the extrusion temperature from 200°C to 220°C resulted in a more substantial improvement, attributed to the lower viscosity of the molten polymer.

Consistent with previous findings, flow rate showed no significant effect. Bed temperature, however, had the most pronounced impact: raising it from ambient (20°C) to 60°C and 100°C greatly improved adhesion by allowing PLA to remain fluid longer and penetrate the textile structure. However, at 100°C, irregular deformation of the print was observed, likely due to prolonged overheating. Z-distance was also varied and found to significantly affect adhesion, in line with earlier studies. Illustrated in Fig. 2, from left to right, are the influences on the adhesion of printing speed, nozzle temperature, bed temperature and flow rate. Wash tests at 40°C did not reveal notable changes in adhesion performance.

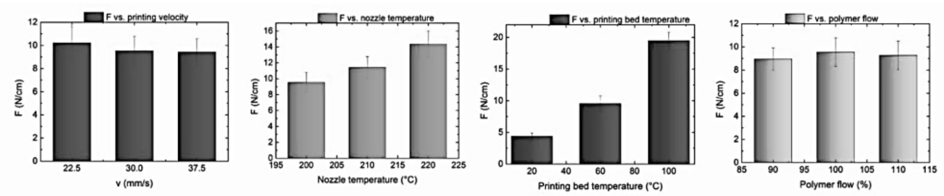

Fig. 2 – Influences on the adhesion of printing speed, nozzle temperature, bed temperature and flow rate (source: Spahiu *et al*., 2017).

Rivera *et al.* (2017) explored various applications and functionalities of direct 3D printing onto textile surfaces. Fig. 3 illustrates how simple segments of straight plastic with a bend angle and a channel built in, can be transformed into a roll by pulling a string through the channel.

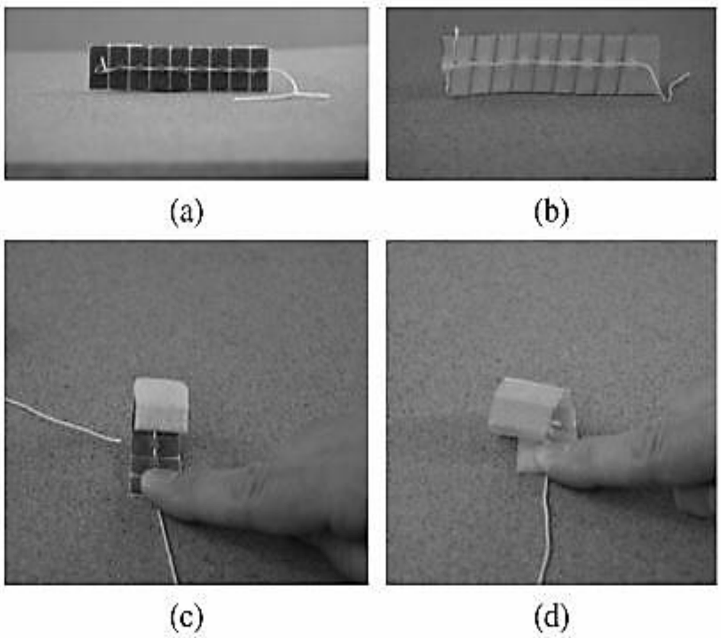

Fig. 3 – Example of a rolling functionality (source: Rivera *et al*., 2017).

Adhesion strength was evaluated using an Instron Model 5567 tensile testing machine to measure the force required to detach the printed polymer from the fabric (Fig. 4). The results indicated that textile type, print geometry, and printer settings significantly affect the degree of adhesion between the materials.

Fig. 4 – Adhesion testing assembly (source: Rivera *et al*., 2017).

The study also highlighted technical challenges, including difficulties in securing the fabric to the print bed and its behavior during printing (Fig. 5). Additional limitations were noted regarding the long-term durability of the combined materials, due to interactions between the rigid polymer and the flexible textile, as well as constraints imposed by the limited build volume when printing larger objects.

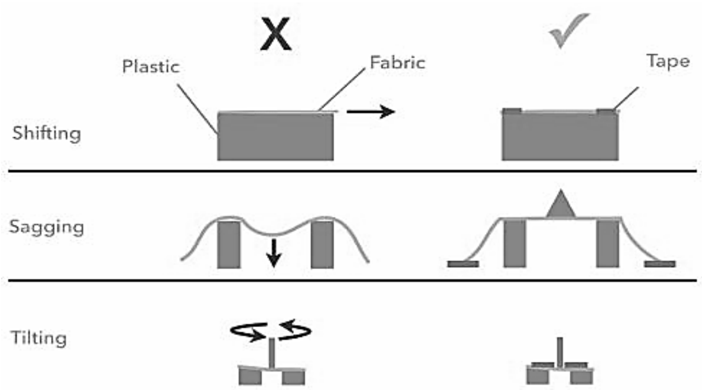

Fig. 5 – Different problems and solutions when printing on textiles (source: Rivera *et al*., 2017).

Hashemi Sanatgar *et al.* (2017) also demonstrated that extruder temperature and print speed have a significant impact on polymer–textile adhesion strength. In contrast, bed temperature was found to be relevant only when it exceeded the glass transition temperature of the textile substrate.

Eutionnat-Diffo *et al.* (2018) highlights the potential of using FDM for smart textile manufacturing, showing that platform temperature, heat transfer, and the structural properties of both polyester fabrics and PLA filament influence adhesion. Achieving optimal adhesion may require adjusting FDM parameters based on the textile substrate or modifying the textile itself. However, challenges remain in ensuring process repeatability across different fabric types due to variations in thermal behavior and structure.

Spahiu *et al.* (2018) examined the influence of Z-distance, bed temperature, identified as the most critical variables. The results indicated that higher bed and nozzle temperatures, combined with a reduced Z-distance (above the nozzle clogging risk threshold), significantly improved adhesion. It was also observed that Z-distance could be increased at elevated temperatures to compensate for thermal expansion of the bed and filament within the nozzle. Additionally, variations in substrate compressibility were noted, suggesting a potential influence on adhesion. While this aspect was not explored in depth within the study. It was later addressed by Meyer *et al*. (2019) which emphasized the importance of optimizing Z-distance, not only based on fabric thickness but also considering the compressibility of the textile substrate.

Eutionnat-Diffo *et al.* (2020b) evaluated the influence of build platform temperature, textile structure, and thermal transfer on the adhesion and wash durability of 3D printed PLA layers on PET fabrics. The results indicated that increased surface roughness, higher porosity, and lower thermal conductivity of the textile substrate enhance adhesion. Platform temperature exhibited a quadratic effect on bonding strength. Although adhesion was reduced by approximately 50% after washing, more porous and rougher textile structures contributed to improved durability of the printed layers.

Kozior *et al.* (2020) reviewed existing literature on 3D printed polymer adhesion to textile substrates, identifying several key 3D printing parameters that influence bonding. The study emphasized that low polymer viscosity and high pressure can promote penetration into the fabric, enhancing mechanical interlocking. Pressure was noted to be closely related to Z-distance and affected by the extrusion temperature. Additionally, the authors pointed out that some parameters commonly studied in inter-layer adhesion–such as print speed–have not been thoroughly investigated in the context of textile printing and remain inconclusive in current literature.

Mpofu *et al.* (2020) demonstrated that 3D printing parameters influence the mechanical and adhesive properties of PLA/textile composites. Extrusion temperature, printing speed, and model height were identified as key factors affecting adhesion (Fig. 6), both before and after washing, whereas infill density had no significant impact by itself. Adhesion force was positively correlated with extrusion temperature and negatively correlated with both printing speed and model height. Washing reduced adhesion in all cases. Similarly, tensile strength increased with temperature and decreased with higher printing speed and model height.

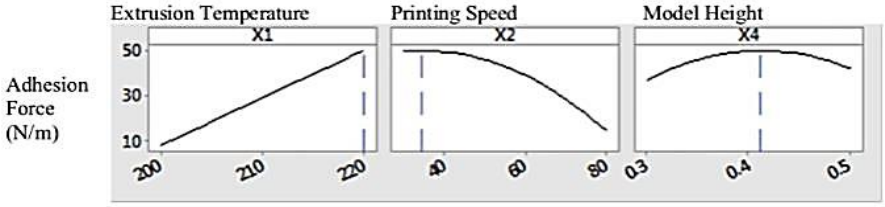

Fig. 6 – Key factors affecting adhesion (source: Mpofu *et al*., 2020).

2.2. Additional parameters (infill pattern, angle and density)

In 3D printing, the infill refers to the internal structure of a printed object, typically composed of a repeated geometric pattern that fills the space between the outer walls (or shells). Its primary function is to provide internal support and influence mechanical properties such as strength, weight, and material consumption. Infill patterns, density, and orientation are customizable and are generally not visible from the outside of the object. Importantly, the infill does not normally come into contact with the build platform or substrate, as it is enclosed by the bottom and top solid layers. Therefore, under standard conditions, infill parameters would not directly affect adhesion to the textile substrate as mentioned by Mpofu *et al.* (2020) in their findings.

However, in some studies, researchers intentionally removed the bottom layers to print directly with the infill structure, in order to be able to change parameters such as pattern, angle and density–settings that were only accessible for infill and not for bottom layers in the slicing software. As a result, findings based on these modified setups may incorrectly attribute adhesion effects to infill properties rather than to the altered behavior of the first printed layer.

Kozior *et al*. (2018) investigated the influence of textile pretreatments and infill orientation on the adhesion strength of PLA printed directly onto cotton fabric. The tests showed that a 90° infill orientation resulted in the highest adhesion, while orientations of 0° and above 90° led to reduced bonding (Fig. 7).

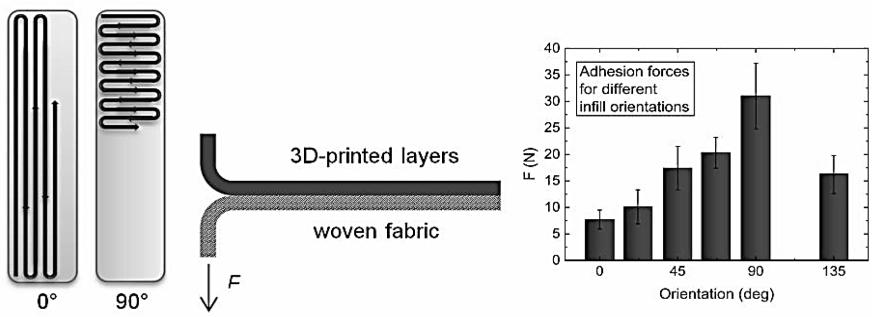

Fig. 7 – Correlation between first layer orientation and adhesion (source: Kozior *et al*., 2018).

Redondo *et al.* (2020) investigated the influence of print angle on the adhesion of 3D printed PLA onto cotton fabric substrates, varying its orientation between 45°, 90°, and 180°. Peel tests revealed that printing at a 45° angle resulted in the strongest adhesion.

Singh *et al*. (2021) also investigated the effect of infill type and density on the adhesion between 3D printed material and textile substrates. The study concluded that increasing the infill percentage enhances the adhesive bonding between the printed polymer and the fabric surface. Fig. 8 illustrates two test samples being printed with honeycomb infill pattern in two different densities.

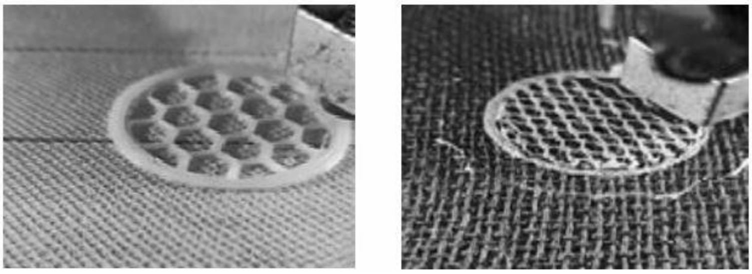

Fig. 8 – Honeycomb pattern in two different densities
(source: Singh *et al*., 2021).

2.3. Testing methods

In the literature, a significant number of researchers have measured adhesion using the T-peel test method. This approach involves printing a thin polymer layer, which bends during testing.

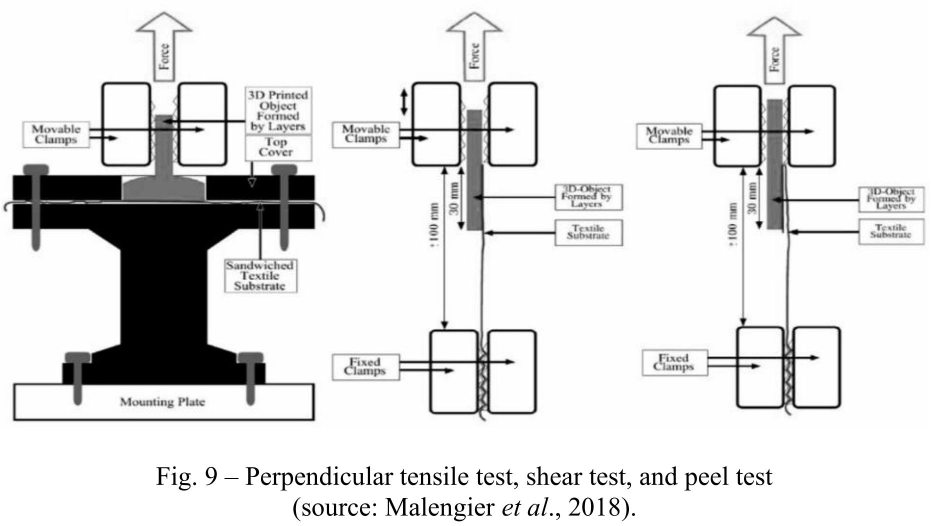

Fig. 9 – Perpendicular tensile test, shear test, and peel test
(source: Malengier *et al*., 2018).

However, except in cases where the polymer is soft or elastic, bending rigid polymers often results in deformation or fracture–either of the polymer or the textile substrate–potentially compromising the accuracy of the results. Malengier *et al*. (2018) presents three proper methods for evaluating adhesion and their properties: (A) perpendicular tensile test, (B) shear test, and (C) peel test (Fig. 9). The shear and peel methods treat the polymer as a solid material and involve printing thicker test pieces to reduce deformation. Despite this adjustment, both methods frequently led to tearing of the textile substrate during testing. The study concluded that the perpendicular tensile test is the most appropriate method for assessing adhesion, as it minimizes the risk of damaging the fabric. In this configuration, the polymer is pulled vertically–along the same direction it infiltrated the textile–without exerting significant lateral stress on the fabric structure.

2.4. Additional Findings in the Literature: TPU, Conductive Materials, and Alternative Approaches

Özev and Ehrmann (2023) investigated the integration of cotton and aramid fabrics into 3D printed structures. Unlike most studies that focus on achieving surface adhesion between the printed material and the textile, this research explored the embedding of fabrics within internal cavities of the print–an approach relevant for stab resistant clothing applications. Small protrusions were designed within the 3D printed structure to secure the fabric in place and prevent vertical displacement. Both PLA and TPU were tested, with TPU yielding promising results despite its higher printing complexity at the time. The integrated protrusions effectively held the textiles in place, showing no fabric movement even after repeated bending tests.

Cakar and Ehrmann (2023) investigated the stab resistance properties of three TPU filaments with different hardness levels (Shore 98A, 85A, and 82A) printed onto viscose fabric. The results showed that the highest adhesion was achieved with the softest filament, TPU 82A, while TPU 85A and 98A demonstrated superior performance in stab resistance tests. These findings suggest a potential multi-material strategy, in which a soft TPU layer (82A) is used as the initial layer to enhance adhesion, followed by harder TPU layers to provide increased stab resistance.

Eutionnat-Diffo *et al.* (2020a) investigated the abrasion resistance of 3D-printed polymer-on-textile (3D-PPOT) materials fabricated via Fused Deposition Modeling (FDM). The study found that weave type, weft density, and platform temperature were the most influential factors affecting both weight loss and wear endpoint. In contrast, the printing direction had no effect on abrasion resistance. Optimal performance was achieved using plain weave fabrics with the highest weft density and the lowest bed temperature. While porous and rough textile substrates improved adhesion between the printed polymer and the fabric, they negatively impacted abrasion resistance. The 3D-printed conductive PLA materials exhibited greater structural compactness, lower porosity, and enhanced fiber cohesion, resulting in higher abrasion resistance and reduced material loss compared to unprinted fabrics. However, abrasion significantly impaired the electrical conductivity of the printed conductive layer.

One of the most innovative studies to strategically exploit printer settings is that of Forman *et al.* (2020), who developed "DefeXtiles"–a material that mimics woven textiles not through traditional pillar structures, but by harnessing under-extrusion, typically considered a 3D printing defect. By deliberately reducing the flow rate from the standard 95–100% to 30–50%, the researchers achieved thin, lightweight, flexible sheets with intermittent bonding that created a woven-like appearance. This work demonstrated how precise control of extrusion parameters can turn a printing flaw into a functional design strategy, enabling the creation of textile-like materials without the need for supports or assembly.

2.5. Limitations and Directions for Future Research

One of the most significant limitations in the current body of research on FDM printing onto textile substrates is the absence of standardized testing protocols for evaluating polymer–fabric adhesion. Various studies employ different methods–such as T-peel, shear, or tensile tests–often with custom geometries, material combinations, and sample preparation procedures. This lack of methodological uniformity makes direct comparisons between studies problematic, limiting the ability to isolate and quantify the individual impact of specific printing parameters across the literature. As a result, it is currently difficult to construct a cohesive framework or set of best practices based solely on the data available. Establishing standardized testing conditions, including sample size, fabric type, print geometry, and load application method, would represent a major step forward for the reproducibility and comparability of results in this field.

In addition, a critical yet often overlooked parameter in the reviewed literature is the cooling fan operation, particularly during the first layer of the print. Only a limited number of studies explicitly state whether the part cooling fan was enabled or disabled, and it is likely that its status varied unintentionally between experiments depending on slicer defaults. This oversight is significant, as active cooling can substantially reduce the surface temperature of the extruded polymer, potentially limiting its ability to bond effectively with the textile substrate. Since adhesion relies heavily on thermal interdiffusion and partial infiltration of the polymer into the porous fabric, maintaining an elevated temperature during the first layer is critical. Future research should systematically investigate the role of cooling fan control–both in terms of on/off status and fan speed–and its interaction with other thermal parameters such as nozzle and bed temperature, in order to fully understand its impact on adhesion performance.

Another promising yet underexplored direction in the context of FDM printing onto textiles is the use of multi-layer or multi-material strategies to enhance adhesion and functional performance. While a few studies have begun to investigate the sequential deposition of different thermoplastic materials–such as a soft initial layer for improved bonding followed by harder layers for structural reinforcement (Cakar and Ehrmann, 2023) –systematic research in this area remains limited. Layered material approaches may enable a more controlled balance between flexibility, durability, and adhesion strength, particularly in wearable applications that require both comfort and resistance to mechanical stress. Further investigations are needed to assess the interfacial behavior between dissimilar materials when printed onto fabrics, as well as the long-term durability of such composites under repeated bending, abrasion, and washing cycles. Incorporating gradient materials or interface-optimized transition zones could represent a significant advancement in the design of textile–polymer hybrid systems.

3. Conclusions

This review has highlighted that adhesion between FDM-printed polymers and textile substrates is highly sensitive to a small set of printer-side parameters, particularly those affecting the first printed layer. Variables such as nozzle temperature, bed temperature, Z-offset, and print speed have consistently shown significant influence over interfacial bonding. When carefully adjusted, these settings can enhance polymer flow, promote mechanical interlocking, and improve overall adhesion quality.

Although the reviewed studies provide valuable insights, direct comparisons remain challenging due to divergent methodologies and experimental setups. Nevertheless, the consistent appearance of key trends across independent research efforts reinforces the importance of printer-controlled variables in textile-integrated additive manufacturing.

By consolidating current findings, this work contributes to a more coherent understanding of parameter influence in FDM-textile systems and lays the groundwork for more systematic and reproducible future studies in this field.

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INFLUENȚA PARAMETRILOR TEHNOLOGIEI FDM ASUPRA IMPRIMĂRII PE SUBSTRATURI TEXTILE

(Rezumat)

Integrarea fabricației aditive în ingineria textilelor și a modei a permis dezvoltarea unor sisteme de materiale hibride și a unor noi strategii de fabricație. Dintre diferitele tehnologii de imprimare 3D, Fused Deposition Modeling (FDM) este utilizată pe scară largă datorită accesibilității sale, compatibilității materialelor și controlului extins pe care îl oferă asupra parametrilor procesului. În timp ce cercetările anterioare s-au axat în principal pe optimizarea aderenței între straturi și a performanței structurale în aplicațiile FDM convenționale, depunerea directă de polimeri pe substraturi textile introduce un set distinct de provocări, în special în ceea ce privește obținerea unei aderențe fiabile la suprafețele flexibile și poroase. Literatura de specialitate existentă a examinat această problemă în principal din perspectiva proprietăților materialelor textile - cum ar fi structura țesăturii, compoziția fibrelor și topografia suprafeței - în timp ce mult mai puține studii au abordat rolul parametrilor de imprimare. Această analiză consolidează și evaluează critic cercetările actuale care investighează influența parametrilor procesului FDM - inclusiv temperatura duzei și a patului, distanța dintre duză și substrat, viteza de imprimare, rata de extrudare și condițiile de răcire - asupra performanței de aderență a interfețelor polimer-textil. Această revizuire urmărește să identifice tendințele recurente, să evidențieze provocările nerezolvate și să contureze direcții promițătoare pentru cercetările viitoare în acest domeniu care evoluează rapid.