

# 3D printing on pre-stressed textiles: peel test evaluation of adhesion factors in 4D textiles

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1

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## Abstract

**Purpose** – 4D textiles are created through 3D printing on pre-stressed textiles. The flexible textiles generate tension during the printing process, while the 3D-printed structure acts as a reinforcement, storing this tension within the material. These components undergo state transitions in response to external stimuli. In such cases, it is essential to ensure that the printed elements remain reliably bonded to the textile substrate and do not delaminate. Therefore, the interface between the 3D-printed structure and the textile property plays a crucial role. In order to solve this potential problem and reduce material and time consumption in the experimental phase, a systematic investigation of adhesion performance is necessary.

**Design/methodology/approach** – This study systematically examines the key parameters influencing adhesion at this interface, including textile type, printing parameters, printed materials and pre-tensioning. A comprehensive 2<sup>n</sup> factorial experimental design was employed to analyse the interactions between these parameters. Adhesion strength was evaluated using 180° peel tests. Mathematical evaluation methods, including Analysis of Variance (ANOVA), effect calculation and confidence interval analysis, are applied to systematically assess the influence of each factor. The evaluation is performed using an organized results table, which simplifies the analysis process and facilitates the interpretation of significant effects and interactions.

**Findings** – In this study, nine factors influencing interfacial adhesion in 4D textiles were analysed using a 2<sup>n</sup> factorial design. Key findings show that nozzle distance critically affects adhesion, with 0.05 mm being optimal. Higher textile pre-tension reduced adhesion, while lower pre-tension enabled 4D shape transformation. Nozzle temperature significantly influenced adhesion, with 220 °C optimal for PLA. Textile structure was also critical: dual tricot fabrics with elastane improved mechanical interlocking. The interaction between pre-tension and textile type also affects adhesion. Material choice affected adhesion, with silicone rubber achieving the highest values. In contrast, mesh orientation, printing speed and bed temperature showed no significant effects within the tested ranges.

**Originality/value** – The findings of this study provide a systematic analysis of interfacial adhesion, supporting the efficient production of 4D textiles and 3D-printed structures on textile substrates. By applying the identified key parameters, strong adhesion can be achieved without repeated trial-and-error testing, ensuring structural integrity for repeated state transformations in 4D textiles. Additionally, improved process reliability contributes to more sustainable manufacturing by reducing material waste and the need for auxiliary bonding agents. These insights enhance the robustness and scalability of 4D-textile production and open new application possibilities in wearable electronics, soft robotics and adaptive architectural structures.

**Keywords** 3D printing, FDM printing, 4D textiles, Adhesion testing, 180° peel test

**Paper type** Research article

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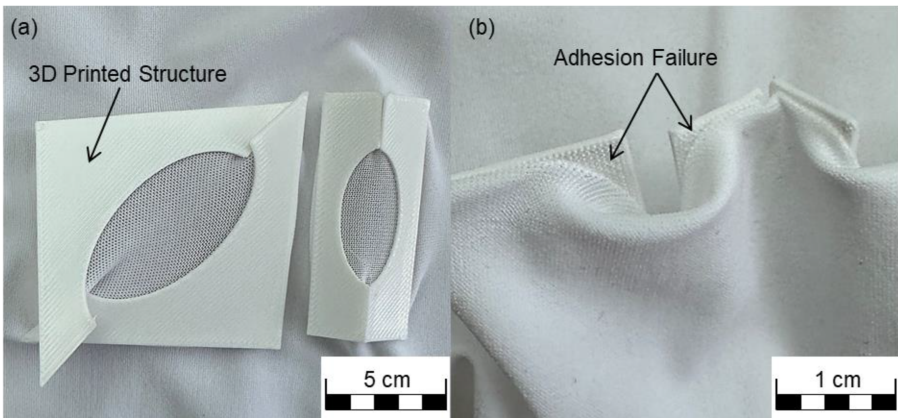
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Introduction

There has been a rapid growth in research regarding three-dimensional (3D) printing in recent years, driven by the design freedom, decentralized production possibilities and material efficiency associated with the technology (Gibson *et al.*, 2021; Abdulhameed *et al.*, 2019). Combining 3D printing and textile materials is still a relatively new research area. Multi-component systems, such as 4D textiles combining textiles and 3D printing, can change their shape over time, unlocking new possibilities. Current developments include textile-based actuators using shape memory polymers (SMPs) for soft robotics and adaptive systems (Biswas *et al.*, 2021). Additionally, smart garments capable of responding to thermal or mechanical stimuli have been realised through the integration of SMPs into textiles. Further studies highlight the application of 4D-printed structures in wearable devices, adaptive fashion elements, and textile-based grippers for soft robotics (Li, 2023; Zarek *et al.*, 2016; Shin *et al.*, 2023). These developments illustrate the increasing interest in integrating functional materials with textiles to create adaptive structures. In this context, 4D textiles are defined as textile-based systems that undergo controlled and reversible shape changes over time, typically triggered by external stimuli such as mechanical loading or environmental changes. In particular, when 3D printing is performed on pre-stressed textiles, these transformations occur as the energy stored in the textile is released after printing, which leads to a structural change in the system (Schmelzeisen, 2018; Schmelzeisen *et al.*, 2018). Further shape modifications can be achieved later by incorporating smart materials that respond to external stimuli (Koch *et al.*, 2021). However, the continuous tensile force from the textile promotes partial delamination of the printed structures, especially at their edges and tips. In some cases, detachment occurred directly after the release of pre-tension, whereas in others, gradual separation was observed after several deformation cycles under constant loading. Figure 1 illustrates a PLA structure detached from the textile directly after printing and release of pre-tension. Delamination is already visible at the sharp edge of the structure, which can be attributed to the concentrated tensile forces acting at the fabric boundary.

Therefore, before exploring potential applications, it is essential to first establish a reliable production process that ensures strong interfacial adhesion. The advantage of this approach lies in identifying optimal process parameters early on, which helps prevent functional structures from detaching after only a few activation cycles. It also reduces the need for repeated trial-and-error testing, saving time, materials and energy. However, a systematic investigation is resource-intensive, as adhesion is influenced by multiple factors, making the analysis more complex. The influencing factors include: printing parameters, the choice of polymers in 3D printing, and textile properties. In this study, a  $2^n$  factorial design was used to



**Figure 1.** (a) 3D printed PLA structure on textile substrate; (b) magnified view depicting adhesion failure. Source: Authors' own work

systematically investigate the effects of multiple parameters on adhesion. To reduce the complexity and avoid an unmanageable number of factor combinations, the parameters were grouped into smaller sets. This approach simplifies both the experimental setup and the evaluation process. The factorial design allowed for the analysis of the individual effects of each factor on adhesion, as well as their interactions. The specimens were tested using peel tests, and the resulting peel force was used as the evaluation criterion. The results were analysed using standard factorial design evaluation tables and visualized through diagrams.

### 3D printing

The technology of 3D printing falls under the category of generative or additive manufacturing processes, which are based on layer-by-layer construction. This process can be divided into three primary steps: First, a 3D dataset is generated using a CAD program, scanning or an imaging technique. Subsequently, this component is divided into layers of uniform thickness by a slicer. The resulting information is then transmitted to the respective manufacturing machine. The various 3D printing technologies differ mainly in the methods used to create and bond these layers (Gebhardt, 2013, 2016). One of the most widely adopted technologies in this domain is fused deposition modelling (FDM), also known as fused filament fabrication (FFF), which is categorized under filament-based 3D printing processes. It works by heating and extruding thermoplastic filaments through a nozzle to build the object layer by layer. FDM is popular for prototyping and creating simple models due to its affordability and ease of use, though it may not provide the highest resolution compared to other technologies (Gebhardt, 2013; Grimm, 2004).

Another 3D printing technology is stereolithography (SLA). SLA uses a liquid resin that is cured layer by layer with ultraviolet (UV) light. A laser or projector selectively hardens the resin in specific areas based on the digital model. This technology is known for producing highly detailed and smooth objects with high precision. A technology that uses solids like FDM is selective laser sintering (SLS). SLS uses a laser to selectively sinter powdered materials, typically plastic, metal or ceramics, to create solid objects. The laser scans and fuses the powder layer by layer according to the digital design. SLS can produce durable, functional parts with complex geometries and is often used for end-use parts in industries like aerospace and automotive. It doesn't require support structures, unlike FDM and SLA (Shahrubudin *et al.*, 2019).

### Textiles

Textile surface structures are produced using yarns composed of individual fibres (Hickert, 2020). Different manufacturing techniques applied to fibres and yarns result in a variety of textile architectures. These can be classified into interlaced, looped, stretched yarn systems, or random fibre systems (Eberle *et al.*, 2022; Gries *et al.*, 2019). An overview of these two-dimensional structures is provided in Figure 2.

This study focuses specifically on knitted fabrics, as their looped construction offers high structural elasticity, making them particularly suitable as substrate materials for 4D textiles. Weft-knitted fabrics consist of loops intermeshed perpendicular to the production direction, while warp-knitted fabrics feature loops aligned along the production direction. Another difference lies in the knitting method: weft knitting employs individually actuated needles, whereas warp knitting utilizes multiple needles moving simultaneously. Warp-knitted structures are formed either from a single yarn or from warp yarn chains. The material is supplied via warp beams, and loops are formed through the interconnection of adjacent warp yarns, as illustrated in Figure 3 (Spencer, 2004; Gries *et al.*, 2019).

A characteristic feature of knitted fabrics is the presence of non-interlocked yarn segments that can move freely relative to one another. This results in low bending stiffness combined with high structural elasticity. Figure 4 illustrates the elastic deformation behaviour in an individual loop and a small-scale knitted structure. (Spencer, 2004)

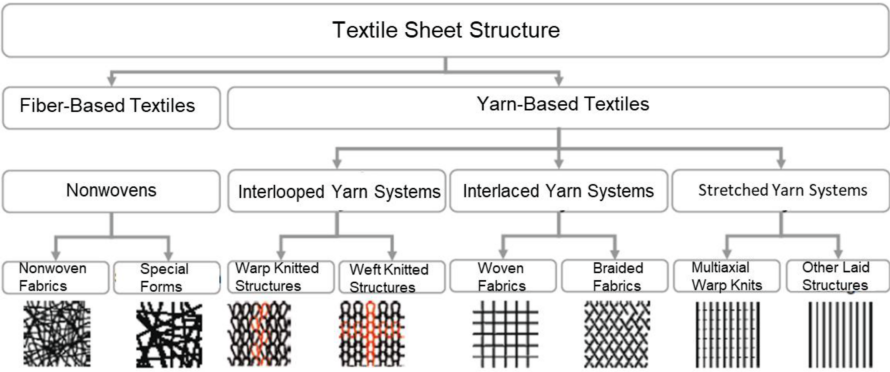


Figure 2. Overview of two-dimensional textile structures (Gries et al., 2019)

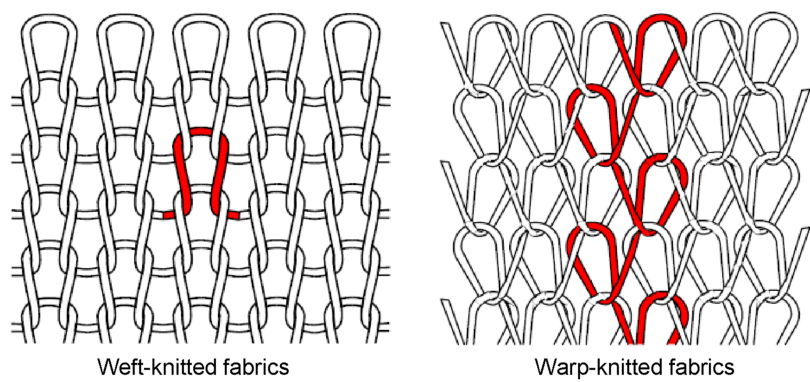


Figure 3. Structural design of weft-knitted and warp-knitted fabrics (Gries et al., 2019)

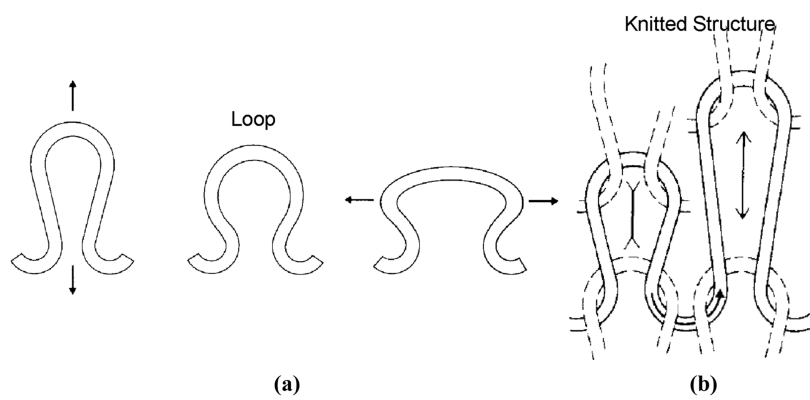


Figure 4. (a) Loop extension and recovery process; (b) yarn movement within the knitted structure during extension and recovery (Spencer, 2004)

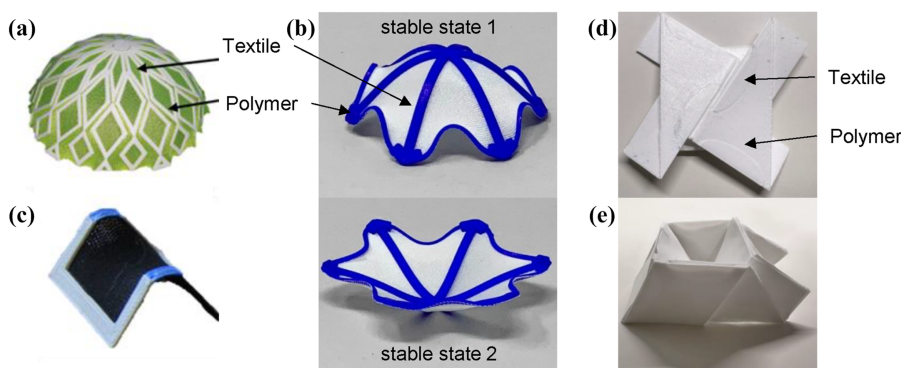


### 4D textiles

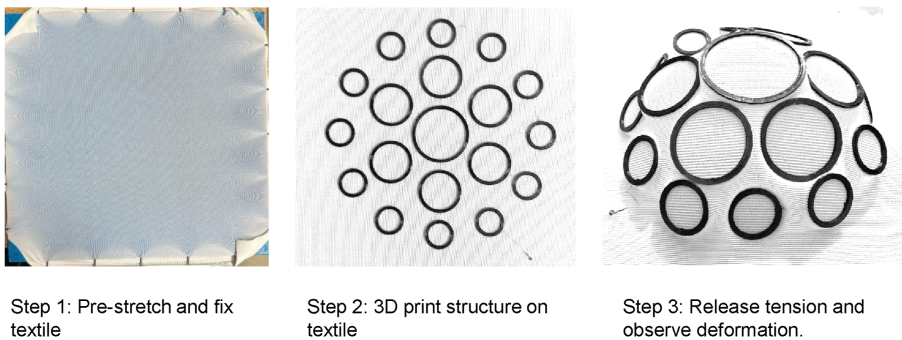
The concept of 4D textiles is derived from 4D printing, which involves 3D printing with smart materials that can change shape or function over time in response to external stimuli. The term “four dimensions” refers to the three spatial dimensions and the temporal dimension, with shape changes potentially occurring within a single spatial axis over time (e.g., from 2D to 3D) (Simonis *et al.*, 2024; Koch *et al.*, 2021). Expanding on this concept, 4D textiles incorporate 3D-printed structures onto textile membranes, which act as a source of stored deformation energy. In 4D printing, shape transformation is typically driven by active materials such as shape memory polymers (SMPs), magnetic materials or liquid crystal elastomers (LCEs), which respond to external stimuli like heat, magnetic fields, or light (Zhang *et al.*, 2022; Lin *et al.*, 2024; Zang *et al.*, 2024). In contrast, 4D textiles often rely on the mechanical energy stored in the textile substrate itself to enable shape changes. By combining this with specially designed printed structures, components with bistable behaviour can be created (Schmelzeisen *et al.*, 2018; Koch *et al.*, 2021). Figure 5 shows several examples of 4D-printed textile samples. In (a), a dome-shaped structure is presented, which forms a curved shape after the release of pre-tension. (b) shows a hinge structure combining two materials: rigid PLA (white) for reinforcement and flexible TPU (blue) in the joint area, allowing controlled bending. In (c), a bistable structure is shown, which can switch between two stable states when an external force is applied (Zang *et al.*, 2024; Koch *et al.*, 2021). (d) and (e) illustrate double-sided printed origami structures that fold themselves into a compact shape after activation.

A defining feature of 4D textiles is their capability to undergo controlled transformations when exposed to specific external stimuli. Consequently, the relaxation of a previously stretched textile after the printing process can result in a predictable curvature (Schmelzeisen *et al.*, 2018). A typical fabrication process for 4D consists of three main steps and is illustrated in Figure 6. First, the textile is pre-stretched and securely fixed onto a needle plate to apply a defined pre-tension. This ensures that the textile remains in a stretched state during the printing process. In the second step, the desired polymer structure is directly printed onto the tensioned textile surface using a 3D printer. Finally, in the third step, the pre-tension is carefully released, allowing the stored energy in the textile to initiate the programmed shape transformation of the structure.

As mentioned in the previous chapter, the materials used for 4D textiles are typically knitted fabrics composed of elastic fibres, such as elastane, in order to combine structural elasticity with material elasticity (Eberle *et al.*, 2022). Commonly used polymers for 3D printing include standard thermoplastics such as polylactide (PLA), polyethylene



**Figure 5.** Examples of 4D-printed textile structures: (a) dome-shaped structure; (b) hinge structure with rigid PLA and flexible TPU; (c) bistable structure capable of reversible state switching (a–c) (Koch *et al.*, 2021); (d, e) double-sided printed origami structures demonstrating self-folding behaviour (d–e). Source: Authors' own work



**Figure 6.** Process steps for manufacturing 4D-printed textile structures. Source: Authors’ own work

terephthalate glycol (PETG), thermoplastic polyurethane (TPU) and acrylonitrile butadiene styrene (ABS). (Franco and Adrian, 2024). In addition to these materials, active materials such as shape memory polymer (SMP) filaments are also being explored for 4D printing applications. However, the integration of these materials with textiles is still at the research stage and requires further development to ensure reliable processing and functional performance.

Interface

The analysis of interfaces in 4D textiles primarily focuses on mechanical adhesion, where a mechanical interlock is achieved as the molten polymer filament penetrates and solidifies within the pores of the textile substrate (Bodaghi *et al.*, 2024; Narula *et al.*, 2018; Schmelzeisen, 2018). In addition to this physical interlocking, molecular-level mechanisms, such as polymer chain diffusion, also play a critical role in enhancing adhesion. According to the diffusion theory, polymers adhere to each other through the diffusion of chain-like molecules, which form strong bonds, thereby enhancing adhesion between the two polymers and leading to a stable interface. As an example, PLA was printed onto natural fibres such as cotton and wool, as well as onto synthetic fibres such as polyester. The results showed significantly better adhesion on polyester, a chemically produced fibre (Voyutskii und Vakula, 1963; Grimmelsmann *et al.*, 2018). This can be attributed to higher material compatibility, as filaments made of a polymer similar or identical to that of the textile, or those coated with such a polymer, exhibit improved adhesion to the textile (Kozior *et al.*, 2020). Polymer diffusion is influenced by several factors, including temperature, polymer compatibility, molecular weight, orientation and molecular structure (Kim, 2018). To understand and optimize these physical interlocking mechanisms, key influencing factors were systematically investigated. Table 1 lists some of the most critical factors (Koch *et al.*, 2021; Kozior *et al.*, 2020; Bodaghi *et al.*, 2024; Narula *et al.*, 2018).

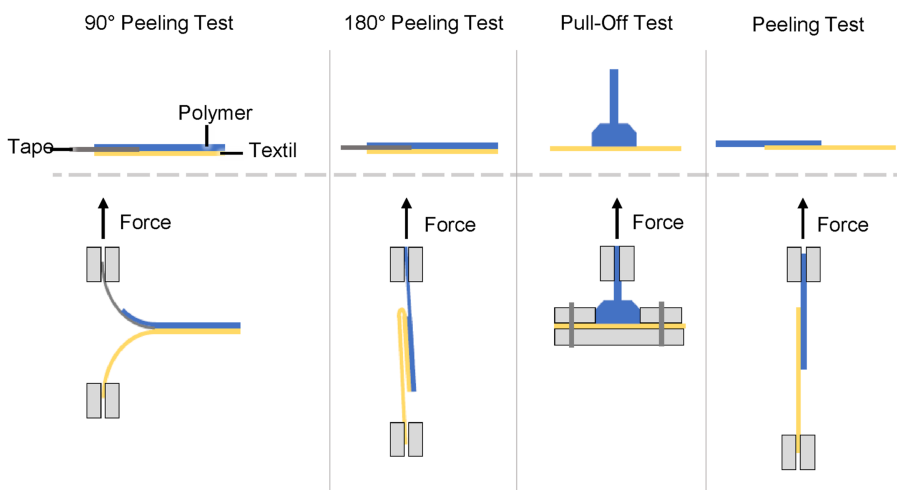
**Table 1.** Factors influencing polymer diffusion

| Material parameters          | Process parameters                  |
|------------------------------|-------------------------------------|
| Pre-tension of textile       | Heating plate temperature           |
| Surface roughness            | Nozzle temperature                  |
| Textile thickness            | Printing speed                      |
| Textile pore size            | Distance between nozzle and textile |
| Material composition         | Flow rate                           |
| Source(s): Authors’ own work |                                     |

Previous studies have identified the following effects of the relevant factors. No clear influence of pre-tension on adhesion strength was observed. However, the ratio of textile width to the width of the printed structure had a noticeable effect: the wider the textile sample, the greater the measured peel force (Narula *et al.*, 2018). The type of textile and polymer, as well as their specific combination, significantly affect adhesion strength. This can be attributed to differences in pore size and surface characteristics such as hairiness and roughness, which together define the textile's surface structure. For instance, Narula *et al.*, (2018) concluded that a reduction in pore size leads to lower peel strength, as it limits the infiltration of the molten polymer into the textile structure. Regarding process parameters, Grimmelsmann *et al.* (Grimmelsmann *et al.*, (2018) demonstrated that the distance between the nozzle and the textile surface has a significant impact on adhesion strength. On the one hand, the distance must be small enough to create sufficient pressure to press the molten polymer into the textile. On the other hand, it must be large enough to allow the material to flow freely from the nozzle. Other parameters, such as printing temperature and printing speed, showed only minor effects on adhesion, and no general conclusion can be drawn, as the material combinations and printing settings varied between studies. Additionally, factors such as build plate temperature and printing speed were found to have no significant influence (Grimmelsmann *et al.*, 2018; Hashemi *et al.*, 2017; Narula *et al.*, 2018).

The testing methods for evaluating the adhesion between the printed structure and the textile can be further developed based on existing methods that characterize adhesion between two materials. The following testing methods are illustrated in Figure 7.

In the 90° peel test, one nonadhered end of the textile and one of the polymers is secured in separate clamps. The adhered layers create a 90° angle relative to the clamps (Malengier *et al.*, 2017). Conversely, in the 180° peel test, the textile is peeled away from the printed object at a 180° angle to induce delamination (Narula *et al.*, 2018). In the perpendicular pull-off test, a dome-shaped object, known as a “dolly”, is printed onto the textile. The textile with the “dolly” is clamped in a test frame, and a force is applied to pull the “dolly” vertically upwards (Malengier *et al.*, 2017). In the shear test, the sample is clamped similarly to the 180° peel test, but in this case, the polymeric part is directly printed onto the textile, eliminating the need for manual separation of the two components.

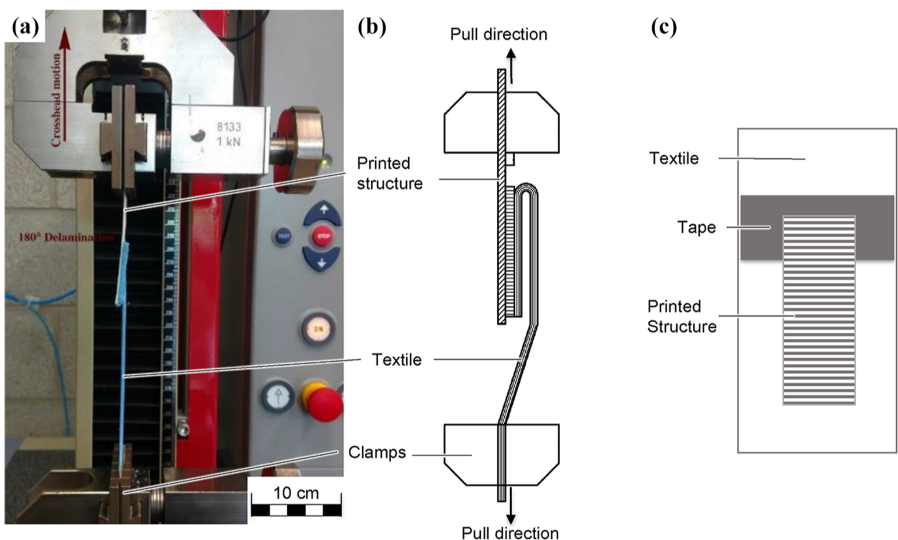


**Figure 7.** Adhesion testing methods for 4D textiles (Koch *et al.*, 2021)

## Method

### Peel test

An adapted testing method based on DIN EN ISO 8510-2 [DIN Deutsches Institut für Normung e. V. \(2010\)](#) is used for the peel tests in this study, where the peel force is defined as the measurement variable. The 180° configuration was selected because it applies the force entirely in the peeling direction, enabling more reproducible results and clearer interpretation. A Zwick/Roell Z2.5 Tensile tester was used with a peel speed of 100 mm/min. The specimen is fixed in a 180° peel angle on the tensile testing machine using two upper and two lower clamps. During the test, the polymer structure is peeled off by the tensile force exerted by the textile. The specimen's dimensions are 100 mm × 20 mm × 0.8 mm. A portion of the polymer structure, 25 mm in length, is not adhered to the textile, allowing the polymer to be clamped with the upper clamp. Two specimens are printed on the textile at a distance of 40 mm from each other. A schematic representation of the testing procedure and the shape of the specimens is provided in the following [Figure 8](#).



**Figure 8.** Adapted testing method: (a) peel test with Z2.5 Tensile tester, (b) schematic illustration of the 180° peel test, (c) schematic diagram of the sample used for peel testing. Source: Authors' own work

### 2<sup>n</sup> factorial experimental design

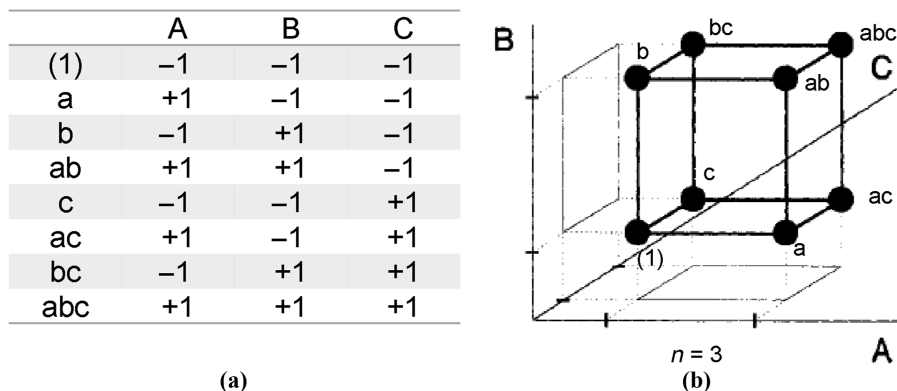
In experimental analysis, it is often difficult to fully eliminate the impact of confounding factors, which can result in biased conclusions. Precisely measuring these influences is equally challenging. The use of 2<sup>n</sup> factorial experimental designs provides an effective solution to this issue, allowing for a systematic and thorough analysis ([Veit, 2022](#)).

A 2<sup>n</sup> factorial design involves examining *n* factors, each at two levels (e.g., high and low), across all possible combinations. This method helps identify the individual effects of each factor on the experimental outcome and uncovers interactions between the factors. By efficiently organizing the experiment, 2<sup>n</sup> factorial designs deliver reliable and valuable results, making them especially useful for identifying key factors and their interactions in complex systems ([Kleppmann, 2016](#); [Veit, 2022](#)).

A 2<sup>n</sup> factorial design for three factors (*n* = 3) can be set up. The letters A, B and C each represent a factor with two settings: “+1” (high level) and “−1” (low level). Experiments are labelled based on the factors set at their high levels. (e.g., “a” for A high, B and C low, “bc” for

B and C high, A low, etc.). The baseline experiment (A low, B low, C low) is denoted as “(1)”. [Figure 9](#): presents a table of all factor combinations and a graphical representation illustrating the general layout of factorial experimental designs for  $n = 3$  ([Soravia, 1996](#); [Veit, 2022](#)).

The following shows an example experimental plan of adhesion between a textile substrate and a printed polymer. Three influencing factors are considered: (A) nozzle distance, (B) pre-tension of the textile and (C) mesh alignment. The corresponding factorial design is shown in [Table 2](#).



**Figure 9.** (a) Complete factor combinations with three factors, (b) graphical layout of a full factorial experimental design with three factors ([Veit, 2022](#); [Soravia, 1996](#))

**Table 2.** Example  $2^3$  factorial experimental design plan for adhesion tests with factors A (nozzle distance), B (textile pre-tension) and C (mesh alignment)

| Trial description |                      | (1)    | a   | b    | ab  | c    | ac  | bc   | abc |
|-------------------|----------------------|--------|-----|------|-----|------|-----|------|-----|
| Factors           | Nozzle distance [mm] | 0.05   | 0.4 | 0.05 | 0.4 | 0.05 | 0.4 | 0.05 | 0.4 |
|                   | Pre-tension [%]      | 30     | 30  | 70   | 70  | 30   | 30  | 70   | 70  |
|                   | Mesh alignment       | course |     |      |     | wale |     |      |     |

**Source(s):** Authors' own work

### Evaluation method for $2^n$ factorial experimental designs

The evaluation of factorial designs can become graphically demanding when multiple influencing factors are involved. To address this, mathematical evaluation methods such as analysis of variance (ANOVA), effect calculation and confidence interval analysis are applied. These methods enable an efficient and systematic assessment of the influence of individual parameters on the experimental outcomes. In this study, a tabular analysis of all experimental factors is used as a first step. Selected factors that appear statistically significant in the evaluation table are then subjected to a more detailed graphical analysis to support and visualize the findings. [Table 3](#) shows a representative evaluation table ([Veit, 2022](#); [Siebertz et al., 2010](#)). For clarity and due to space constraints, raw measurement data are not displayed. The calculation methods used in this table will be explained in detail in the following chapter.

- (1) The first table block, shown at the top of the table, contains the basic experimental parameters, including the number of factors, repetitions, and calculated degrees of freedom. Confidence levels and corresponding critical t-values from the t-distribution are listed. These values are used to determine the critical threshold for significance evaluation based on  $t * SE_{effect}$ .



Table 3. Evaluation table of a 2^3 factorial

|                                |       |                        |       |                        |       |       |                |                         |          |                       |              |       |
|--------------------------------|-------|------------------------|-------|------------------------|-------|-------|----------------|-------------------------|----------|-----------------------|--------------|-------|
|                                |       |                        |       |                        |       |       |                | Confid<br>ence<br>level | 90%      | 95%                   | 99%          | 99.9% |
| Number<br>of<br>factors<br>(n) | 3     | repetit<br>ions<br>(m) | 6     | Degrees<br>freedom (f) | of    | 40    | t-value        | 1.68                    | 2.02     | 2.07                  | 3.35         |       |
|                                |       |                        |       |                        |       |       | t*SEeff<br>ect | 1.72                    | 2.07     | 2.74                  | 3.63         |       |
| Factors                        | A     | B                      | C     | AB                     | AC    | BC    | ABC            | Mean                    | Variance | Standard<br>deviation | SE<br>effect |       |
| (1)                            | -1    | -1                     | -1    | 1                      | 1     | 1     | -1             | 10.69                   | 1.00     | 1.00                  | 0.50         |       |
| a                              | 1     | -1                     | 1     | -1                     | -1    | 1     | 1              | 9.63                    | 1.18     | 1.08                  | 0.54         |       |
| b                              | -1    | 1                      | -1    | -1                     | 1     | -1    | 1              | 10.56                   | 10.77    | 3.28                  | 1.64         |       |
| ab                             | 1     | 1                      | -1    | 1                      | -1    | -1    | -1             | 5.69                    | 3.52     | 1.88                  | 0.94         |       |
| c                              | -1    | -1                     | 1     | 1                      | -1    | -1    | 1              | 12.79                   | 17.51    | 4.18                  | 2.09         |       |
| ac                             | 1     | -1                     | 1     | -1                     | 1     | -1    | -1             | 7.98                    | 2.13     | 1.46                  | 0.73         |       |
| bc                             | -1    | 1                      | 1     | -1                     | -1    | 1     | -1             | 8.57                    | 0.22     | 0.47                  | 0.23         |       |
| abc                            | 1     | 1                      | 1     | 1                      | 1     | 1     | 1              | 3.22                    | 1.27     | 1.13                  | 0.56         |       |
| Effect                         | -2.01 | -1.63                  | -0.50 | -0.54                  | -0.53 | -0.61 | 0.41           | 8.64                    | 4.7      | 2.17                  | 1.02         |       |
| 2*<br>Effect                   | 4.02  | 3.26                   | 1     | 1.09                   | 1.06  | 1.23  | 0.82           |                         |          |                       |              |       |
| 90%                            | yes   | yes                    | no    | no                     | no    | no    | no             |                         |          |                       |              |       |
| 95%                            | yes   | yes                    | no    | no                     | no    | no    | no             |                         |          |                       |              |       |
| 99%                            | yes   | yes                    | no    | no                     | no    | no    | no             |                         |          |                       |              |       |
| 99.9%                          | yes   | no                     | no    | no                     | no    | no    | no             |                         |          |                       |              |       |

Source(s): Authors' own work

- (2) The second table block lists all 2^3 factorial combinations.
- (3) The table block next to the factorial combinations presents the calculated statistical parameters: mean values, variance, standard deviation and standard error of the effect. In the last row, are shown overall means and the calculated standard error of effects *SEeffect*.
- (4) The table block under the factorial combinations includes the effect values and the corresponding absolute doubled effect values used for significance testing.
- (5) The bottom table block summarizes the significance results across confidence levels from 90% to 99.99%, indicating with “yes” or “no” whether the significance criteria are met.

Analysis of Variance (ANOVA)

ANOVA is used to distinguish between apparent and actual effects in experimental designs and provides parameters to assess model quality. The mean value  $\bar{y}$ , estimated variance  $\sigma^2$  and the standard deviation  $s$  of a target variable is calculated as:

$$\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i$$
$$\sigma^2 = \frac{1}{n-1} \sum_i^n (y_i - \bar{y})^2$$
$$s = \sqrt{\sigma^2}$$

The standard deviation  $s$  is the square root of the variance and indicates the spread of results (Soravia, 1996; Siebertz *et al.*, 2010).

*Effect.* An effect quantifies the influence of a factor on the system. It is calculated using the contrast method. In this method, the effect of a factor is calculated as the difference between the average response when the factor is at its *high level* (+) and at its *low level* (−):

$$Ei^* = \frac{1}{n}(\bar{y}_i^+ - \bar{y}_i^-)$$

Here,  $n$  is the number of factor,  $\bar{y}_i^+$  is the mean value of the response variable when factor  $i$  is set to its high level (+1),  $\bar{y}_i^-$  is the mean value when factor  $i$  is at its low level (−1) (Siebertz *et al.*, 2010). For instance, in a  $2^3$  factorial design, the main effect of factor A can be estimated using the contrast method by averaging the differences between experimental conditions that differ only in the setting of factor A. This represents the average contrast between the A− and A+ levels:

$$E_A^* = \frac{1}{3}(\bar{y}_a + \bar{y}_{ab} + \bar{y}_{ac} + \bar{y}_{abc} - \bar{y}_{(1)} - \bar{y}_b - \bar{y}_c - \bar{y}_{bc})$$

To compare effects consistently across all factors, a normalised effect is used. This is obtained by scaling the contrast by  $\frac{1}{2^n}$  (Veit 2022). For the current case:

$$E_A = \frac{1}{2^3}(\bar{y}_a + \bar{y}_{ab} + \bar{y}_{ac} + \bar{y}_{abc} - \bar{y}_{(1)} - \bar{y}_b - \bar{y}_c - \bar{y}_{bc})$$

This definition corresponds to the so-called half-range effect, which describes the average change in the system's response resulting from moving the factor from its low to high level, normalised over all possible factor combinations. This allows for a direct and meaningful comparison of effects within the factorial design framework (Veit, 2022).

*Standard deviation of the effect.* The standard deviation of the effect is calculated based on the mean square error of the entire dataset  $MS_{Effect}$  and the total number of experiments  $N = n \cdot m$ , where  $m$  represents the number of repetitions (Kleppmann, 2016; Veit, 2022). The result is scaled accordingly:

$$SE_{Effect} = \sqrt{\frac{4}{N} \cdot MS_{Effect}}$$

*Confidence interval for the mean  $\mu$ .* With a given confidence level and degrees of freedom:

$$f = 2^n \cdot (m - 1)$$

The confidence interval is expressed as:

$$\bar{y} - t \cdot s_{\bar{y}} \leq \mu \leq \bar{y} + t \cdot s_{\bar{y}}$$

This range is referred to as the confidence interval. The total width  $G$  and half-width  $B$  of the confidence interval are:

$$G = (\bar{y} - t \cdot s_{\bar{y}}) + (\bar{y} + t \cdot s_{\bar{y}}) = 2t \cdot s_{\bar{y}}; B = t \cdot s_{\bar{y}}$$

The appropriate  $t$ -values depend on the confidence level and degrees of freedom, typically obtained from standard  $t$ -distribution tables. (Kleppmann, 2016; Veit, 2022).

*Significance testing for the effect.* To assess the statistical significance of the effects, the following criterion is applied:

$$|2 \times E_i| \geq t_{\alpha/2, f} \cdot SE_{Effect}$$

Where,  $E_i$  is the estimated effect,  $t_{\alpha/2, f}$  is the critical value from the t-distribution for a chosen significance level  $\alpha$  and degrees of freedom  $f$ ,  $SE_{Effect}$  is the standard error of the effect (Veit, 2022).

Experimental approach

Parameters

A total of nine factors were investigated across five separate experimental series. Some factors were repeated in multiple series to thoroughly account for their interactions within the factorial design. The decision not to test all factors simultaneously in a single experiment is based on the need to progressively analyse the complexity and impact of each factor and its interactions. Testing all factors simultaneously would significantly complicate the interpretation of results and could lead to ambiguous conclusions. By distributing the factors across several experimental series, it becomes possible to capture the influence of each factor more precisely while systematically investigating their interactions. The specific experimental series are listed in Table 4 and Table 5.

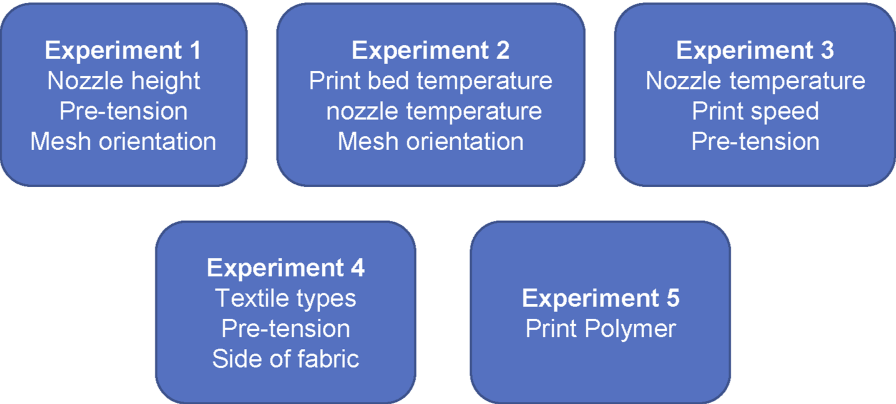
Table 4. Factors used in the experimental design

| Factor                        | Values                            |
|-------------------------------|-----------------------------------|
| F1 print bed temperature [°C] | [0, 70]                           |
| F2 nozzle temperature [°C]    | a:[195, 215]; b:[190, 220]        |
| F3 nozzle height [mm]         | [0.05, 0.4]                       |
| F4 print speed [mm/s]         | [20, 70]                          |
| F5 pre-tension [%]            | [30, 50, 70, 80,100]              |
| F6 mesh orientation [–]       | [stitch courses, stitch wales]    |
| F7 side of fabric [–]         | [left, right]                     |
| F8 textile types [–]          | [Eurojersey, Buttinette]          |
| F9 polymer [–]                | [PLA, Silicon, Multi PLA and TPU] |
| Source(s): Authors’ own work  |                                   |

Table 5. Experimental test series, factors and constants

| Test series                  | Factor      | Constant                                                                                                            |
|------------------------------|-------------|---------------------------------------------------------------------------------------------------------------------|
| 1                            | F3, F5, F6  | [Nozzle temperature: 215°C, Print bed temperature: 65°C, Speed: 50 mm/min, Fabric side: right, Textile: Eurojersey] |
| 2                            | F1, F2a, F6 | [Printing speed: 50 mm/min, Nozzle distance: 0.05 mm, Pre-tension: 70%, Fabric side: right, Textile: Eurojersey]    |
| 3                            | F5, F4, F2b | [Print bed temperature: 60°C, Nozzle distance: 0.05 mm, Fabric side: right, Textile: Eurojersey]                    |
| 4                            | F8, F5, F7  | [Nozzle temperature: 220°C, Print bed temperature: 60°C, Speed: 20 mm/min, Nozzle distance: 0.05 mm]                |
| 5                            | F9          | The process parameters vary due to differences in the polymer’s processing behaviour                                |
| Source(s): Authors’ own work |             |                                                                                                                     |

An overview of the varied factors for each corresponding experiment is shown in [Figure 10](#).



**Figure 10.** Overview of the varied factors for the corresponding experiment. Source: Authors’ own work

*Polymers and printers*

In this study, three polymers were selected for evaluation: PLA, TPU and silicone. PLA (polylactide) is noted for its biodegradability and excellent biocompatibility, making it highly popular in 3D printing and medical technology ([Liao et al., 2019](#)). TPU (thermoplastic polyurethane) represents a significant class of polymers used in additive manufacturing, characterized by excellent abrasion resistance, good corrosion resistance, low weight and a wide range of mechanical strength and elasticity ([Buckley et al., 2010](#); [Liu et al., 2019](#)). Silicone, a synthetic polymer, offers favourable elasticity and heat resistance, and can be processed into various forms such as elastomers, gels and adhesives ([Zare et al., 2021](#)).

For the single-material experiments involving PLA, black Ultimaker PLA ([Ultimaker, n.d.](#)) was printed on an Ultimaker 3 Extended in contrast, the multi-material experiments used light-blue PLA from [Maertz \(n.d.\)](#) and red TPU from [Kimya \(2025\)](#), printed on a modified Creality Ender 3V2 equipped with dual extruders, as the original Ultimaker printer was not capable of simultaneous dual-material printing. Additionally, silicone ([The Dow Chemical Company, n.d.](#)) was printed using a LiQ320 from InnovatiQ, which specializes in liquid silicone processing. [Table 6](#) summarizes the key properties of these materials and their respective processing conditions.

**Table 6.** Used polymers and their properties

| Material properties | PLA black      | PLA light-blue | TPU 92A                    | Silicon                         |
|---------------------|----------------|----------------|----------------------------|---------------------------------|
| Chemical name       | Polylactide    | Polylactide    | Thermoplastic polyurethane | –                               |
| Supplier            | Ultimaker      | MAERTZ         | Kimya                      | Dow SILASTIC™ 3D 3335           |
| Specific gravity    | 1.24           | 1.24           | 1.16                       | 1.12                            |
| Durometer           | Shore D 83     | N.A.           | Shore A 92                 | Shore A 44                      |
| Hardness            |                |                |                            |                                 |
| Viscosity           | N.A.           | N.A.           | N.A.                       | Part A158 Pa.s, Part B 159 Pa.s |
| Print Temperature   | 205–240 °C     | 205 ± 10 °C    | 210–250 °C                 | –                               |
| Melting Temperature | 145–160 °C     | 115 ± 35°C     | N.A.                       | –                               |
| Tensile Modulus     | 3250 ± 119 MPa | 3120 MPa       | 43.1 MPa                   | 9.5 MPa                         |

**Source(s):** Authors’ own work

*Textile*

In the production of 4D textiles, the fabric is typically subjected to tension to induce elongation. Highly elastic warp-knitted fabrics with elastane yarn are well-suited for 4D applications due to their pronounced elasticity and strong elastic recovery force (Sultan, 2008). In this study, two warp-knitted fabrics with a high proportion of elastane were selected because of their high extensibility, which allows for significant deformation under mechanical activation, as well as their ability to quickly and reliably return to their original shape. Moreover, both textiles exhibit good structural stability under cyclic loading conditions, making them ideal candidates for investigating programmable shape changes in 4D textile systems.: “Sensitive® Fit” from EUROJERSEY and a highly elastic jersey fabric “Sportswear” purchased from Buttinette. The relevant textile data are summarized in Table 7.

**Table 7.** Data on textiles used in this study

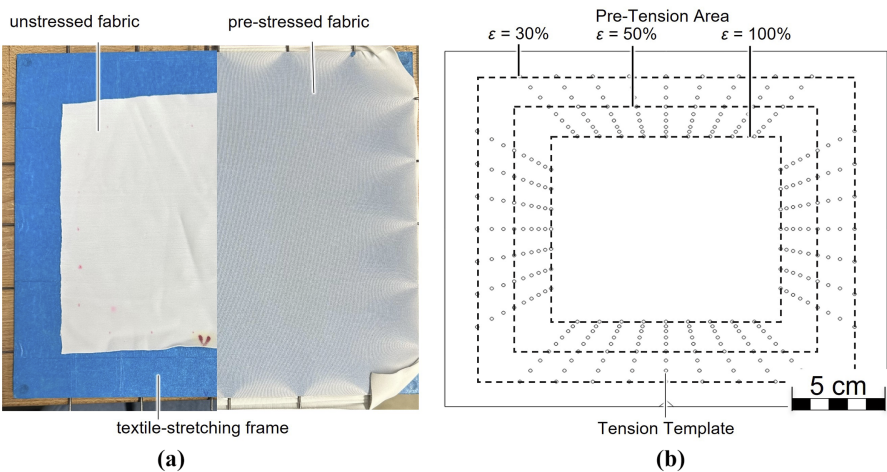
| Textile supplier           | Eurojersey     | Buttinette          |
|----------------------------|----------------|---------------------|
| Name                       | SENSITIVE® FIT | Jersey “Sportswear” |
| Composition                | 68% PA, 32% EA | 80% PA, 20% EA      |
| Weight (g/m <sup>2</sup> ) | 150 (+/-2%)    | 190 (+/-3%)         |

**Source(s):** Authors’ own work

*Sample preparation*

The pre-stressed fabric is used in 4D textiles as a tensioned spring to store potential energy. For this purpose, a textile-stretching metal frame is used, which is equipped with nails on all four sides. The knitted fabric is stretched over these nails to fix it in place. Figure 11 illustrates both an unstressed and a pre-stressed knit fabric with a pre-stress of 100%.

The pre-tension  $\epsilon$  is expressed as a percentage and is defined as follows:



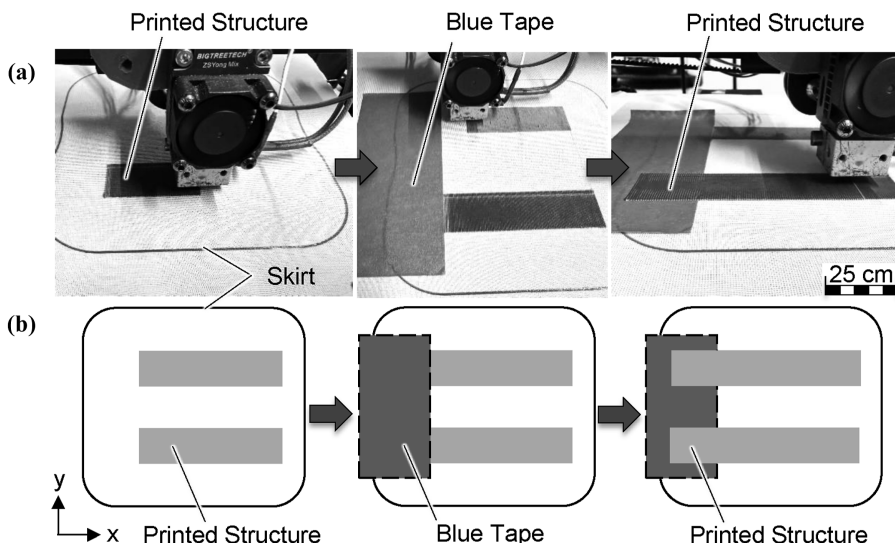
**Figure 11.** (a) The pre-stressed principle. (b) The magnitude of the different pre-stressed. Source: Authors’ own work

$$\varepsilon = \frac{\Delta L}{L_0} \times 100 \% = \frac{L_s - L_0}{L_0} \times 100 \%$$

The change in the length of the textile is described by the formula  $\Delta L = L_s - L_0$  where  $L_0$  represents the unstressed length of the textile, and  $L_s$  corresponds to the edge length of the tensioning plate or the stretched length of the textile. For each printing plate, a corresponding template is created, marking the unstressed length  $L_0$  of each edge, which corresponds to a pre-stress range of 30%–100%.

The dimensions of each sample are 100 mm × 20 mm × 0.8 mm. A 25 mm section of the polymer structure remains unbonded to the textile substrate to allow fixation by the upper clamp during testing. Two samples are printed side by side on the textile with a spacing of 40 mm between them. The fabrication sequence of the samples is presented in Figure 12.

- (1) Markings are applied to the textile using the pre-tensioning template, which specifies a target stretch. The textile is then stretched onto the needle plate, guided by these markings. Once the textile is positioned on the needle plate, it is loaded into the printer.
- (2) A polymer strip is then applied along the edge of the textile. This initial pre-print ensures a uniform flow of the polymer melt.
- (3) The first rectangle is printed next. The process starts by printing the outline of the rectangle, followed by filling in the interior.
- (4) A separable material, such as adhesive tape (a Blue Tape), is applied next to the first rectangle. This allows the tape to be easily removed after printing, facilitating better evaluation of the samples in subsequent tests.
- (5) The second rectangle is then printed on top of the adhesive tape and the first rectangle. Again, the outline is printed first, followed by the interior.



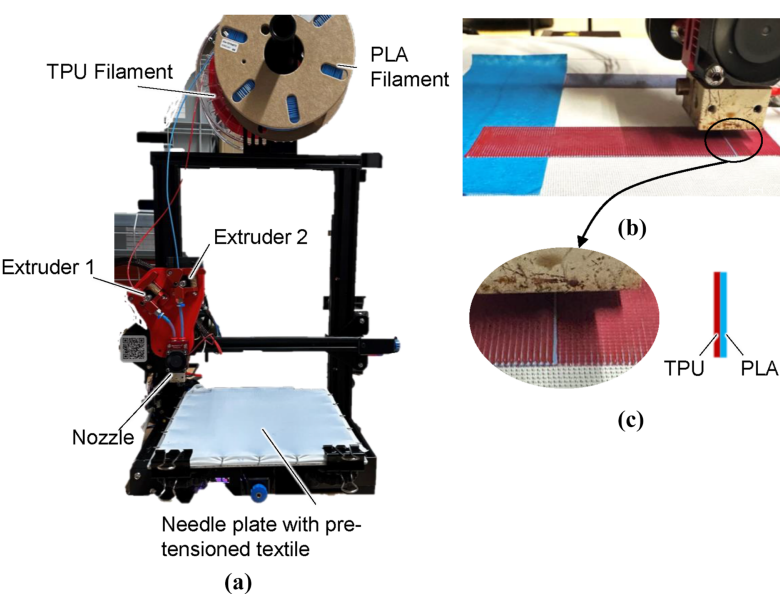
**Figure 12.** (a) Sample fabrication process. (b) Schematic representation of the process (Schmelzeisen *et al.*, 2018). Source: Authors' own work.



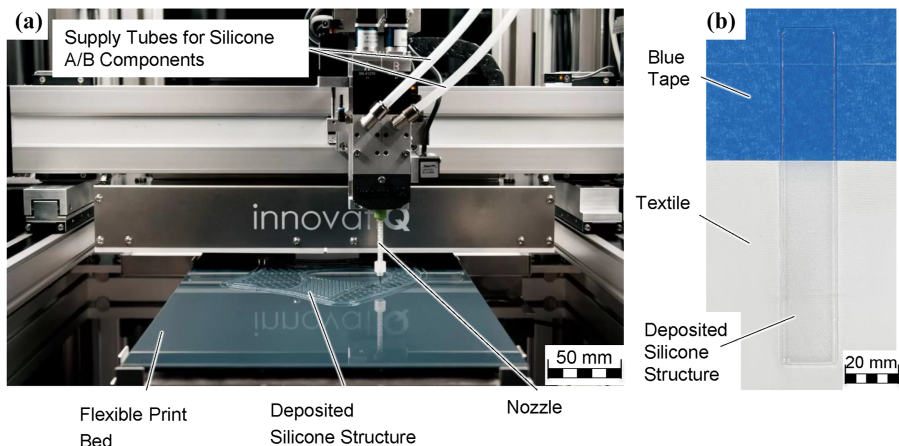
- (6) After printing, the plate is removed from the printer, and the textile is detached from the needle plate.

The fabrication process for the PLA/TPU composite samples follows the same procedure as that used for pure PLA. However, a modified 3D printer equipped with dual extruders was used to enable the simultaneous deposition of two materials. During printing, equal volumes of PLA and TPU were co-extruded. It is illustrated in Figure 13. In the figure, PLA is shown in blue and TPU in red. The two materials are deposited simultaneously and side-by-side, forming a composite structure during the extrusion process (Bodaghi *et al.*, 2024). The dimensions of the PLA/TPU samples are identical to those of the pure PLA reference samples.

The fabrication process for the silicone samples differs from that of thermoplastic materials. Two-component silicone rubber (components A and B) is directly extruded and mixed inside an extended static mixing nozzle. In conventional silicone 3D printing, each printed layer is typically cured immediately after deposition using a high-intensity heating lamp. However, since the samples in this study are printed directly onto textile, the use of high thermal loads was avoided to prevent thermal damage to the fabric. Instead, the printed parts were post-cured in a laboratory oven at 60°C for one hour. Additionally, due to the high elasticity of the silicone and to facilitate mounting in the peel testing machine, the dimensions of the samples were adapted accordingly. Each sample measures 125 mm × 20 mm × 0.8 mm, with a non-bonded gripping section of 50 mm at one end to allow secure clamping during mechanical testing. Figure 14 presents the InnovatiQ 3D silicone printer alongside a printed silicone rubber sample used in this study.



**Figure 13.** (a) Dual-extruder 3D printer used for composite fabrication (source: authors' own work). (b) Simultaneous co-extrusion of PLA (blue) and TPU (red) forming a side-by-side composite structure during the printing process; (c) enlarged view of the printed PLA/TPU sample and a schematic illustration of material flow inside the nozzle. Source: Bodaghi *et al.*, 2024



**Figure 14.** (a) The InnovatiQ printer, (b) a silicone rubber sample. Source: Authors' own work

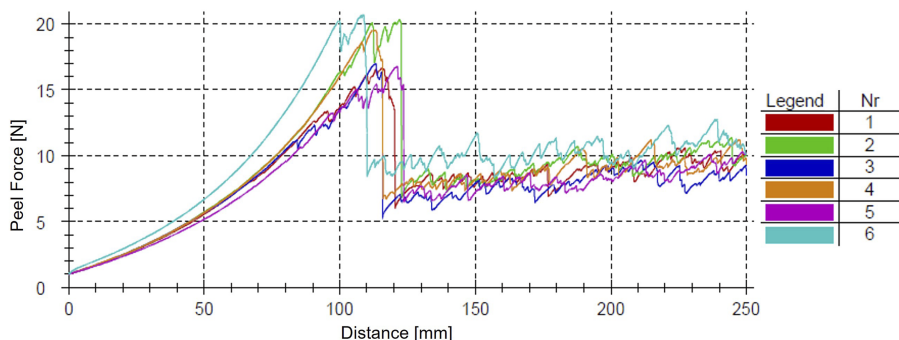
## Results and discussion

### Peel test diagram

Figure 15 shows an example peel test diagram of one factor combination. In this combination, the test was repeated six times and six coloured lines are shown in the diagram. The exact numerical values are not the focus here; rather, this example serves to illustrate the type of information that can be extracted from a typical peel test diagram. The diagram illustrates the relationship between the applied peel force and the resulting displacement of the specimen. At the beginning of the diagram, the force increases non-linearly, indicating the deformation of the textile. The highest point in the diagram represents the maximum peel force that the specimen can withstand before the textile and polymer structure separate. After reaching the maximum peel force, the force decreases with increasing displacement until the specimen undergoes peel failure.

For the evaluation of peel force, the maximum peel force is used as the assessment criterion. The average maximum peel force is calculated for each test combination and compared with the values of other test combinations.

*Experiment 1.* In the first experiment, the factors *A* (nozzle distance), *B* (pre-tension) and *C* (mesh orientation), along with their interactions (e.g., AB: nozzle distance and pre-tension), were investigated for their effects on adhesion. The evaluation table below presents the resulting effects and statistical indicators (see Table 8).



**Figure 15.** A typical peel test diagram. Source: Authors' own work

**Table 8.** Evaluation table for Experiment 1, presenting the effects of factors A (nozzle distance), B (pre-tension), C (mesh orientation) and their interactions

|                                |       |                        |       |                        |       |       | Confid<br>ence<br>level | 90%   | 95%      | 99%                   | 99.9%        |
|--------------------------------|-------|------------------------|-------|------------------------|-------|-------|-------------------------|-------|----------|-----------------------|--------------|
| Number<br>of<br>factors<br>(n) | 3     | repetit<br>ions<br>(m) | 6     | Degrees<br>freedom (f) | of    | 40    | t-value                 | 1.68  | 2.02     | 2.07                  | 3.35         |
|                                |       |                        |       |                        |       |       | t*SEff<br>ect           | 1.72  | 2.07     | 2.74                  | 3.63         |
| Factors                        | A     | B                      | C     | AB                     | AC    | BC    | ABC                     | Mean  | Variance | Standard<br>deviation | SE<br>effect |
| (1)                            | -1    | -1                     | -1    | 1                      | 1     | 1     | -1                      | 10.69 | 1.00     | 1.00                  | 0.50         |
| a                              | 1     | -1                     | 1     | -1                     | -1    | 1     | 1                       | 9.63  | 1.18     | 1.08                  | 0.54         |
| b                              | -1    | 1                      | -1    | -1                     | 1     | -1    | 1                       | 10.56 | 10.77    | 3.28                  | 1.64         |
| ab                             | 1     | 1                      | -1    | 1                      | -1    | -1    | -1                      | 5.69  | 3.52     | 1.88                  | 0.94         |
| c                              | -1    | -1                     | 1     | 1                      | -1    | -1    | 1                       | 12.79 | 17.51    | 4.18                  | 2.09         |
| ac                             | 1     | -1                     | 1     | -1                     | 1     | -1    | -1                      | 7.98  | 2.13     | 1.46                  | 0.73         |
| bc                             | -1    | 1                      | 1     | -1                     | -1    | 1     | -1                      | 8.57  | 0.22     | 0.47                  | 0.23         |
| abc                            | 1     | 1                      | 1     | 1                      | 1     | 1     | 1                       | 3.22  | 1.27     | 1.13                  | 0.56         |
| Effect                         | -2.01 | -1.63                  | -0.50 | -0.54                  | -0.53 | -0.61 | 0.41                    | 8.64  | 4.7      | 2.17                  | 1.02         |
| 2*<br>Effect                   | 4.02  | 3.26                   | 1     | 1.09                   | 1.06  | 1.23  | 0.82                    |       |          |                       |              |
| 90%                            | yes   | yes                    | no    | no                     | no    | no    | no                      |       |          |                       |              |
| 95%                            | yes   | yes                    | no    | no                     | no    | no    | no                      |       |          |                       |              |
| 99%                            | yes   | yes                    | no    | no                     | no    | no    | no                      |       |          |                       |              |
| 99.9%                          | yes   | no                     | no    | no                     | no    | no    | no                      |       |          |                       |              |

Source(s): Authors' own work

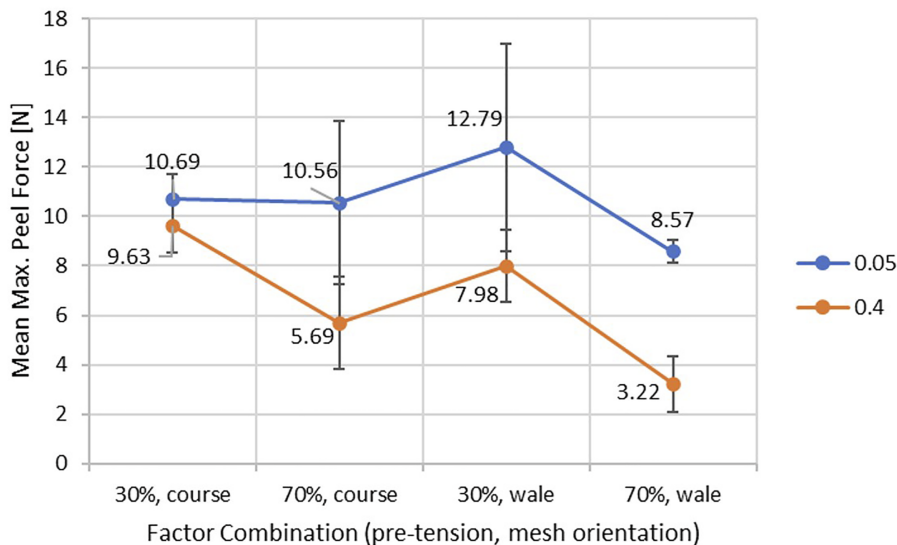
The evaluation table provides an overview of how the individual factors and their interactions influence adhesion performance. Among the three investigated factors, A (nozzle distance) and B (pre-tension) exhibit a strong and statistically significant negative effect on adhesion strength. In contrast, C (mesh orientation) and the interaction factors show no statistically significant influence within the tested parameter range. These findings form the basis for a more detailed analysis of each factor in the following sections.

The factor A (*nozzle distance*) has a strong and statistically significant negative influence on adhesion, with an effect value of  $-2.01$  confirmed at a 99.9% confidence level. Specifically, a reduction in nozzle distance to the textile surface enhances the adhesion at the polymer-textile interface.

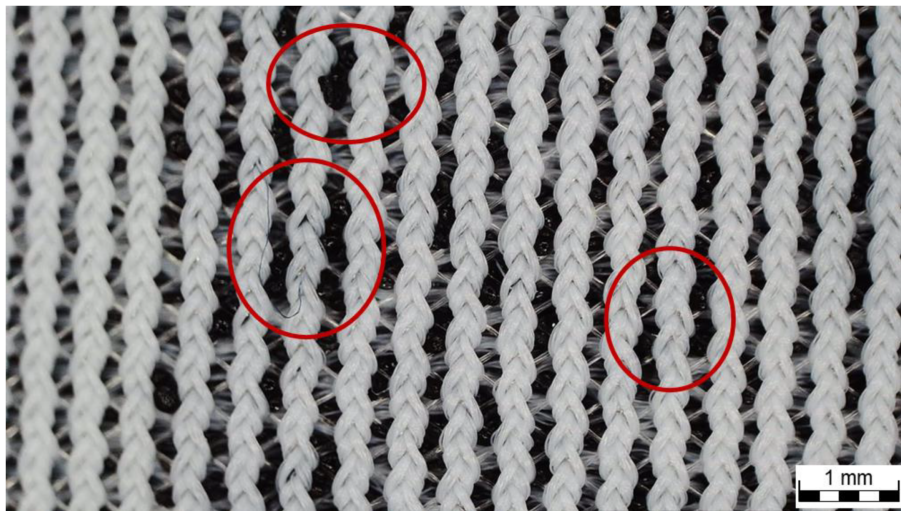
This effect is illustrated in the following diagram [Figure 16](#), where the mean maximum peel force for a nozzle distance of 0.05 mm is notably higher than for 0.4 mm. While some overlap exists in the data for a pre-tension of 30% due to a larger standard deviation, a clear trend is observed. At a pre-tension of 70%, the effect of nozzle distance on adhesion becomes statistically significant.

According to David Schmelzeisen ([Schmelzeisen et al., 2018](#)), the molten polymer creates a mechanical bond with the textile by penetrating the interstices of the textile and solidifying. The close placement of the nozzle on the textile surface exerts additional pressure on the molten polymer, facilitating its penetration into the pores of the textile. The following [Figure 17](#) shows the backside of a sample with a pre-tension of 30% and a nozzle distance of 0.05 mm. The red-crossed area highlights the polymer penetration through the pores of the textile.

The effect value for factor **B (pre-tension)** is  $-1.63$ , indicating a statistically significant negative influence on adhesion at the 99% confidence level. The results indicate that greater pre-tension in the textile leads to lower adhesion. This observation is also supported by [Figure 18](#). This illustrates the adhesion performance of textile samples with two levels of pre-tension (30% and 70%) across different nozzle distances. A consistent trend can be observed: samples with 30% pre-tension exhibit higher adhesion compared to those with 70% pre-



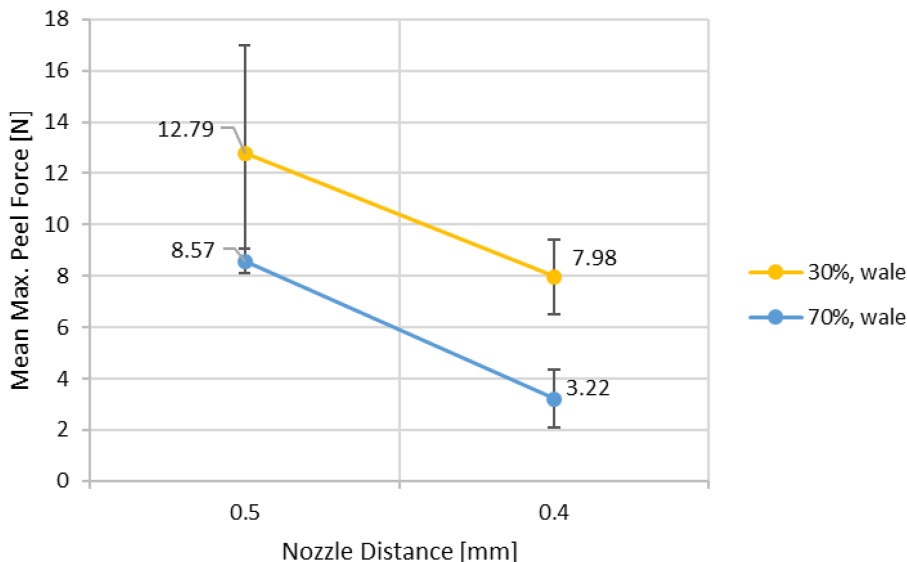
**Figure 16.** Mean maximum peel force as a function of nozzle distance and pre-tension. Source: Authors' own work



**Figure 17.** Polymer penetration through the pores of the textile. Source: Authors' own work

tension. This effect is particularly pronounced at a nozzle distance of 0.05 mm, where the difference in maximum peel force between the two conditions is most significant. Specifically, at 0.05 mm, the mean maximum peel force recorded for the 30% pre-tension samples is approximately 50% higher than that for the 70% pre-tension samples.

After printing, the pre-tension in the textile is released. However, in the regions where the polymer is deposited, the pre-tension remains locally preserved. This leads to mechanical stress within the polymer structure, causing deformation. With higher initial pre-tension, the resulting recovery forces are stronger and act against the printed material, especially at the edges, which



**Figure 18.** Mean maximum peel force at different levels of pre-tension in the textile. Source: Authors' own work

can cause partial detachment of the polymer from the textile surface. In addition, increased pre-tension alters the textile's microstructure. It enlarges the interstitial spaces between the yarns but simultaneously reduces the pore depth. As a result, the available space for the polymer to anchor mechanically within the textile is limited, further reducing adhesion strength. The analysis also revealed that factor *C* (*mesh orientation*) does not have a significant influence on adhesion. This indicates that the orientation of the mesh during printing does not affect the adhesion results.

*Experiment 2.* In the second experiment, the factors *A* (*print bed temperature*), *B* (*nozzle temperature*), and *C* (*mesh orientation*), along with their interactions, were evaluated for their effects on adhesion. The results were analysed using the same method. The evaluation table (see [Table 9](#)) summarizes the findings. The analysis revealed that none of the three factors had a significant influence on adhesion at a confidence level higher than 90%. Additionally, the interactions between these factors showed no notable impact on adhesion. However, it was observed that the effect value for factor *B* (*nozzle temperature*) was very close to the 85% significance threshold. To further investigate, a confidence level of 85% was calculated based on the *t*-distribution and compared to the observed effect. This comparison suggests that nozzle temperature does have an influence on adhesion, although the effect is not strong enough to be statistically significant at the 90% level.

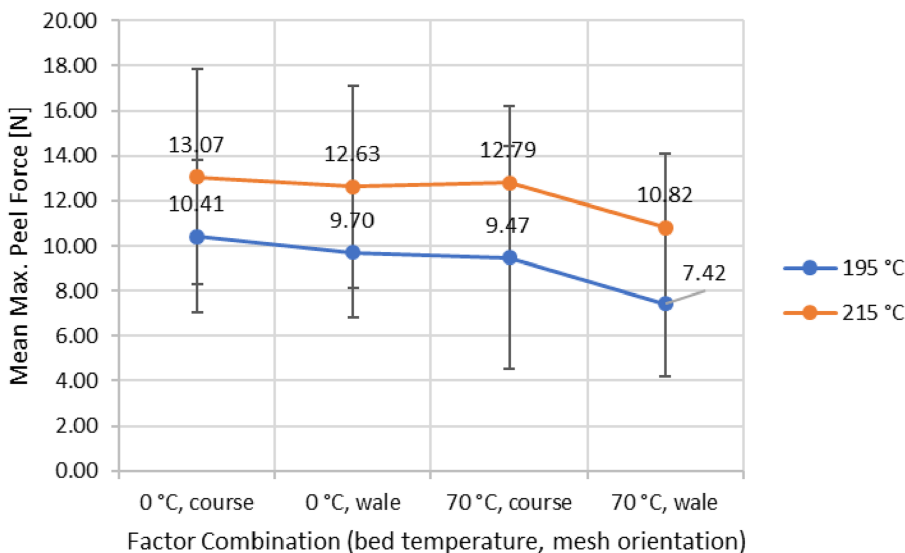
It should be noted that the variance within the experimental data was relatively high, which impaired the quality of the dataset and complicated the analysis based on the evaluation table. The increased variance likely stems from inconsistencies in the 3D printing process itself, as well as minor variations in manual pre-tensioning and relaxation of the textile samples prior to testing. Despite these limitations, a general trend was observed: higher nozzle temperatures led to stronger adhesion at the interface. This can be attributed to the lower viscosity of PLA at elevated temperatures, allowing the molten polymer to more easily penetrate the textile pores and form stronger mechanical interlocks. However, it is critical to ensure that the nozzle temperature remains within the appropriate range according to the supplier for the polymer to ensure a successful printing process. Excessively high nozzle temperatures can result in over-extrusion, while too low temperatures may cause under-extrusion, clogging and weak interlayer adhesion, all of which negatively affect print quality and mechanical performance.

**Table 9.** Evaluation table for Experiment 2, presenting the effects of factors A (print bed temperature), B (nozzle temperature), C (mesh orientation), and their interactions

|                       |       |                 |       |                        |       | Confidence level   | 85%   | 90%   | 95%      | 99%                | 99.9%     |
|-----------------------|-------|-----------------|-------|------------------------|-------|--------------------|-------|-------|----------|--------------------|-----------|
| Number of factors (n) | 3     | repetitions (m) | 12    | Degrees of freedom (f) | 40    | t-value t*SEeffect | 1.47  | 1.68  | 2.02     | 2.07               | 3.35      |
| Factors               | A     | B               | C     | AB                     | AC    | BC                 | ABC   | Mean  | Variance | Standard deviation | SE effect |
| (1)                   | -1    | -1              | -1    | 1                      | 1     | 1                  | -1    | 10.41 | 11.40    | 3.38               | 1.69      |
| a                     | 1     | -1              | 1     | -1                     | -1    | 1                  | 1     | 9.47  | 24.54    | 4.95               | 2.48      |
| b                     | -1    | 1               | -1    | -1                     | 1     | -1                 | 1     | 13.07 | 22.67    | 4.76               | 2.38      |
| ab                    | 1     | 1               | -1    | 1                      | -1    | -1                 | -1    | 12.79 | 11.68    | 3.42               | 1.71      |
| c                     | -1    | -1              | 1     | 1                      | -1    | -1                 | 1     | 9.70  | 8.27     | 2.88               | 1.44      |
| ac                    | 1     | -1              | 1     | -1                     | 1     | -1                 | -1    | 7.42  | 10.50    | 3.24               | 1.62      |
| bc                    | -1    | 1               | 1     | -1                     | -1    | 1                  | -1    | 12.63 | 20.16    | 4.49               | 2.25      |
| abc                   | 1     | 1               | 1     | 1                      | 1     | 1                  | 1     | 10.82 | 10.56    | 3.25               | 1.63      |
| Effect                | -0.66 | 1.54            | -0.65 | 0.14                   | -0.36 | 0.04               | -0.02 | 10.79 | 14.97    | 3.87               | 1.82      |
| 2* Effect             | 1.32  | 3.08            | 1.29  | 0.28                   | 0.72  | 0.09               | 0.05  |       |          |                    |           |
| 85%                   | no    | yes             | no    |                        |       |                    |       |       |          |                    |           |
| 90%                   | no    | no              | no    | no                     | no    | no                 | no    |       |          |                    |           |
| 95%                   | no    | no              | no    | no                     | no    | no                 | no    |       |          |                    |           |
| 99%                   | no    | no              | no    | no                     | no    | no                 | no    |       |          |                    |           |
| 99.9%                 | no    | no              | no    | no                     | no    | no                 | no    |       |          |                    |           |

Source(s): Authors' own work

To better illustrate the influence of nozzle temperature on adhesion, a diagram was created (see Figure 19). It can be clearly observed that the mean maximum peel force at higher nozzle temperatures is greater compared to lower temperatures. However, due to the high variance in



**Figure 19.** Mean maximum peel force at different nozzle temperatures. Source: Authors' own work



the experimental data, it is difficult to draw a definitive conclusion solely based on these results. According to the evaluation table, the effect reaches significance only at a confidence level of 85%, which is below the commonly accepted thresholds for statistical significance.

Nonetheless, findings from other studies support the observed trend (Mishra et al., 2022). It has been shown that the viscosity of PLA decreases with increasing temperature, allowing the molten polymer to more easily penetrate the textile pores. Upon solidification, this leads to stronger mechanical interlocking between the polymer and the textile structure, thereby enhancing adhesion strength.

*Experiment 3.* In Experiment 3, the investigated factors included *A (pre-tension)*, *B (printing speed)* and *C (nozzle temperature)*. Based on the findings of the previous experiment, where nozzle temperature showed a slight but notable influence on adhesion, a broader temperature range was selected for this trial in order to further explore and validate its effect. The nozzle temperature was varied between 190 °C and 220 °C, representing the lower and upper bounds of the recommended processing range for PLA. This extended range was chosen with the expectation of obtaining a statistically significant effect. The evaluation results are summarized in Table 10.

According to the table, factor A (pre-tension) again shows a negative influence on adhesion, consistent with the results from Experiment 1. Factor B (printing speed) does not exhibit a statistically significant effect, whereas factor C (nozzle temperature) shows a positive and statistically significant effect, with a confidence level of up to 90%. These results confirm the initial hypothesis.

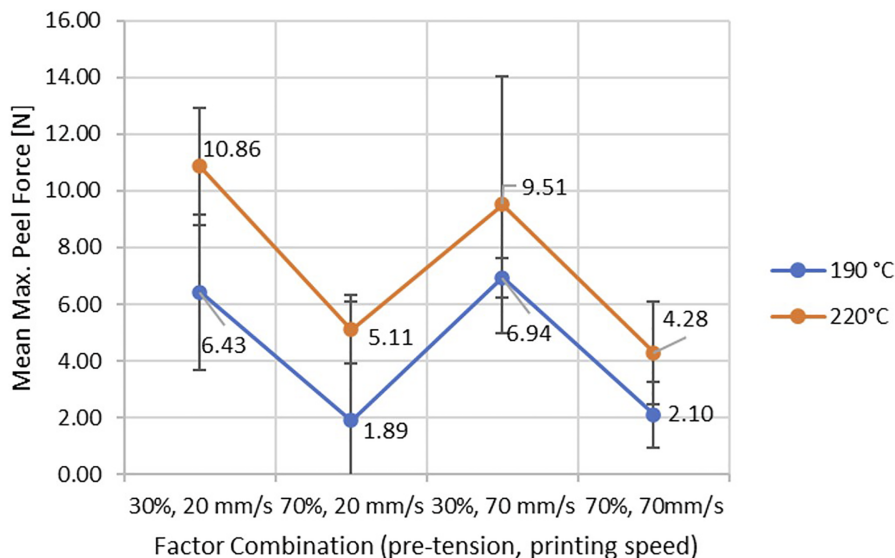
Since the influence of pre-tension (factor A) has already been thoroughly discussed in Experiment 1, a separate analysis or illustration is not repeated here. However, to better visualize the impact of nozzle temperature (factor C), a diagram was created (see Figure 20). As in Experiment 2, the graph reveals a clear trend: the line representing higher nozzle temperatures consistently lies above the one for lower temperatures, indicating improved adhesion at elevated temperatures. This observation aligns well with the findings in the evaluation table.

**Table 10.** Evaluation table for Experiment 3, presenting the effects of factors A (pre-tension), B (printing speed), C (nozzle temperature) and their interactions

|                                |       |                        |      |                           |       |       |                | Confid<br>ence<br>level | 90%      | 95%                   | 99%          | 99.9% |
|--------------------------------|-------|------------------------|------|---------------------------|-------|-------|----------------|-------------------------|----------|-----------------------|--------------|-------|
| Number<br>of<br>factors<br>(n) | 3     | repetit<br>ions<br>(m) | 4    | Degrees of<br>freedom (f) | 24    |       | t-value        | 1.71                    | 2.06     | 2.80                  | 3.75         |       |
|                                |       |                        |      |                           |       |       | t*SEeff<br>ect | 2.63                    | 3.17     | 4.30                  | 5.76         |       |
| Factors                        | A     | B                      | C    | AB                        | AC    | BC    | ABC            | Mean                    | Variance | Standard<br>deviation | SE<br>effect |       |
| (1)                            | -1    | -1                     | -1   | 1                         | 1     | 1     | -1             | 6.43                    | 7.56     | 2.75                  | 1.37         |       |
| a                              | 1     | -1                     | 1    | -1                        | -1    | 1     | 1              | 1.89                    | 0.47     | 0.69                  | 0.34         |       |
| b                              | -1    | 1                      | -1   | -1                        | 1     | -1    | 1              | 6.94                    | 17.60    | 4.20                  | 2.10         |       |
| ab                             | 1     | 1                      | -1   | 1                         | -1    | -1    | -1             | 2.10                    | 1.36     | 1.17                  | 0.58         |       |
| c                              | -1    | -1                     | 1    | 1                         | -1    | -1    | 1              | 10.86                   | 4.32     | 2.08                  | 1.04         |       |
| ac                             | 1     | -1                     | 1    | -1                        | 1     | -1    | -1             | 5.11                    | 1.49     | 1.22                  | 0.61         |       |
| bc                             | -1    | 1                      | 1    | -1                        | -1    | 1     | -1             | 9.51                    | 20.55    | 4.53                  | 2.27         |       |
| abc                            | 1     | 1                      | 1    | 1                         | 1     | 1     | 1              | 4.28                    | 3.33     | 1.82                  | 0.91         |       |
| Effect                         | -2.54 | -0.18                  | 1.55 | 0.03                      | -0.20 | -0.36 | 0.10           | 5.89                    | 7.09     | 2.66                  | 1.54         |       |
| 2*<br>Effect                   | 5.09  | 0.36                   | 3.10 | 0.05                      | 0.40  | 0.72  | 0.21           |                         |          |                       |              |       |
| 90%                            | yes   | no                     | yes  | no                        | no    | no    | no             |                         |          |                       |              |       |
| 95%                            | yes   | no                     | no   | no                        | no    | no    | no             |                         |          |                       |              |       |
| 99%                            | yes   | no                     | no   | no                        | no    | no    | no             |                         |          |                       |              |       |
| 99.9%                          | yes   | no                     | no   | no                        | no    | no    | no             |                         |          |                       |              |       |

Source(s): Authors' own work





**Figure 20.** Mean maximum peel force at different nozzle temperatures. Source: Authors' own work

Although the data variance in this experiment remains relatively high, similar to that observed in Experiment 2, this does not compromise the validity of the results. The evaluation based on a  $2^n$  factorial design provides robust statistical support for the conclusion that, within the recommended processing temperature range for filament, higher nozzle temperatures result in improved adhesion between the polymer and the textile. As already discussed in Experiment 2, the underlying mechanism can be attributed to the reduction in PLA viscosity at elevated temperatures. This reduced viscosity allows the molten polymer to penetrate more effectively into the textile structure. As a result, stronger mechanical interlocking occurs upon solidification, which enhances the overall adhesion strength.

*Experiment 4.* In Experiment 4, the factors *A* (textile type), *B* (pre-tension) and *C* (fabric side) were analysed. The type of textile had a highly significant effect on adhesion, while pre-tension exhibited a consistent negative influence on adhesion, as observed in previous experiments. The fabric side, however, showed no significant impact. Additionally, the interaction between textile type and pre-tension (AB) demonstrated a statistically significant effect on adhesion at the 90% confidence level. The corresponding evaluation table is presented in Table 11.

As in the previous experiments, the influence of textile type (factor A) is further illustrated using a diagram (see Figure 21).

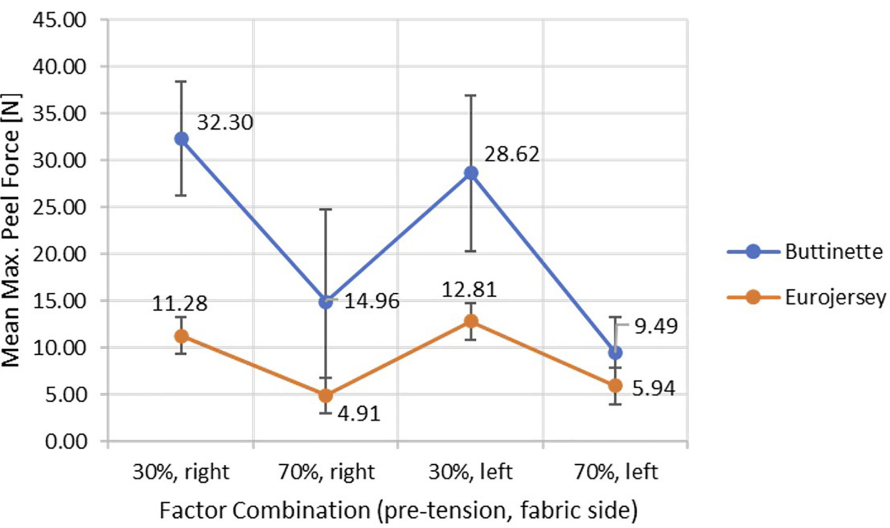
The mean maximum peel force on Buttinette fabric was higher than on Eurojersey. Notably, at 30% pre-tension, a clear difference is evident despite the standard deviation, indicating significantly stronger adhesion on Buttinette. To better understand this difference, the textile structures were examined. Samples printed on Buttinette exhibited greater adhesion compared to Eurojersey, which is attributed to structural differences between the two fabrics. Figure 22 provides a microscopic comparison of both fabric surfaces. Microscopic analysis revealed that the Buttinette fabric is composed of two yarn systems: a tricot system and a cloth system, while Eurojersey features only one tricot system.

At the same level of 70% pre-tension, Buttinette exhibited smaller pores than Eurojersey. Additionally, the two-layered structure of Buttinette provides more bonding points for the molten polymer, resulting in superior adhesion compared to Eurojersey. These results are consistent with the findings of Schmelzeisen (2018), who stated that pores on the adherend surface must exceed a certain minimum size to allow proper filling by the liquid adhesive. However, if the pores become

**Table 11.** Evaluation table for Experiment 4, presenting the effects of factors A (textile type), B (pre-tension), C (fabric side) and their interactions

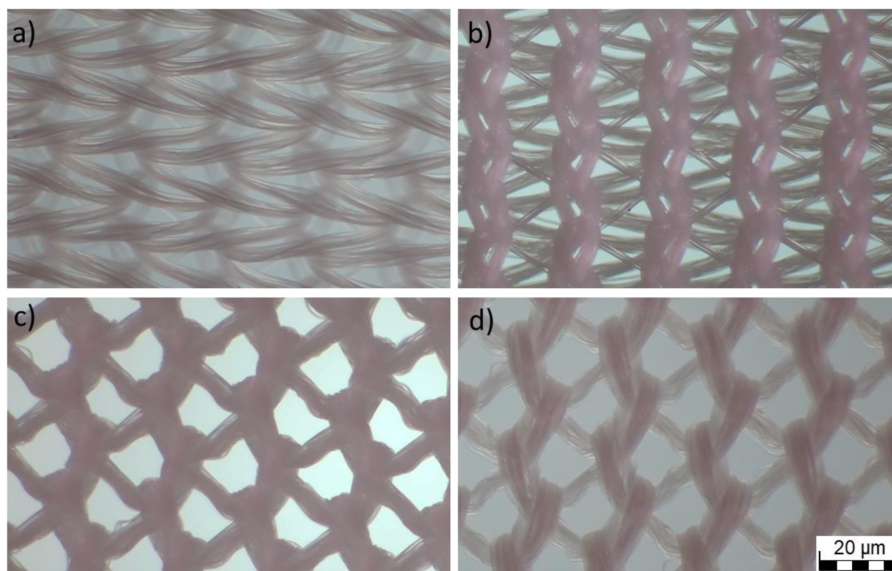
|                       |       |                 |      |                        |      |       |       |                  |          |                    |           |       |
|-----------------------|-------|-----------------|------|------------------------|------|-------|-------|------------------|----------|--------------------|-----------|-------|
|                       |       |                 |      |                        |      |       |       | Confidence level | 90%      | 95%                | 99%       | 99.9% |
| Number of factors (n) | 3     | repetitions (m) | 4    | Degrees of freedom (f) | 24   |       |       | t-value          | 1.68     | 2.02               | 2.07      | 3.35  |
|                       |       |                 |      |                        |      |       |       | t*SEffect        | 4.36     | 5.24               | 7.01      | 9.20  |
| Factors               | A     | B               | C    | AB                     | AC   | BC    | ABC   | Mean             | Variance | Standard deviation | SE effect |       |
| (1)                   | -1    | -1              | -1   | 1                      | 1    | 1     | -1    | 11.28            | 10.41    | 3.23               | 1.61      |       |
| a                     | 1     | -1              | 1    | -1                     | -1   | 1     | 1     | 23.65            | 37.37    | 6.11               | 3.06      |       |
| b                     | -1    | 1               | -1   | -1                     | 1    | -1    | 1     | 4.91             | 4.11     | 2.03               | 1.01      |       |
| ab                    | 1     | 1               | -1   | 1                      | -1   | -1    | -1    | 14.96            | 95.38    | 9.77               | 4.88      |       |
| c                     | -1    | -1              | 1    | 1                      | -1   | -1    | 1     | 12.81            | 10.27    | 3.20               | 1.60      |       |
| ac                    | 1     | -1              | 1    | -1                     | 1    | -1    | -1    | 32.30            | 68.70    | 8.29               | 4.14      |       |
| bc                    | -1    | 1               | 1    | -1                     | -1   | 1     | -1    | 5.94             | 1.49     | 1.22               | 0.61      |       |
| abc                   | 1     | 1               | 1    | 1                      | 1    | 1     | 1     | 9.49             | 14.14    | 3.76               | 1.88      |       |
| Effect                | 5.68  | -5.59           | 0.72 | -2.28                  | 0.08 | -1.83 | -1.70 | 14.42            | 30.23    | 5.50               | 2.75      |       |
| 2* Effect             | 11.37 | 11.19           | 1.43 | 4.56                   | 0.15 | 3.66  | 3.41  |                  |          |                    |           |       |
| 90%                   | yes   | yes             | no   | yes                    | no   | no    | no    |                  |          |                    |           |       |
| 95%                   | yes   | yes             | no   | no                     | no   | no    | no    |                  |          |                    |           |       |
| 99%                   | yes   | yes             | no   | no                     | no   | no    | no    |                  |          |                    |           |       |
| 99.9%                 | yes   | yes             | no   | no                     | no   | no    | no    |                  |          |                    |           |       |

Source(s): Authors' own work



**Figure 21.** Mean maximum peel force for different textile types. Source: Authors' own work

too large, adhesion strength decreases. In addition, our findings indicate that pore size alone does not play a decisive role in adhesion. Instead, the relationship between pre-tension and textile thickness is critical. This is reflected in the findings related to the interaction with pre-tension: with lower pre-tension, the pores are smaller, but the fabric is thicker, creating more bonding points for the polymer. Moreover, the interaction between factors A and B (textile type and pre-



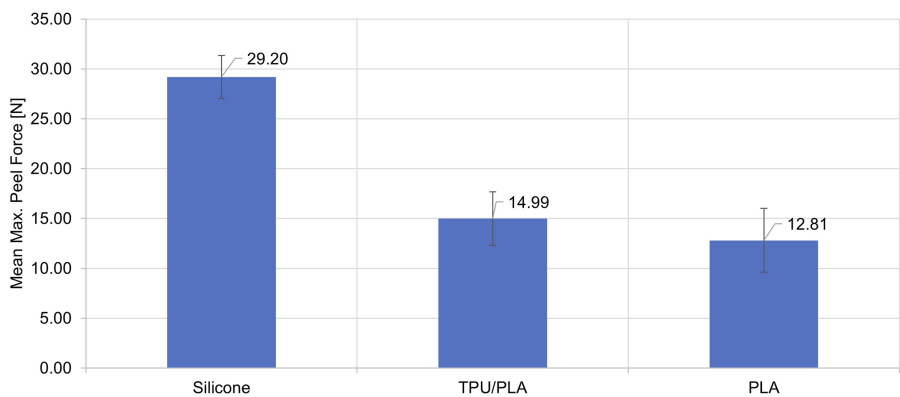
**Figure 22.** Microscopic images of textiles under 70% pre-tension: (a) Buttinette textile – left fabric side, (b) Buttinette textile – right fabric side, (c) Eurojersey textile – left fabric side, (d) Eurojersey textile – right fabric side. Source: Authors' own work

tension) indicates a negative effect on adhesion. This indicates that the combination of certain fabric structures with higher pre-tension results in a greater reduction of adhesion than expected from the individual effects of each factor. This can be explained by the fact that increased pre-tension enlarges the pore size but simultaneously reduces fabric thickness, leading to fewer effective bonding points for the polymer. Additionally, higher residual elastic forces in the pre-tensioned textile act against the printed polymer, further weakening the mechanical interlocking and reducing overall adhesion.

*Experiment 5.* In this experiment, three different materials, pure PLA (Ultimaker, n.d.), multi-material arrangement of PLA and TPU (Maertz, n.d.; Kimya, 2025), and silicone (The Dow Chemical Company, n.d.), were tested under process-specific optimal conditions. These conditions included 30% pre-tension, minimal nozzle distance and from the supplier recommended printing temperatures, with slight variations in parameters depending on the specific process (e.g., minimal feasible nozzle distance was calibrated for each machine). In this section, only one parameter was analysed, specifically the type of material. For this reason, a full  $2^n$  factorial design was not applied. As in previous trials, the average maximum peel force of each material sample was used as the primary metric for comparison.

The results, presented in Figure 23 indicate that silicone exhibited the highest peel strength, while pure PLA displayed the lowest. This outcome is strongly influenced by viscosity. Silicone, deposited through the mixing of two gel components, has a relatively low viscosity, allowing it to permeate the textile more effectively. Additionally, the post-print heat-curing step enables the silicone to form multiple mechanical interlocks within the textile structure, further enhancing adhesion.

The multi-material arrangement of PLA/TPU achieved an intermediate peel strength. TPU's lower viscosity in a semi-molten state facilitates improved penetration into the textile pores, resulting in stronger adhesion compared to pure PLA. These observations are consistent with previous findings from Experiment 2 and the results reported by (Bodaghi et al., 2024).



**Figure 23.** Mean maximum peel force for different polymers (silicone, TPU/PLA and PLA). Source: Authors' own work

### Conclusions and recommendations

In this study, nine different parameters influencing interfacial adhesion in 4D-textiles were investigated using a  $2^n$  factorial design approach. The analysis was based on a combination of evaluation tables and supporting diagrams to ensure robust conclusions. The selected factors covered material properties of the printed polymers, textile characteristics and process parameters. The following key findings were obtained.

- (1) Nozzle distance between the print head and the textile surface was found to be essential for achieving strong adhesion. The closer the nozzle, the stronger the interfacial bond. However, the nozzle must not be too close, as excessive proximity can damage the textile through heat exposure. For the Ultimaker 3D printer used in this study, the optimal nozzle distance was 0.05 mm.
- (2) Textile pre-tension had a strong and statistically significant influence on adhesion. Higher pre-tension led to reduced adhesion, which can be attributed to residual elastic forces in the fabric acting against the printed polymer after deposition. A pre-tension of 30% resulted in relatively strong adhesion. In addition, the curvature of the printed structure could be observed after the release of the pre-tension, demonstrating the characteristic 4D behaviour of the textile-polymer composite.
- (3) Nozzle temperature also influenced adhesion, showing statistical significance at the 90% confidence level. Within the recommended processing window for PLA, higher nozzle temperatures led to increased adhesion. This effect is likely due to the slightly lower viscosity of PLA at elevated temperatures, which improves flowability and penetration into textile pores. In this study, 220 °C was identified as the optimal nozzle temperature for PLA.
- (4) The textile structure plays a significant role in adhesion. Textiles with a dual tricot system exhibited smaller and more numerous pores, which enabled better mechanical interlocking by increasing the number of potential anchoring points for the molten polymer. A highly elastic fabric with elastane content and dual tricot construction was found to be optimal for 4D textile applications.
- (5) The interaction between pre-tension and textile type also affects adhesion
- (6) The material type used for printing also had a significant effect on adhesion. Among the materials tested, silicone rubber, pure PLA and a PLA/TPU blend. Silicone showed the

highest adhesion. This is attributed to its low viscosity during extrusion, which allows better penetration into the textile structure and thus stronger mechanical bonding.

- (7) In contrast, mesh orientation, printing speed and print bed temperature were found to have no significant influence on adhesion within the tested parameter ranges.

The findings of this study provide a systematic analysis of interfacial adhesion and can facilitate the production of 4D textiles and 3D-printed structures on textile substrates. By applying the identified key parameters, strong adhesion can be achieved without the need for repeated trial-and-error testing. In the context of 4D textiles, this is particularly important, as reliable adhesion ensures the structural integrity required for repeated state transformations during actuation cycles.

Moreover, the improved reliability and reproducibility of the adhesion process contribute to more efficient and sustainable manufacturing by minimizing material waste and reducing dependence on auxiliary bonding agents. These insights not only enhance the robustness and scalability of 4D-textile production but also pave the way for broader adoption in fields such as wearable electronics, soft robotics, and adaptive architecture.

Future research could focus on exploring the interaction between molten polymers and textile materials at the microscopic level to provide deeper insights into the adhesion mechanisms. Additionally, the use of adhesive agents, primers, and surface modification techniques can be investigated to further improve the interfacial adhesion between polymers and textile substrates. For polymer-to-polymer interfaces, specialized adhesion promoters and compatible material pairings could also be explored. Moreover, advanced surface treatments such as plasma activation offer promising approaches for enhancing adhesion performance in 4D textile systems and warrant further investigation.

Additionally, developing a comprehensive database of adhesion properties for various polymers on pre-tensioned textiles through systematic testing could offer valuable guidance for process optimization and material selection.

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