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# Laser-Based Powder Fixation on Textiles for Highly Functionalized Coatings

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**Abstract**

In recent years, the demand for Smart and Technical Textiles has increased, especially with the incorporation of sensors and actuators. However, current conductive textile structures, achieved by integrating conductive yarns, wires, and strands or by conventional coating and printing technologies, lack kink resistance, reliability, and the required grade of functionalization. The proposed process allows the application of a multi-material powder comprising a blend of polymer powders and functional pigments, e.g., metal particles. The technology is characterized by a nozzle-based application of the loose powder mixture and a subsequent laser fixation step. This enables the fabrication of individualized and highly functionalized coated substrates based on a digital data set. However, it was noticed that the laser beam path overshoots the targeted tracks for various reasons, such as substrate surface, heat-affected zone, different powder types used, and their interaction with the laser are discussed here.

**Keywords:** Powder; Coating; Multi-material; Additive Manufacturing; Smart textiles

## 1. Introduction

Smart textiles have significantly grown over the past decades, yielding tangible research and development. The investment for innovation has simultaneously grown with the assistance of the growth of the Internet of Things (IOT). Smart textiles historically gained attention with silk thread exhibiting the shape memory effect. The intelligence of textiles to respond to stimuli differs smart textiles from regular textiles. Smart textiles react either actively or passively based on the type of functionality required and the embedded system of electronics, electrical, mechanical, optical components, and other materials (Gehrke et al., 2019) (Stoppa and Chiolerio, 2014).

Research has expanded to include conductive, thermochromic, photochromic, and photoluminescent functionalities, enabling applications in health monitoring, interactive fashion, protective gear, and more (Ferrara and Bengisu, 2014). Despite rapid advancements, challenges persist in the production of smart textiles with reliable conductivity, durability, and fine-resolution patterning. Traditional techniques involving integration of conductive yarns, screen printing of functional materials, and direct coating of functional materials onto the surface of a woven textile (excluding yarn coating) often fall short in meeting industrial requirements for mechanical flexibility, kink resistance, washability, and adhesion (Stoppa and Chiolerio, 2014). To address these challenges, research into powder-based surface coating methods was undertaken, and corresponding experiments were conducted. The primary troubleshooting was by selecting a material that is flexible enough to match a woven textile. Thermoplastic polyurethanes (TPUs) have shown impeccable durability which offering the necessary flexibility at a process temperature feasible and a broad range. TPUs with broad processing temperatures and commercially available are suitable to enhance the reproducibility of the research. However, the thermoplastic polymer alone does not show significant electrical conductivity to enable direct connection to sensors and actuators. Functional pigments like colour-changing pigments and metallic powders, when mixed with thermoplastics in required ratios, will offer the functionality while retaining the flexibility. The dry powder mixtures were initially applied using conventional methods with a stencil and a doctor blade. Later, the research introduced a new approach that combines digital powder deposition using a vibrating nozzle and laser fixation to enable individualized, repeatable, and digitalized coating of textiles with functional powders (Shivakumar et al., 2024).

The Powder Coating Technology developed at TITV Greiz, as shown in Figure 1 Schematic representation of the two-stage laser-based powder fixation on textiles (left) and an installed functional laser-based powder fixation machine (right)offers an alternative route, using a powder blend of polymer binder and functional pigments. This method ensures greater functional pigment content, mechanical resistance, and reproducibility across batches. Previous implementations relied on manual stencil-based powder deposition, which limits resolution to ~3 mm, design flexibility, and powder reuse. The project overcame these limitations through a vibrating nozzle-based powder delivery system, enabling localized and digital control of powder application followed by laser fixation. This allowed for filigree, individualized patterns, eliminating the manual application method. The digitalized format also offered high durability under washing, abrasion, and flexibility.

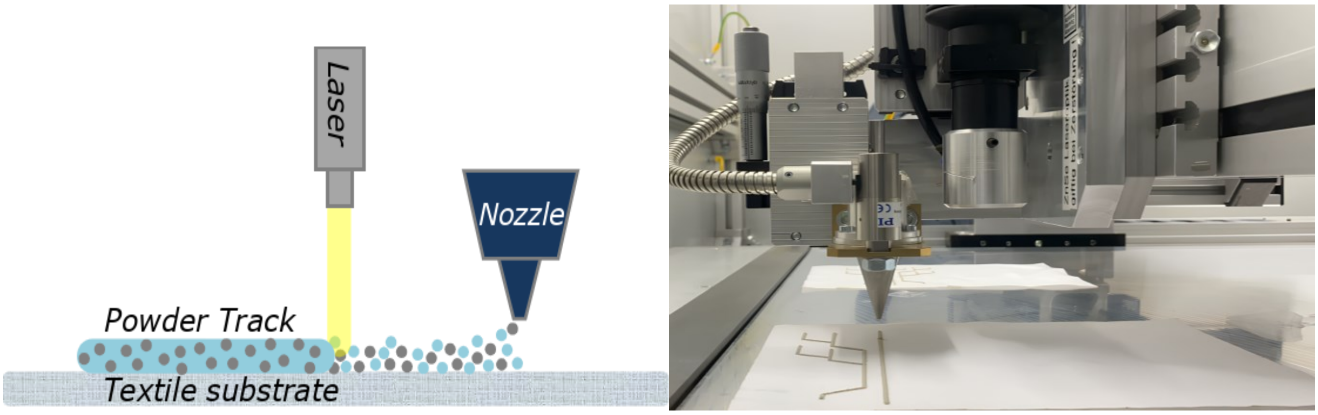


Figure 1 Schematic representation of the two-stage laser-based powder fixation on textiles (left) and an installed functional laser-based powder fixation machine (right)

This paper expands on that base by investigating the applicability of the laser-based powder coating technology of electrically conductive and thermochromic pigments. These pigment systems offer a new layer of visual or sensory feedback in textile substrates, which is key for both aesthetic feedback and sensoric applications. The study on such pigments offers insights into laser-material interaction of laser-sensitive materials like thermochromic pigments and understanding the influence of the laser on textile-based substrates. The importance lies in drawing the requirements of laser process parameters and beam alignment to ensure selective laser interaction during the manufacturing of technical textiles. The paper is limited to the results of conductive and thermochromic pigments; previous experiments have indicated that stencil-based powder coating methods can be postulated to incorporate a wider range of functional pigment systems laser-based powder coating. This includes, e. g. magnetic, radiation-resistant, laser-protective, photochromic, and photoluminescent for advanced multifunctional textile development.

## 2. Materials and Experimental Procedures

### 2.1 Materials

The textile substrates used in this study are commercially available plain-woven cotton/polyester (CO/PES) blend, knitted polyester, and non-woven polyester. This hybrid substrate was selected due to its prevalent use in wearable textile applications, offering both thermal resistance and mechanical flexibility. Silver-coated aluminium spheres (conductive, metallic core-shell particles), silver flakes (conductive, flat metallic particles), and thermochromic pigment powders (pigments responsive to temperature changes) are used for functionalization. Commercially available thermoplastic polyurethane (TPU), with a melting range of 50° to 200°C were tested, selected as binder powder, and mixed with pigment concentrations ranging from 30% to 80% by weight. Thermochromic pigments that shift from deep blue to white near 30°C with less than 30% by weight will be used for surface functionalization suitable for human body interaction. The preferred TPU powder had a particle size above 5 µm, with a typical D90 value in the range of 20–80 µm, depending on market availability. The powders were loaded into vials, dried, and mixed for 10 minutes using TURBULA® T2F powder mixing machine to ensure a thorough blend. All loose powder handling was conducted under a fume hood with appropriate personal protective equipment, including lab coat, gloves, and N95 mask.

### 2.2 Powder Application Methodology

A numerically controlled laser-powder system was custom-designed according to our research requirements, by Bayerisches Laser Zentrum in Erlangen, Germany is used for both powder application and laser beam tracing. The system includes a piezo-actuated nozzle fed from a dry powder hopper and moved across the textile surface using a custom NC control software. The nozzle drops powder in a line pattern as it pans across the fabric, with deposition parameters tuned for each formulation. Parameters for the nozzle involve vibration frequency, nozzle height (vertical distance between the nozzle end to the textile surface), deposition speed, and wave function. Various CAD software can be used to create 2D contours (Straight lines and Bézier curves) and converted to Drawing Exchange Format (.dxf) format. The fabric was clamped on a 600 x 600 mm heated bed equipped with magnetically clamping bars to ensure a wrinkle-free surface. A lint roller is rolled across the fabric to remove any surface contaminants, including lint from the textile. The bed is temperature-controlled in the range 20–80°C, tailored to the powder mixture and to favour sintering.

### 2.3 Thermal Fixation Methodology

A water-cooled $CO_2$-laser in the mid-infrared range was employed as the beam source in this study. The laser module is mounted adjacent to the powder deposition nozzle. The laser operates under the same NC controls as the powder nozzle, with laser parameters adjustable both at the local and global scale. Laser power, scan speed, and focal plane position were varied experimentally to identify optimal fixation conditions for each powder. Parameters ranged from 9 W to 55 W and scan speeds between 0.03 m/min and 6m/min. The laser is used to sinter the thermoplastics present in the powder mixture while maintaining the functional pigments to remain as discrete entities inside the matrix. The Gaussian nature of the beam profile was accounted for alignment protocols. Post-laser processing involved heat pressing at 50–200°C to enhance mechanical bonding between the sintered powder and the textile substrate for permanent fixation. The post-processing thermal parameters were adjusted according to the properties of the thermoplastic binder used.

### 2.4 Characterization

A 3D optical profilometer was used to measure powder line heights and widths using a Keyence VHX light microscope. 3D images of powder tracks were scanned to determine the maximum, average, and standard deviation of track geometry. Electrical conductivity was tested for fixed metallic pigment lines using a two-point probe method, and these results are published (Shivakumar et al., 2024) and are not presented here. Substrate damage was assessed visually and microscopically with an additional study made on direct laser and textile interaction without any powder application. Burnt marks, delamination, or pigment discoloration were recorded during the study.

## 3. Results and discussion

Powder deposition onto the textile substrate was achieved within a defined process window using a vibrationally actuated nozzle. However, early-stage experiments revealed two persistent challenges that limited the consistency and quality of the deposited tracks: (1) accumulation of powder at the line terminations, resulting in localized "mountain" formations and (2) discontinuities occurring intermittently along the deposition path. Figure 2 shows the powder track quality at the early stages and after recitifying the defects. These issues were not only detrimental to the resolution of the printed features but also indicative of powder flow dynamics. Analysis of the deposition tracks indicated that the discontinuities occurred in a non-periodic, seemingly stochastic manner. No correlation was observed between the spatial frequency of defects and the periodicity of the applied waveform, suggesting that the discontinuities were not the result of harmonic interference or

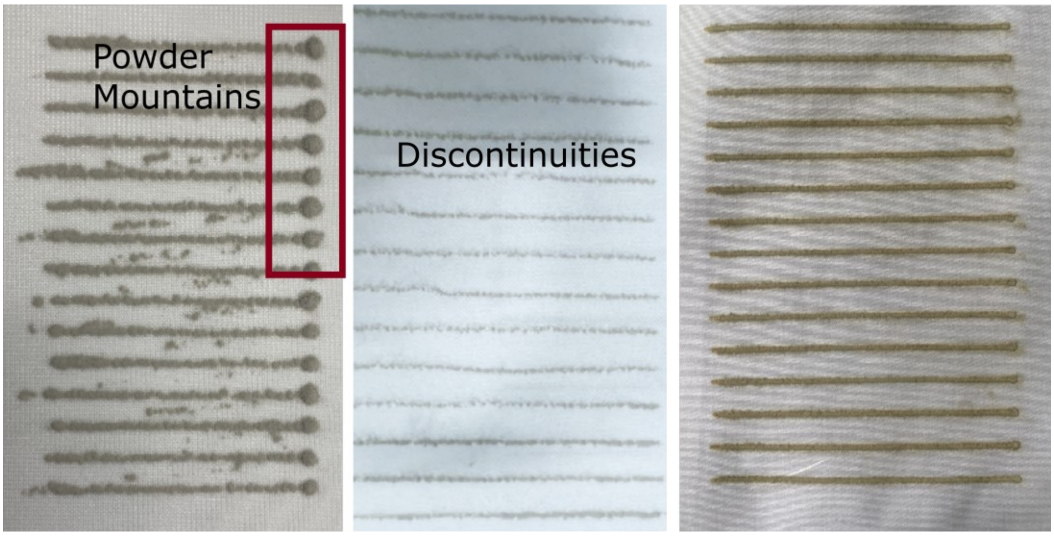


Figure 2 Progression of powder track quality from agglomeration defects to stable, continuous tracks using optimized nozzle.

standing wave effects within the system. This observation led to the exclusion of wave function modulation, the sine waveform, as a viable control mechanism for mitigating these defects.

Further experiments highlighted a pronounced sensitivity of deposition behaviour to powder morphology. Specifically, powders with irregular geometries and broad size distributions exhibited greater anomalies during deposition. A powder fluidization study was conducted to assess the flowability of these mixtures, and the results indicated that inter-particle surface friction could lead to clogging within the system (Airoldi et al., 2024). Additionally, investigations into piezoelectric excitation frequency demonstrated that operation outside optimal frequency bands led to clogging, inconsistent flow, or complete failure of deposition. This frequency-dependent behaviour was found to be material-specific and was also observed in other formulations, including spherical conductive particles and binder-only systems. The identification of an optimal excitation frequency, as well as nozzle orifice diameter for each material, emerges as a critical factor for ensuring consistent deposition (Chueh et al., 2020) (Wu et al., 2020). Test of nozzle frequency in the range of 100 to 3500 Hz with sinusoidal function yielded several frequencies starting from 100 Hz to several hundreds of Hz for different powder mixtures with varied pigment ratios and pigment shapes. A frequency from 500 to 600 Hz was chosen for conductive and thermochromic pigments that suited the best for the given orifice diameter and nozzle design.

Adjustments to deposition speed, which is the nozzle movement speed, as shown in Figure 3 Comparison of the influence of nozzle speed on the sharpness of the deposited powder tracks.

, improved the contour sharpness of the powder track. While careful tuning of this parameter reduced discontinuities, the issue of terminal accumulation remained partially resolved. The subsequent modification in the nozzle design to incorporate an adjustable orifice diameter, which cumulatively enabled more precise control overflow rate and improved adaptability to system dynamics. This included the breaking of powder bridges formed at the bottom of the interior walls of the nozzle and the inter-particle friction was significantly reduced to improve the flowability of the powder mixture. These modifications enhanced the reliability and versatility of the deposition system, offering a more universal approach to powder handling in vibrationally driven printing processes. This gradual and cumulative powder deposition development is presented in Figure 2 and Figure 3 Comparison of the influence of nozzle speed on the sharpness of the deposited powder tracks.

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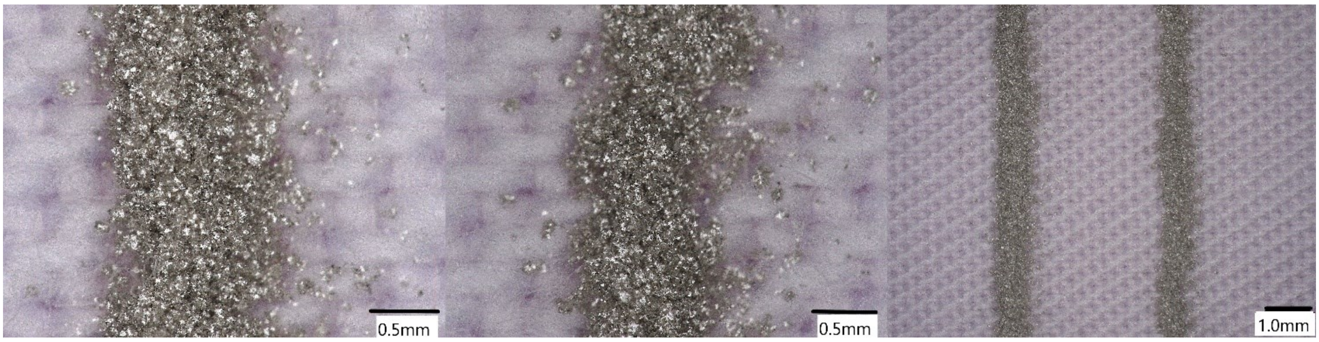


Figure 3 Comparison of the influence of nozzle speed on the sharpness of the deposited powder tracks.

3D optical profilometry of the printed tracks revealed highly irregular powder deposits. As shown in the color-coded 3D map in **Fehler! Verweisquelle konnte nicht gefunden werden.**, the laser-fixed powder tracks exhibited differences in geometry and variability. Silver-flake deposits reached a maximum height of 728.8 µm (mean ≈ 655.6 µm, σ ≈ 50.8 µm), whereas silver-coated aluminium tracks peaked at 614.9 µm (mean ≈ 507.1 µm, σ ≈ 69.9 µm). Laterally, flake-based tracks averaged 1.30 mm (σ ≈ 0.084 mm) and the spherical silver-coated aluminium tracks 1.05 mm (σ ≈ 0.10 mm). The numerical data is presented in Table 1. The Powder height variation also accords with the textile surfaces not being flat, as the woven fabrics offer wave-like variation in the base height. Additionally, the powder can slide into the crests and be lifted at the troughs of the woven structures. These differences are consistent with powder flow theory: irregular, plate-like flakes tend to interlock and pile more steeply than smooth spherical particles (Xue et al., 2023) (Zegzulka et al., 2020) (Li et al., 2022).

Table 1 Powder track height width comparison.

| | Silver flakes (µm) | Silver coated aluminium (µm) | |
|---|---|---|---|
| **Height** | | | |
| | 655.64 | 507.081 | Average |
| | 50.81 | 69.89 | StdDev. |
| **Width** | | | |
| | 1.30 | 1.05 | Average |
| | 0.08 | 0.10 | StdDev. |

Additionally, TPU flowability was favoured by conductive experiments mostly under room temperature and atmospheric pressure conditions while maintaining a minimum humidity of 20 % and a maximum of 60 %. This data was supported by the powder providers and understanding the powder flowability of the binder particles in normal and mixed states (Zinatlou Ajabshir et al., 2024) In other words, the higher angle of repose of the flake particles results in taller and slightly wider powder piles under vibrational deposition, whereas the nearly spherical silver-coated aluminium powders spread more readily. The measured dimensions reflect this behaviour: flake powders consistently produced thicker and marginally broader tracks compared to the silver-coated aluminium powders. Despite the established theories on powder flowability, challenges remain due to the textile surface characteristics and the powder mixture particle morphology. Although the silver-coated aluminium powder and TPU particles are nearly spherical, they possess irregular, stochastic edges that affect deposition behaviour (Mehrabi et al., 2023).

The loose powder tracks were deposited on the textiles, and the width resulted in a range between 1 and 1.3 mm, which is narrower than the pre-set laser beam diameter of 1.5 mm. Here, the beam diameter is set to 1.5mm in accordance with the manufacturer's guide, as the goal was to achieve 1.5 mm in the final width of the powder track. The beam diameter was obtained experimentally by tracing on the substrate directly without any powder application. During post-processing, the heat press reduces the powder track height to below 200 µm, preferably less than 100 µm, resulting in a smoother, more comfortable surface for touch and better mechanical bonding to the textile surface. The applied pressure and heat caused the powder to spread, increasing the track width to approximately 1.5 mm.

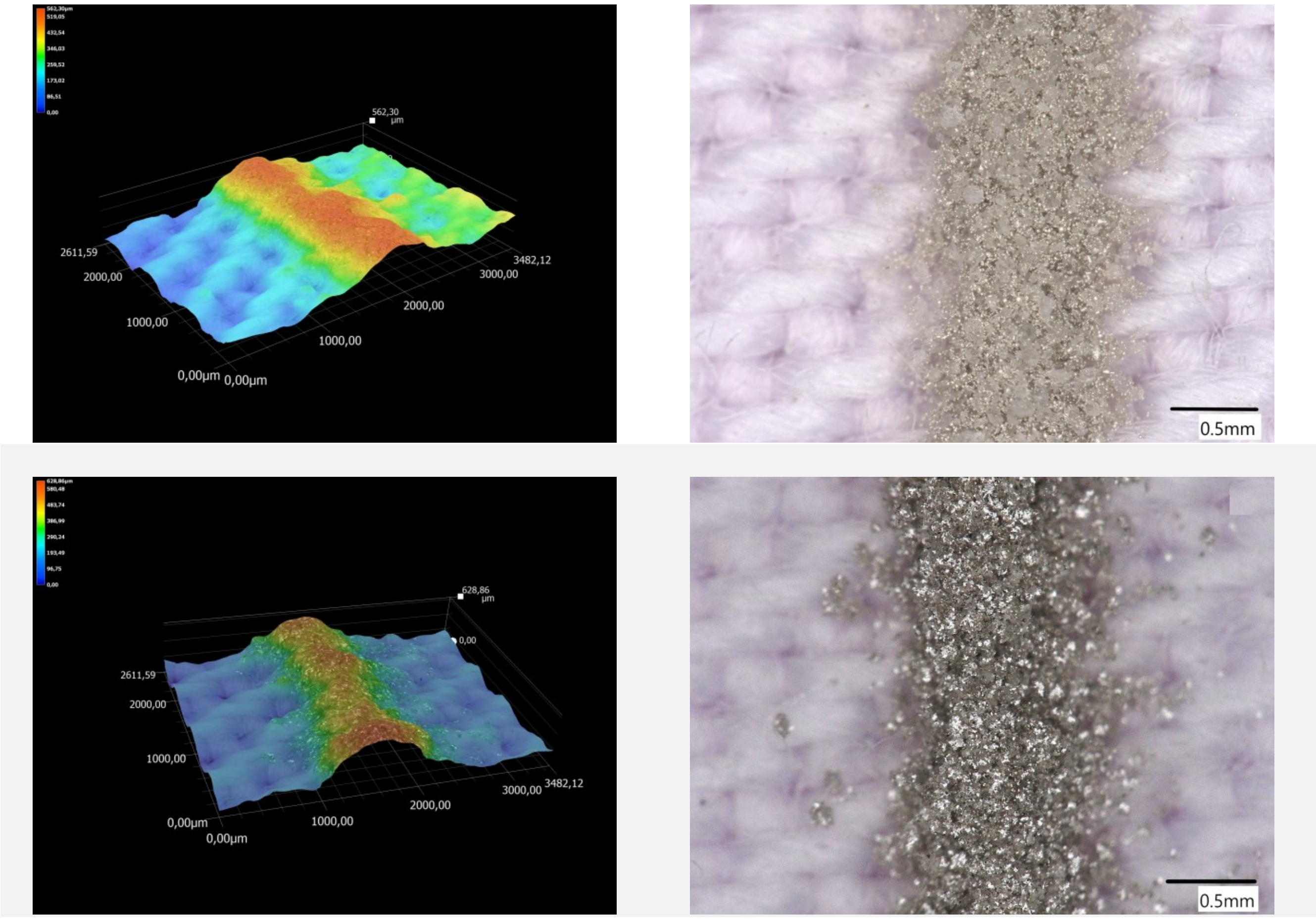


Figure 4 3D optical profilometry (left) and microscopic images (right) of laser fixed conductive powder tracks on textile before thermal fixation.

The Gaussian profile of the laser beam suggests that approximately 95 % of the laser intensity within ±2 standard deviations (2σ) should align with the applied powder track width. However, the remaining 5 % of laser energy will directly impact the textile substrate and lead to thermal damage (Esteves and Alonso, 2007). Experiments showed that there must be a close alignment between powder track width and laser beam diameter. When the laser beam hits the pure textile, the substrate materials will absorb the thermal energy, resulting in damage to the textile. Results of the substrate damage are shown in Figure 5. This was confirmed by localized scorching on the CO/ PES woven substrate, when the applied powder width was smaller than the diameter of the laser beam spot, resulting in substrate destruction due to yarn melting. In PES-based non-woven fabrics, melted tracks were evident, while the loose fibre structure of fleece facilitated rapid heat accumulation, occasionally leading to ignition. Such uncontrolled burning presents significant risks to equipment, operators, and material safety, as similarly reported in laser processing studies of synthetic textiles (Hung et al., 2017) (Angelova, 2020) (Mandre et al., 2023).

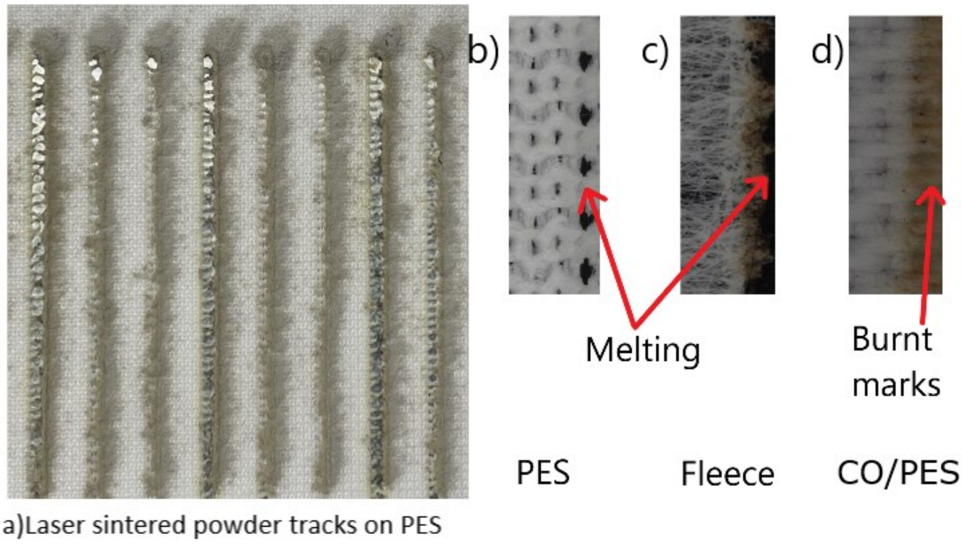


Figure 5 Laser–material interaction observed as: (a) powder tracks on PES; (b) melting in PES; (c) melting in non-woven thin fleece; and (d) burnt marks in CO/PES blend textile substrate.

During experimentation, the thermal response of the textile, powder tracks, and the underlying metal base plate contributes to the heat-affected zone (HAZ) formation. Textiles are held under tension to maintain the flatness on the base plate, which slightly increases the tension between fibres as well. Observations suggest that the burning and melting of these fibres may alter the tension between fibres and distort the flatness of the textile, leading to laser beam misalignment. Additionally, from observations, the reflected rays from the base plate, which are possibly transmitted through the porosity of the textiles, further complicate heat transfer dynamics, highlighting the need for a detailed study of these combined effects to characterize the HAZ. Experimental results from adjusted laser parameters to selectively target powder while preserving the textile substrate are presented in the Figure 6. The laser selectively sintered the thermoplastics without affecting the functional pigments. The functional pigments remained discrete and unharmed by the laser, preserving the functional properties of the particles. This distinction from prior results and the quality of such powder coating necessitate the tailoring of the laser beam profile with respect to its parameters when working with such sensitive materials. To address this, adaptive laser control methods are recommended. Techniques such as dynamic focus control or beam shaping could tailor the spot size to match the real-time powder track width, minimizing thermal spillover (Cao et al., 2017). Alternatively, pre-scanned mapping of the powder pattern could ensure that only powder-covered regions are irradiated, further protecting the textile substrate and functional pigments.

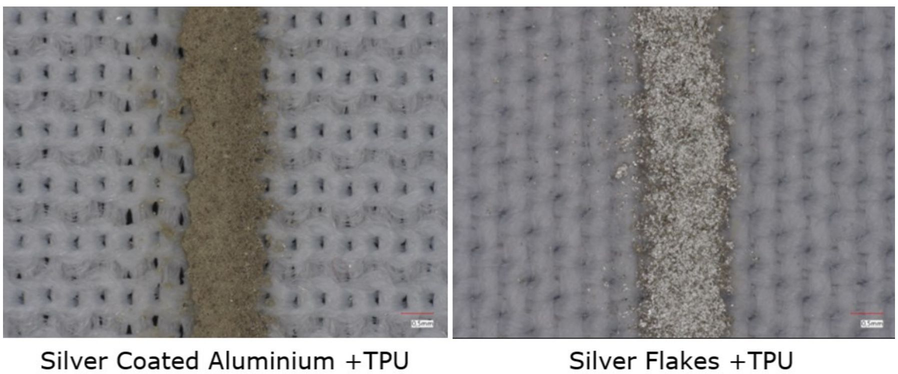


Figure 6 Final printed conductive powder tracks with adjusted laser profile and the heat-affected zone.

Thermally sensitive pigments depend on the integrity of leuco dye microcapsules, which begin to degrade at temperatures around 200 ± 20 °C. Overexposure to laser irradiation irreversibly degraded thermochromic and photosensitive pigments, as evidenced by pigment bleaching and loss of smart functionality in initial trials. To prevent this, laser power and dwell time were reduced, resulting in lower sintering of the binder particles, which was compensated by post-process heat pressing for permanent fixation. However, with optimized processing temperatures and precise beam alignment, it is possible to achieve robust thermochromic surfaces on textiles (Hakami et al., 2022) *(Liu et al., 2023)*. Here in Figure 7, the thermochromic behaviour of changing colors when surface temperature changes approximately from below 30°C to above 30°C is demonstrated from the experiments.

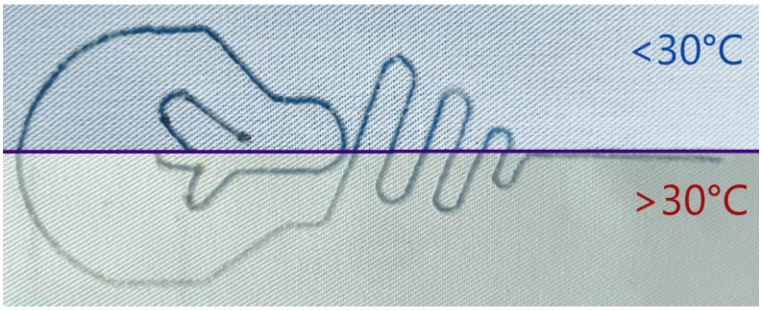


Figure 7 Thermochromic surface functionalization with behaviour demonstration (colour change from blue to white).

**Conclusions**

The study demonstrates a laser-based powder fixation method for achieving conductive, thermochromic, and other functional coatings onto the surface of textiles. The laser sintering process fixes the thermoplastic, binding the functional pigments and securing the powder mixture onto the surface of the textile. The laser traces have drawn out the anomalies in the powder track width and sharpness of the edges. Adjusting the parameters of the vibrating powder nozzle, such as diameter, application speed, frequency of vibration, as well as powder morphology and humidity, has guided the powder deposition quality. The laser tracks narrower than the powder tracks have reduced the 2σ laser power influence on the textiles. So, reducing the laser power in such a way that the 2σ values of the Gaussian curve have no effect by maintaining these values lower than the thermal properties of the textile substrate. A top hat laser can be a suggested alternative method for future studies. So, combined powder nozzle and laser adjustments have mitigated common issues like deposition discontinuities, powder accumulation, and thermal damage to fabrics.

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