Metal-Textile Laser Welding for Wearable Sensors

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Electronic textile (E-textile), an emerging technology, has the potential to revolutionize consumer electronics by transforming them into wearable devices. Highly conductive, textile conductors, suitable for commercialization, have yet not been developed. Here, a new metal-textile laser welding method is presented for a rapid one-step, stable, and cost-efficient manufacturing of electrically conductive textiles. This method is a direct on-textile approach for customized 2D nanothick metal coatings with flexible design. Different metals, like palladium, silver, or copper can be welded on functional membranes and textiles containing polymers. As shown by bonding a copper 2D pattern on a polyamide textile, the resistivity does not vary if compared to the bulk material. The generated interlocking bonding ensures strong physical adhesion between the partly molten polyamide fibers and a copper layer, resisting up to 10 000 abrasion cycles using the standardized Martindale test and up to 42 000 flexion cycles using the industrial standardized Schildknecht test. A promising application for textile integrated conductors is body monitoring sensors. The feasibility of a laser welded resistance temperature sensors on a functional membrane is demonstrated without impairing its mechanical stability. This technology presents suitable properties and variabilities for a wide range of application in E-textiles and its commercialization.

1. Introduction

Electronic textiles (E-textiles) as an important category of smart textiles, are emerging as high-end flexible devices that fit the human body comfortably, comparable to our daily clothes while providing additional functions.[1,2] The development of E-textiles relies on innovative technologies to incorporate transistors[3] and conductors[4,5] into textiles, enabling various functional components such as energy harvesting and storages devices,[6,7] and mechanically sensitive sensors[8,9] or soft wearable electromechanical systems.[10] The electronic conductors connecting the multiple and separate electronic devices are the essential components of E-textiles, introducing the difficulty to combine conductivity with flexibility within the same material. Organic conductors, such as derivated polythiophene ionomers (e.g., PEDOT/PSS), have answered to this need by providing a ductile conductive platform.[11] However, metals still retain superior electrical conductivity,[12] which make them more suitable for e-textiles if the rigidity challenge can be overcome. Additionally, conductors with design diversity possess clear advantages in comparison to the bulk conductive textiles.[13] The patterned conductors: 1) expand the complexity of the topographic electrical response from materials; 2) preserve the inherent textile breathability and permeability on the macroscale; 3) enable the design of personalized e-textiles in respect to fashion. So far, there are two basic approaches to construct conductive patterns on textiles.[13,14] One is to incorporate individual 1D-based conductors such as conductive fibers or yarns into the 2D textiles.[15,16] The process includes the metallizing of 1D textiles or fibers and subsequently weaving, knitting, or embroidering such 1D textile-based conductors to a pre-designed position on the 2D textiles.[17] The development of weaving and knitting machinery opens the avenue for large-scale production.[17] Nevertheless, the freedom of the pattern design is limited in woven or knitted structures as the 1D conductors are constrained in the warp or weft directions. Embroidery, through which the patterns can be endowed with higher flexible design, is an extremely expensive production method.[18] Another approach is the deposition of a conductive layer, like conductive metal nano-inks, onto or within 2D textiles.[14] Printing technologies, including screen printing,[13,19] inkjet printing,[20,21] direct printing,[22] etc. are the most widely adopted strategy to deposit conductive patterns on diverse substrates. Herewith, conductivity is ensured by percolation between different nanoparticle domains present within the ink material and surrounded by isolating polymer domains that act as fillers, dispersing and hardening agents. Thus, the time-evolution of their nanoparticle aggregation status tremendously
influence the respective conductivity values. Furthermore, due to the complexity of textile surfaces, multiple steps such as repetitive printing cycles and post-processing are generally required to guarantee the continuity of the conductive path. Therefore, a simple, rapid, stable, and cost-efficient way to construct customized conductive patterns has not yet been developed to advance the full commercialization of e-textiles.

Herewith, we demonstrate a direct on-textile approach for the development of 2D metal nanocoating patterns with a flexible pattern design by using a laser welding technology. The precise and controllable laser energy application allows for selectively melting the textile surface. Under the pressure exerted by the laser head, the metal layer is conformably joined on the molten area. The constructs ensure strong physical adhesion bridges between the metal layer and the space-resolved molten fibers with remarkable resistance to fatigue cycles with industrial durability experiments for textiles. Here, we analyze the electrical resistance, as well as the abrasion resistance and the flexion performance of the welded structures. Furthermore, we demonstrate the versatility of this method by applying different metals on common textile structures. We show, that laser welding allows a very precise bonding of metals on polymers without altering the functionality of textiles or thin polymeric membranes. To demonstrate the high precision of the process, metal structures were welded on a 40 µm thick membrane and it was shown that the functionality of the membrane remained intact.

The present work explores for the first time the potential of laser welding in the fabrication of e-textile. This method is universally applicable to a wide range of combinations between different metals and thermoplastic fibers.

2. Results and Discussion

2.1. Principle of Thin Metal Layer Laser Welding on Textiles

Laser welding is a well-known technology to facilitate bonding between thermoplastic substrates. However, laser welding of ultrathin metal foils (ranging from 170 to 1000 nm) on thermoplastic fibers has never been reported. This method was developed to link polyamides membranes and textiles with themselves or with fibers. The laser energy locally heats the polymers above the melting point leading to the physical interlocking of the materials. So far, this technology has only been used for polymer–polymer bonding requiring the melting of both materials. The rationale behind this work is to explore whether selective melting of the thermoplastic fibers could ensure sufficient adhesion with the metal foil to obtain a metallic structure in nanometric range on textile surfaces in a space-controlled manner for wearable sensors application.

The laser beam with the wavelength of 940 nm (which is, besides 808 and 980 nm, the most common wavelength for plastic laser welding) is absorbed by a black, soot-colored, and polytetrafluoroethylene (PTFE) coated fiberglass fabric attached to a transparent 1 mm polycarbonate (PC) plate on top of the metal foil. The absorbed energy of the laser, converted to thermal energy is transported through the metal foil to the underlying textile or membrane while a pressure of 1 bar is applied by the optical sphere (see Figure 1a). The computer-controlled CNC table can generate any 2D metal pattern, whereas larger areas are welded by generating overlapping lines (ranging from 0.8 to 4.4 mm diameter) next to each other (see Figure 1b,c,d).

The energy introduced to the PTFE–metal foil–textile package can be adjusted by the feedforward of the CNC table with up to 1500 mm s⁻¹, the spot diameter of the laser beam (focus) ranging here from 0.8 to 4.4 mm or by the laser power itself of up to 42 W. This laser energy density  is defined in Equation 1.

\[ E_d = \frac{P_0}{v_b \cdot d_0} \] (1)

The resolution of this method is limited by the spot diameter of the laser beam. By adjusting the parameters of the energy density of the laser, different bonding strengths between the metal foil and the textile will be achieved, uncorrelated to an increase of the energy density. Here, the laser energy density is independent of time, whereas thermal density, related to laser energy density, time, and thermal conductivity, correlates with the bonding strength. In the future, an optimum regarding the bonding strength and material integrity needs to be found for each material combination, probably by trial and error due to the complex heat transfer mechanisms in this multicomponent system.

Compared to alternative welding methods like ultrasonic welding, laser welding allows the bonding of fragile thin membranes and textiles. With ultrasonic welding, the bonding strength is weaker and the materials can be damaged.

2.2. Morphology and Electrical Properties

We are able to laser weld copper, palladium, and silver with textiles (Figure 2). The copper structures were chosen for the in-depth analysis because of its commonness in conductors, cost efficiency as well as antimicrobial efficiency making it favorable for wearable applications. Copper foils were welded on a polyamide textile with different energy densities by changing only the laser power to find the setting at which the adhesion is the highest while the thermal degradation of the textile structure is the lowest (see Table 1). The polyamide textile was chosen because of its lower degradation rate in the melt phase and higher resistance to hydrolysis if compared to polyester textile. Independently of the laser energy density, the welded copper has a specific resistance of 2.74 × 10⁻⁸ Ωm on the polyamide which is close to the literature value of 1.68 × 10⁻⁸ Ωm. Here, the spot diameter was set to 1 mm and the speed to 10 mm s⁻¹ for all samples. The criteria for the settings are that the metal layer has a consistent bonding to the molten polyamide while the polyamide does not degrade. Differential scanning calorimetry (DSC) and thermal gravimetric analysis (TGA) have been used to determine the melting and carbonization temperatures of the polyamide-6 textile (220 and ~368 °C). However, it is desirable to stay below the temperature at which chain scission occurs which would lead to a decrease in its mechanical integrity. Hence, the recommended upper temperature for polyamide-6 processing of 290 °C is chosen.
as the upper limit. The laser energy densities were adjusted to obtain temperatures between the melting point and the maximum recommended processing temperature (referred to settings #1 to #5). As the process temperature in the textile is unknown, the cross-sections of the intersection were quantitatively analyzed with an SEM and optical microscope.

The polymer of the top layer textile melts due to the induced and converted laser energy. The solid metal foil is pressed by the focus sphere onto this liquefied polymer and when solidifying, the two components form a mechanical bond due to interlocking. At lower laser energies (settings #1 and #2, Figure 3b,c,h), the melt viscosity of the surface layer in the thermoplastic textile is probably still too high to ensure an adequate anchoring of the metal layer. Resulting bonding gaps have been observed in settings #1 and #2 (Figure 3b,c,h). If the laser energy is too high, chain scission phenomena start to occur in the polymer due to hydrolysis of the amide bond or even combustion, which influences the mechanical integrity of the textile, like settings #4 and #5 (Figure 3e,f,h). Furthermore, it has been observed, that even though the focus of the optic

| Setting # | Laser Power [W] | Energy Density [J mm\(^{-2}\)] |
|-----------|-----------------|-------------------------------|
| 1         | 1.9             | 0.19                          |
| 2         | 2.2             | 0.22                          |
| 3         | 2.6             | 0.26                          |
| 4         | 3.0             | 0.30                          |
| 5         | 3.6             | 0.36                          |
sphere is 1 mm, the actual molten spot diameter ranges from 0.8 to 1.2 mm for the settings #1 to #5. This is attributed to the heat flux in the metal and textile. Setting #3 with a spot diameter of 1 mm, corresponding to the laser spot, showed the most consistent bonding without degradation of the polymer, as shown in the SEM and microscope pictures. For this reason, this setting has been chosen for further testing.

An increase of the laser energy density also increases the local temperature of the metal foil, which increases the oxidation of copper and therewith its electrical resistivity. However, as the elevated temperature lasts only for a short time, and the measured specific resistance corresponds to the literature value, this effect was neglected.

We hypothesize, that the adhesion is based on form fitting between the polymer and the metal foil generated during the process. More precisely, the liquefied polymer infiltrates the surface roughness of the metal foil and generates mechanical interlocking. This mechanism was investigated by Dadvar et al. with liquefied wax droplets on a porous surface as well as by Pershin et al. with plasma-sprayed nickel coatings. The bonding is enhanced when the solidifying melt penetrates deep into the rough surface before it freezes. Therefore, the interlocking strength is depending on the fluid flow and heat transfer. Here, the viscosity of the liquefied fluid, influenced by its temperature and polymer type, as well as the surface roughness, temperature, and thermal conductivity of the metal foil are parameters determining the bonding strength. The chemical inertness of the elemental copper, palladium, and silver strongly suggest that in the applied temperature range only physical and no chemical adhesion takes place at the metal-polymer interface.

2.3. Mechanical Durability

To characterize the robustness of the laser welded bond, the specific electrical resistance is measured while the abrasion is tested by the Martindale Abrasion and Pilling Test according to ISO 12947-1 and the flexion resistance is tested according to ISO 7854 - method B: Schildknecht. For the Schildknecht flexion durability test, a sample design was used in which 6 parallel lines of 50 mm length are connected in series to measure them at once. As the location and intensity of the folds during the flexion test are not uniform within a sample, 6 lines ensured sufficient statistics to determine the effects of flexion between the samples. This design increases the length of the lines to 300 mm and therewith the chance of failure at an imperfection. For the Martindale test, a simple straight line was chosen, which is in line with the literature.

The eight samples (S1–S8) in the Schildknecht machine showed two distinct results: S2, S3, and S5 showed a rapid increase in resistance, implying that the welded structure was strongly affected by the flexion manifested by partial fractures, while the majority of the samples showed a linear increase, R² ranging from 0.9865 to 0.9999, with a small slope (see Figure 5a). This indicates a slow and steady deterioration of the structures with increasing flexion cycles (fatigue fracture). S1 and S7 failed after more than 13 700 flexion cycles on the Schildknecht apparatus. S4 and S6 resisted more than 42 000 cycles and had a resistivity ratio of 1.5 and 2, respectively.

The Martindale abrasion test shows variations in the samples (S1–S6) regarding the change of resistivity ratio due to abrasion. S5 failed after 4000 cycles, whereas S2 resisted 10 000 cycles with a resistivity ratio of 2.1 (see Figure 5b and Table 2).
The Schildknecht and Martindale durability results show spread performance between different specimens. We hypothesize that these variations are caused by running the equipment manually, although special emphasis was put to minimize inconsistent factors. More precisely, the variability in the performance can be attributed to the manual positioning of the metal foil onto the textile, which can be strongly avoided if the whole process is automatically performed. The challenge is to apply a 2D process on a complex 3D textile. The high flexibility of the metal foil can lead to planar misalignment causing creases or connection gaps. An automated process could ensure perfect alignment of the metal foil to the warp or weft structure of the textile and thus optimize the metal-polymer bonding. Another cause for this variation could be inconsistencies in the textile and/or wear in the PC and PTFE layer influencing the heat flux.

The Martindale abrasion test of the textile-copper foil laser welding shows higher mechanical durability than other coating methods in the literature. This performance may be caused by the strong mechanical adhesion forces of the surface roughness interlocking mechanism. Beyond that, the Martindale abrasion performance is in the range of incorporated conductors in textiles (see Table 2).

We introduced the Schildknecht flexion test according to ISO 7854\[38\] as a new method for the determination of resistance by flexion of conductive textiles. This standardized method is commonly used to determine the adhesion of membranes laminated on textiles and is therefore well suited to analyze the metal-textile adhesion. During the flexions, the structures are bent in an inconsistent manner of up to 180° with radii lower than 5 mm. This method is, however, different from the ones described in the literature to determine the robustness of conductive textile structures and therefore, a direct comparison is not possible. Uzun et al. bent a MXene-coated textile by 90°, with unknown bending radius, achieving 1000 cycles while the resistivity ratio remained stable.\[46\] Liu et al. bent an Ni-coated fabric on a 25 mm cylinder and obtained a stable resistivity ratio for 900 cycles.\[47\] Another approach by Yang et al. was to bend their Ni-coated cotton fabric (multi-layer package) by 180° with a 5 mm radius, achieving 10 000 cycles with a resistivity

![Figure 4. Martindale and Schildknecht setup. a) Martindale setup of the six samples. b) Schildknecht setup of the eight samples maximum position meaning the left samples are at most compressed and right samples at extended position.](image)

| Type         | Method                          | Materials                                | Cycles       | Pattern         | Change of resistivity ratio ($R/R_0$) | Reference |
|--------------|---------------------------------|------------------------------------------|--------------|-----------------|---------------------------------------|-----------|
| Coating      | Laser welding                   | Copper on polyamide                      | 4000–10 000  | Line (120 mm)   | 2–3.8                                 | This work |
| Coating      | Electroless plating process     | Copper on knitted cotton                 | 250          | Area            | 5010, 6660, or failure                | Hassan et al. 2020\[39\] |
| Coating      | Spin-coating                    | Polyester fabrics                         | 1000         | Area            | 1.3                                   | Lin et al. 2005\[40\] |
| Coating      | Hand-brushing dipping and spray painting | 3-decanylpyrrole on wool               | 2000         | Area            | 2 to 3000                             | Foitzik et al. 2006\[41\] |
| Incorporated | Sewing                          | Silver-plated polyamide threads onto cotton | 3000        | Line (70 mm)    | 1.7–2.9                               | uz Zaman et al. 2019\[42\] |
| Incorporated | Sewing and embroidery techniques | Silver-plated polyamide threads onto cotton | 3000        | Line (70 mm)    | 1.3–6.4                               | Atakan et al. 2020\[43\] |
| Incorporated | PPY coated wool yarn            | Knitted fabric                            | 40 000       | Area (90 × 45)  | 9                                     | Varesano et al. 2005\[44\] |
| Incorporated | Woven conductive network        | Blend of enameled Cu alloy filament and conventional tex-yarns | 50 000       | Line            | ≤1.04                                 | Bogan et al. 2019\[45\] |
ratio of 1.2.\textsuperscript{7} With the Schildknecht flexion test, our conductive samples sustained 13 700 to 42 000 cycles with a resistivity ratio of 1.5 to 3.5, showing the high flexion stability of the welded structures.

The performance test of the laser welded copper lines on the polyamide where performed with the chosen laser setting #3 of a laser energy density of 0.26 J mm\textsuperscript{-1} with the parameters of 1 mm spot diameter, 10 mm s\textsuperscript{-1} feedforward, and 2.6 W. However, a change in the parameter will have an impact on mechanical performance. As expected, with the same laser energy density but with different parameters a change of the bonding was observed, due to changes in the temperature profile and heat flux. The heat flux in general and here through the different layers is a function of time, and therefore, a change of laser power and feedforward speed can result in the same laser energy density but with a locally altered thermal density. This change in thermal density leads to a change in the viscosity of the liquefied polymer and a change of the heat conduction, especially through the metal foil. An increase of the laser energy density does not automatically lead to an increase in adhesion. Here we have found visually the optimal setting while modifying the dimension of laser power. However, the system’s multidimensionality (e.g., feedforward, spot diameter, etc.) is why we assume that it can be further optimized.

2.4. Laser Welded Resistance Temperature Sensor

To demonstrate the potential of this laser welding technology for wearable sensor applications, we welded a metal structure on a Sympatex, polyether-ester block copolymer, membrane of 40 µm thickness for the continuous monitoring of temperature. Such a sensor on this breathable membrane could be potentially integrated into firefighters’ clothing and act as an indicator to monitor potential thermal damages to the membrane.\textsuperscript{88} Alternatively, such sensors could serve for the non-invasive monitoring of the firefighters’ core temperature to prevent heat stress related health problems.\textsuperscript{49}

Three samples with different laser energy density were manufactured and measured regarding the lowest specific resistance as well as qualitatively analyzed with a microscope regarding the most remaining non-molten structure of the membrane to determine the best processing conditions. Three samples manufactured with the chosen processing condition were welded as resistance temperature detectors (RTD) with a straight-line pattern design. Specifically, we aimed at obtaining a good resistor, while maintaining the functionality of the membrane in terms of water vapor permeability and water tightness. Therefore, the membrane with the laser welded temperature sensor was analyzed regarding it temperature-resistivity relationship as well as its functionality of water tightness using the water column test according to ISO 811\textsuperscript{50} - hydrostatic pressure test. Three samples of both the welded and untreated membranes were measured.

The water permeability test of the welded membrane reaches 6170 mm (±70 mm), whereas the untreated reaches 5920 mm (±150 mm). They show almost the same water column with an average difference of 250 mm, corresponding to 4%.

The temperature sensor on the membrane shows a linear relation with the coefficient of determination $R^2$ of 0.997 (see Figure 6). The temperature resistance coefficient of 0.0039°C\textsuperscript{-1} corresponds to the literature value of copper of 0.00394°C\textsuperscript{-1}.\textsuperscript{51} The temperature sensors have an accuracy (towards the linear fit) of up of ±1 °C from 25 to 60 °C, ±2 to 100 °C, and ±75 °C for a temperature higher than 140°C. The integrity of the membrane is only maintained up to 180 °C (DSC analysis), while such temperatures will not be reached easily in practice. A comparable, flexible Ni filled binary polymer temperature sensor achieved an accuracy of ±2.7 °C whereas conventional, ridged RTDs have an accuracy of ±0.17 °C.\textsuperscript{52} At temperatures above 140 °C, the variability increased. This is caused by changes in resistance due to oxidation of copper starting at 140 °C.\textsuperscript{53} Another influence could have been the self-heating error which occurs during the measurement of the resistance.\textsuperscript{54}

The water permeability test investigated a change in the functionality of the membrane. It was observed that water drop penetration did not occur at the metal-membrane structure. The difference in the water column may be a variability caused by the small sample size of three. Even though there is a change of 4% on average in the water column, the membrane functionality and in particular the water permeability, was not affected.

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Figure 5. Resistivity ratio $R/R_0$ over the number of cycles the sample was on a) the Schildknecht flexion machine and b) the Martindale abrasion machine.
2.5. Outlook

Even though the laser welding parameters have been optimized by the laser power, the method might have room for improvement regarding mechanical durability by also optimizing the other laser energy density dimensions like feedforward. Future research needs to investigate the change of performance in the Martindale Schildknecht test with the change of laser welding parameter with the same and different laser energy densities, to find the optimum. Such an optimum can in the first step be found by an empirical approach and in the second step create, based on those data, a heat transfer model for different textile structures predicting the laser settings. For further optimization, modified cooling dynamics could be introduced to investigate if and how the adhesion improves. Furthermore, the process itself can be optimized as well. With the optimization of the laser welding process, for example, with an automated process perfect alignment of the metal foil to the textile could be ensured and eliminate inconstancies and therewith weak points. As a mechanical failure will first take place at the weakest point of the welded structure, we assume that with such a setup, the performance of the Schildknecht test of 40 000 cycles (S4 and S6) and the Martindale test with 10 000 cycles (S2) could be reached consistently. This performance corresponds to durabilities higher than most existing technologies (see Table 2). Future durability tests need to investigate the washability of such structures, which causes multiple stresses (apart from mechanical flexion and abrasion stress also chemical and temperature stress). Further, performance improvement could be achieved by an additional protective coating like an atmospheric plasma treatment. Such a coating can protect the conductive layer from external influences (e.g., abrasion) and increase the adhesion to the textile as it would function as a top sandwich layer preventing the conductive layer from detaching.

Besides the application of energy harvesting and storage devices, flexible electronics and sensors, a potential application are soft wearable electro-mechanical systems. More precisely, electromagnet brakes or electrostatic brakes, like those used in the haptic feedback glove DextrES[10] could be textile integrated using laser welding technology. Two laser welded, metal coated textiles, separated by a dielectric film, each functioning as an electrode, are electrically charged causing attractive electrostatic forces and therewith frictional forces between the two textile layers. Such mechanisms could find application in haptic feedback for grasping in virtual reality, in exosuits for rehabilitation, or in wearable assistive devices for the suppression of involuntary movements like tremor.

3. Conclusion

This work introduces a simple, rapid, stable, and cost-efficient way to construct customized conductive patterns with different metal foils on different textiles and membranes containing thermoplastic polymers. The bonding of the metal-textile laser welding technology is based on mechanical interlocking after the substrate is in-situ melted by the laser’s energy and infiltrates into the surface roughness of the metal foil. By adjusting the parameter of the laser energy density, we conclude from our observations that different bonding strengths of the conductive area can be achieved. The laser welded samples sustained up to 42 000 flexion cycles showing the highest mechanical flexion durability compared to literature. The samples sustained up to 10 000 cycles on the standardized Martindale abrasion test, presenting the highest abrasion durability in coated conductive structures. We suggest that future validation of conductive textiles should be carried out with the standardized Martindale method for abrasion testing and the newly introduced Schildknecht method for flexion testing. The Martindale as well as the Schildknecht test are defined after an ISO (ISO 12947-1 and ISO 7854, respectively) which makes them predestined for consistent execution and comparisons between researchers.

Furthermore, we present the feasibility of a temperature sensor (RTD) stable up to 140 °C with copper on a functional membrane without influencing its functionality. The RTD shows a linear relation with temperature ($R^2 = 0.997$) and matches the temperature resistance coefficient of copper in literature with 0.0039 °C$^{-1}$.

This proof-of-concept shows suitable properties and variabilities for a wide range of applications in e-textiles. Metal-textile laser welding is therewith a promising technology for the commercialization of customized e-textiles.

4. Experimental Section

Laser Welding Setup: The laser beam with the wavelength of 940 nm, created by NOVOLAS Basic AT Compact (Leister Technologies AG, Kaegiswil, Switzerland) was guided to the materials by light guides and focused with Globo Optic (Leister Technologies AG, Kaegiswil, Switzerland). A computer with the software Wingman 2.5 (IsoDev GmbH, Wegscheid, Germany) controlled an XY (1300 mm x 2000 mm) CNC table (Gunnar AG, Altstätten, Switzerland) at which the optic was mounted. Globo Optics air suspended sphere applied a pressure of 1 bar on a 1 mm polycarbonate plate (PAS-PC plate, faigle Kunststoffe GmbH, Hard, Austria) on which a black, soot-colored, and PTFE coated
fibre glass fabric (5075 AS, Kastilo Technische Gewebe GmbH, Ulm, Germany) was attached to, compressing and holding the layers in place.

**Electrical Characterizations:** All resistances were measured using the 4 probe method and a digital multimeter (Model 2000 6½-Digit Multimeter, Keithley Instruments, Solon, Ohio, USA) connect by wires cling to the textile with a 2-part epoxy adhesive (83315 – Silver Conductive Epoxy Adhesive, M.G. Chemicals, Surrey, B.C., Canada). The samples were stored for 24 h and tested in a climate-controlled room according to ISO 139 (20 °C, 65% relative humidity).

**Microscopic Analysis:** The laser welded samples had been cut with a surgical knife for a cross-section. The optical analysis was performed by taking pictures of the welded textile cross-section with a field emission scanning electron microscope (FE-SEM S-4800, Hitachi High-Tech Corporation, Tokyo, Japan) and an optical microscope (VHX-SS50, Keyence Corporation, Osaka, Japan). For the optical microscopy analysis, the samples had been put in a mixture of epoxy resin and epoxy hardener (20:3430-064 and 20:3432-016, EpoxiCure 2, Buehler, Illinois Tool Works, Lake Bluff, Illinois, USA) for 24 h. After curing, the in epoxy embedded cross-section samples were sanded from rough to fine, whereas the last step was to polish them. The samples for the SEM had been clamped vertically and coated with 7 nm palladium (EM ACE600, Leica Microsystems GmbH, Wetzlar, Germany).

**Materials and Settings:** For the mechanical tests a calendered polyamide (PA 6) taffeta lining textile with a density of 37 g m⁻² (Extremtextil, Dresden, Germany) has been used. For the temperature sensor, a 40 µm thick functional polyether-ester block copolymer membrane (ST26560-40mu, Sympatex Technologies GmbH, Unterhöhring, Germany) was used. This membrane was breathable, that is, it was water vapor permeable (e.g, sweat) (water vapor resistance Ret = 11 m²Pa W⁻¹ according to ISO 11 092) while being air- and watertight. The welded thin copper foil had a thickness of 1 µm (Michael Brandenberger AG, Thalwil, Switzerland).

**Mechanical Durability:** The robustness of the laser welded bond was characterized by the resistivity ratio changed by the Martindale µpolyamide (PA 6) taffeta lining textile with a density of 37 g m⁻² (Extremtextil, Dresden, Germany) has been used. For the temperature sensor, a 40 µm thick functional polyether-ester block copolymer membrane (ST26560-40mu, Sympatex Technologies GmbH, Unterhöhring, Germany) was used. This membrane was breathable, that is, it was water vapor permeable (e.g, sweat) (water vapor resistance Ret = 11 m²Pa W⁻¹ according to ISO 11 092) while being air- and watertight. The welded thin copper foil had a thickness of 1 µm (Michael Brandenberger AG, Thalwil, Switzerland).

**Temperature Sensor Characterization:** The sensor was placed on a hot plate (Heidolph MR 3004 safety, Heidolph Instruments GmbH & CO. KG, Schwabach, Germany) and heated from ambient temperature to 150 °C. A glass slide was situated on the temperature sensor to guarantee the conformal contact between the textile and hot plate. A commercial temperature sensor with an accuracy of ±0.3K had been used to track the temperature of the hot plate (Fluke 52 K/J Digital Thermometer, Fluke Corporation, Everett, WA, USA). An ISO 811 [48] - hydrostatic pressure test was performed with the HydroTester (FX 3000, TEXTTEST AG, Schwerzenbach, Switzerland). The samples were stored for 24 h and tested in a climate-controlled room after ISO 139 (20 °C, 65% relative humidity).

**Acknowledgements**

The authors thank the laboratory and especially Pierrine Zeller for the technical support.

**Conflict of Interest**

The authors declare no conflict of interest.

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**Data Availability Statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Keywords**

conductive textile coating, e-textiles, flexible electronics, laser welding, temperature sensors, wearables

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