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Improving durability and electrical performance of flexible printed e-textile conductors via domestic ironing

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Abstract

The electrical performance of printed conductors often degrades over time due to recurrent or infrequent exposure to practical stresses such as bending and washing. To avoid this, a repair mechanism is required to return the conductor to prime condition, enhancing lifetime and durability during extended stress cycles. In this study, domestic ironing is used to repair and restore the electrical resistance of printed conductors damaged by prolonged bending and washing cycles at standard ironing temperatures. The results of reliability tests on screen-printed conductors on two polyurethane-coated fabrics and six different laminate sheets adhered to the fabrics revealed that ironing significantly enhances the electrical performance of the conductors, limiting the change in electrical resistance to less than 20% after 400 000 bending cycles and to less than 1 Ω after 50 wash cycles. Although laminated conductors are more durable and generally outperformed conductors on the printed primer layer, in both cases, the results showed that the sample could be left for 24 h for 'self-relaxation' and would also return to the original value, implying that for future wear, either immediate ironing or leaving the garment for a period between uses could effectively 'fix' any bending or washing damage.

1. Introduction

Textiles are multipurpose fibre materials with widespread applications across diverse industries. They are essential materials for a broad suite of domestic processes and industrial applications within healthcare, fashion, automobile, sports, civil engineering, agriculture, the military, etc [1–3]. This makes them a ubiquitous platform for enabling a new paradigm of smart materials for IoT applications. Textiles are lightweight materials with intrinsic softness, flexibility, breathability, drapability, and textural comfort. By embedding flexible electronics into textiles, more utility and efficiency can be derived from within native textile environments where the use of conventional rigid electronics can be obtrusive and impractical.

E-textiles research presents a pathway for combining such electronic functionality with textiles of different materials (natural/synthetic or organic/inorganic fibres) [4–6], structures (knitted, wovens and nonwovens, calendered, etc) [7–11], and surface finish [12–14] while preserving the inherent physical properties that made textiles desirable and versatile materials. So far, the research literature shows that e-textiles are produced by fusing a variety of functional materials such as electrically conductive films [15, 16], piezoelectric films [17, 18], and thermo/photochromic films [19] with the textiles using any or a combination of (a) rapid prototyping and additive manufacturing processes such as 3D printing [20], ink-jet printing [21], spray-coating [22] and dispenser printing [23] for low-throughput manufacturing, (b) microfabrication processes based on thin-film materials [24], and flexible 1D filaments/yarns [25] and, (c) traditional manufacturing processes within the textile industry (e.g. screen printing [26], lamination [27], weaving [10], sewing and embroidery [28]) for high-throughput manufacturing. These methods have also delivered few commercial e-textile products [3] and notable prototype devices, for example wearable bio-potential and activity monitors [26], large area wearable displays [29, 30], camouflage/stealth fabrics [31], touch and proximity sensors [32], wearable pH sensors [33], textile-based passive electronic components [34], transistors [35], textile-based energy harvesters [36], supercapacitors and batteries for energy storages [37–39]. Regardless of the manufacturing method of the e-textile, striking a balance between seamless electronics integration and long-term reliability of embedded electronic functionality (e.g. electrical interconnects or conductors [40], sensors [41], and actuators [42]) remains an ongoing research challenge.

For screen-printed e-textiles, reliability significantly degrades through repeated exposure of printed conductors to external mechanical stresses, for example, bending and washing [43]. This must improve before screen printing can be considered a commercially viable and economically sustainable process of producing e-textiles. Screen printing is a low-cost, straightforward, and high-throughput manufacturing process that offers the flexibility to customise any design or circuit pattern on any textile (e.g. ready-to-wear garments, upholsteries in homes or automobiles, etc). To improve the durability of screen-printed conductors, researchers avoid the rough surface of textiles using printed planar materials, referred to as primer or interface layers [44], and laminate sheets [27, 42] to smooth the textile and allow the printing of flexible and stretchable conductors. The use of primer layers guarantees that the printed e-textile can be realised in a single printing process, whereas the use of laminate sheets adds extra steps to the fabrication process, such as heat pressing the sheet to the textile and machine cutting to custom-fit sheet size to the printed circuit to aid textile breathability. Furthermore, the material properties and geometry of the printed conductors have also been modified to enhance flexibility and elasticity [45–49]. As a result, mechanically resilient materials such as graphene [46], CNTs (carbon nanotubes) [47], silver nanowires or nanoflakes in TPU matrix [42, 48] and others have emerged to improve the performance of printed conductors, and these are implemented on textiles using nature-inspired designs [49], serpentine structures [50], and other fractal designs [51] to mitigate the impact of tensile and bending stresses. Other durability-enhancing techniques include the neutral axis engineering of printed conductors within e-textile structures to ensure zero stress during bending [52], and the waterproofing and abrasion-proofing of conductors using thermoplastic materials as encapsulation layers to minimise failures [15, 44]. These methods have the advantage of slowing the rate at which the electrical performance of the conductors deteriorates in response to dynamic mechanical stresses. They are, however, not useful for preserving the pristine electrical properties (e.g. electrical resistance) of conductors during recurrent stress cycles. They also do not trigger repairs or restoration of the electrical properties to their original state.

The capacity to repair printed conductors is crucial for increasing the functional lifespan of screen-printed e-textiles. The use of self-healing conductive hydrogels [53], an electric-field assisted self-healing procedure to facilitate conductor repair [54], and thermal heating of thermoplastic elastomer conductors to reset the electrical characteristics of the conductor [43] are popular mechanisms for accomplishing this. However, the self-healing efficiency of hydrogels remains low because mechanical properties are difficult to fix completely. Moreover, the trade-offs and/or effects of many repair cycles to recover damaged conductors using these approaches are unknown. Although liquid metals such as gallium and its alloy eutectic gallium–indium (EGaln) are compositionally suitable for repeated repair cycles [55], their low melting point restricts their applicability for wearable applications. While enclosing liquid metals within microfluidic channels would limit leakages at temperatures below the melting point, this method is impractical for creating intricate circuits on textiles.

This research presents a simple approach for repairing the electrical resistance of stress-induced printed conductors using domestic hot ironing. Ironing is the final stage of a standard laundry process and it is often a required treatment for removing creases from clothing. Printed conductors can benefit from this domestic annealing process to eliminate mechanical stress residues, and reset the conductor's electrical characteristics, particularly after mechanical stress cycles such as bending and washing. Screen-printed silver conductors on various laminate sheets and polyurethane-coated textile substrates are used to investigate the impact of repeated repair cycles on the mechanical durability of the printed conductors after bending and washing. This study explores the effect of the laminate and primer-coating materials on the reparability and reliability of the printed conductor. The primer coating is a polymer layer that planarizes the textile surface and allows flexible and uniform conductive films to be easily printed on the textile. This research aims to improve the design and maintenance of printed e-textile devices, allowing them to last longer. The findings show that a straightforward household ironing procedure can recover the electrical functionality of printed electronic textiles after mechanical stress cycles.

2. Materials and methods

2.1. Material selection

The materials used in this work are primer films (or interface layer), conductive paste, and textile substrates as shown in table 1. The primer films comprise two commercial screen-printable UV pastes

Table 1. Material properties.

Classification	Material name	Material type	Thickness	Weave structure	Colour	Supplier	Droplet contact angle	Surface classification
Primer Pastes	UV-IF-1004	TPU			Clear	Smart Fabric Inks		Hydrophilic
	UV-IF-1039							Hydrophobic
Laminate Sheets	Elecrom Stretch HC		80 μm		White	Policrom Screens Ltd	89.1°	Hydrophilic
	Elecrom Stretch Clear	PET	120 μm		Clear		95.9°	Hydrophobic
	Elecrom Stretch White		120 μm		White		104.4°	
	Elecrom Flex		100 μm		Clear		48.4°	Hydrophilic
	Platilon U073		50 μm			Covestro Ltd	78.1°	
	Epurex VPT Film	Polyurethane	80 μm				84.7°	
Conductive Paste	TC-C4001	Silver			Silver	Smart Fabric Inks	—	Hydrophilic
Textile substrates	Optic White—A1656	Polyester/cotton	190 μm	Twill 2 × 1	White	Klopmann Ltd		
	IsacordPoly60	Polyester	207 μm	Plain	Green	University of Southampton		

and six laminate polymer sheets containing four different PET (poly-ethylene-terephthalate) films and two TPU (Thermoplastic Polyurethane) sheets shown in table 1. Smart Fabric Inks supplied the screen-printable UV pastes UV-IF-1004 and UV-IF-1039, which were used as interface and encapsulation materials. These state-of-the-art printable dielectric materials offer good printability, flexibility, and strong adhesion to textiles [15]. Policrom Screen Ltd and Covestro Films Ltd supplied the PET and TPU laminate sheets. These sheets were chosen as an alternative to screen-printed interface layers for smoothing the surface of the textile. Furthermore, lamination provides an easy way to reduce the thickness of the material needed to smooth the textile surface.

A commercial silver paste, TC-C4001, supplied by Smart Fabric inks, was used to screen print dumbbell conductor patterns on two textile substrates: Optic White–A1656 and the Isacord fabrics. The first commercial polyester-cotton fabric is from Klopman International while the second is a custom-woven all-polyester fabric, IsacordPoly60 that increases the flexibility of printed e-textiles by requiring a thinner printed primer layer [7]. Both textiles were chosen to represent the standard materials used in the textile industry for garment manufacturing.

2.2. Material properties

The surface properties of the primer films were investigated with a KRUSS drop shape analyzer (DSA 30) by measuring the contact angle of water droplet on the films. When the measured contact angle, θ, of the

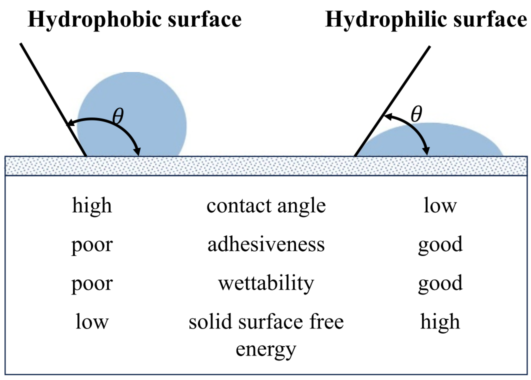


Figure 1. Surface properties characterization based on the contact angle of a liquid droplet [56].

water droplet is more than 90°, the film is hydrophobic, as shown in figure 1. This also means that the film exhibits poor wetting, adhesion, and surface energy. When θ is less than 90°, the film is hydrophilic and exhibits good wetting, adhesion, and surface energy. Table 1 depicts the surface classification of the primer films.

2.3. Fabrication and test methods

2.3.1. Weaving process for custom-made fabric

IsacordPoly60 fabric, a custom-made fabric, was woven on a Toika electric handloom using a double weave arrangement. This approach allows a set of warp and weft strands to be interwoven into a fabric. Two sets of warp yarns were wound around two independent back beams of the loom and threaded

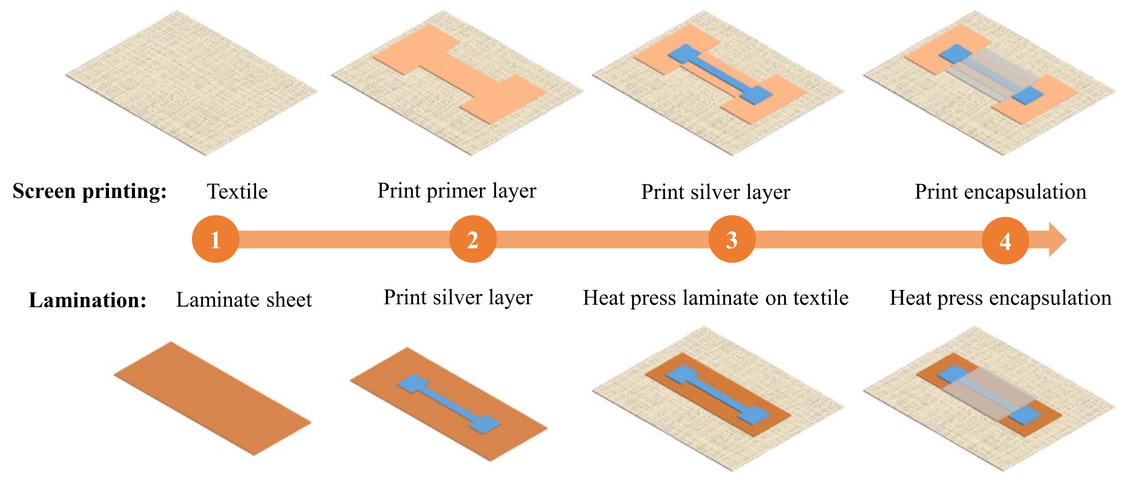


Figure 2. Screen printing and lamination of conductors on textiles.

through the iron heddles. These warp yarns were repeatedly woven with separate weft yarns to create a stable and even two-layer fabric with a simple weave structure [25].

2.3.2. Screen printing and lamination processes

Flexible conductors were screen printed on the textiles and laminate sheets with a DEK 248 semi-automatic screen printer following the steps shown in figure 2. A dumbbell geometry was used for the test patterns to aid in the testing and measurement of the samples after printing. Before printing, the substrates were bonded to a flat rectangular alumina plate to provide mechanical support throughout the printing process.

To obtain a visually smooth surface, primer layers with average thicknesses of 135 μm and 300 μm were screen printed on IsacordPoly60 and Optic-White fabrics by printing the UV-IF-1004 paste through a stainless stencil screen with an emulsion thickness of 40 μm and mesh count of 250 meshes cm^{-1}. The paste was UV-cured for 30 s after each print. Following that, 5 μm thick silver was screen printed on primed fabrics and the laminate sheets with TC-4001 paste. The silver conductor was oven-cured for 15 min at 130 °C on primed fabrics and dried for 10 min at 60 °C on laminate sheets. The printed conductors on the primed fabrics were encapsulated by printing a film of UV-IF-1004 and/or UV-IF-1039 pastes for additional waterproofing. The average thickness of the encapsulation layer is 80 μm.

Conductors on laminate sheets were heat pressed on the fabrics using a commercial heat press, Geo Knight DK20S at the bonding conditions shown in table 2. Examples of resulting samples from the printing and lamination processes are shown in figure 3.

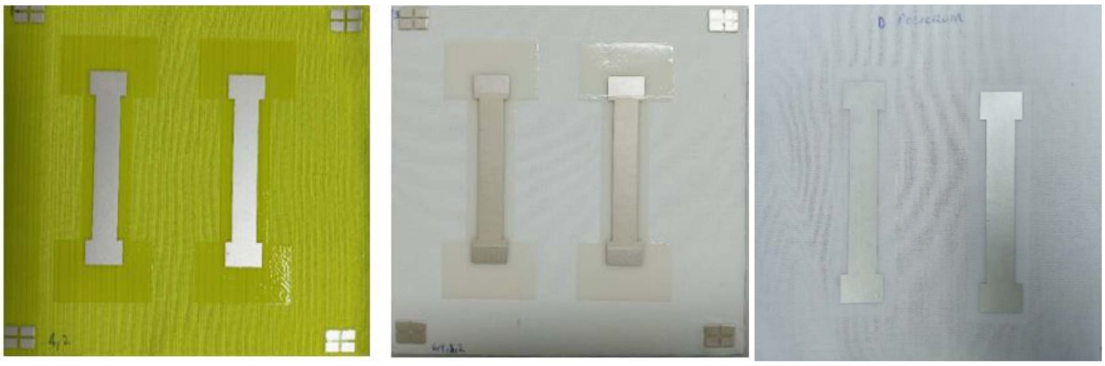
Table 2. Bonding parameters for laminate sheets.

Laminate sheet	Bonding temperature (°C)	Bonding time (s)
Elecrom Stretch HC	170	30
Elecrom Stretch Clear	160	15
Elecrom Stretch White	170	30
Elecrom Flex	190	60
Platilon U073	160	30
Epurex VPT Film	160	20

2.4. Bending and wash test methods

Bending and washing reliability studies were carried out to assess the reparability of the printed silver conductors. Figure 4 depicts the bending test set-up for 90° cyclic bending of the printed conductors over a 10 mm radius mandrel. The maximum bending angle for any flex circuit is typically 90° [25]. To achieve the 90° bending, the samples were held in tension by a 1.2 N weight affixed to the end of the sample. The electrical resistance of the samples before and after bending was measured using a Keithley 2000 multimeter. Real-time measurement of the electrical resistance of the printed conductors during bending was also acquired with the Keithley multimeter operated by a LABVIEW application. Litz wires were glued to the samples with silver conductive adhesive epoxy and allowed to set for 24 h at room temperature before connecting to the multimeter.

Wash tests have been conducted using a domestic washing machine (Beko washing machine WME7247W) to simulate practical applications. The samples were sewn onto a T-shirt and washed in accordance with the ISO:6300:2000 washing standard of 40 °C at 1000 rpm for 1 h with about 2 kg loading. The samples were washed with Surf non-biological detergent using wash test parameters provided in table 3.



(a) IsacordPoly60 fabric (b) Optic White fabric (c) Laminated Elecrom film

Figure 3. Printed and laminated conductors on polyester fabrics.

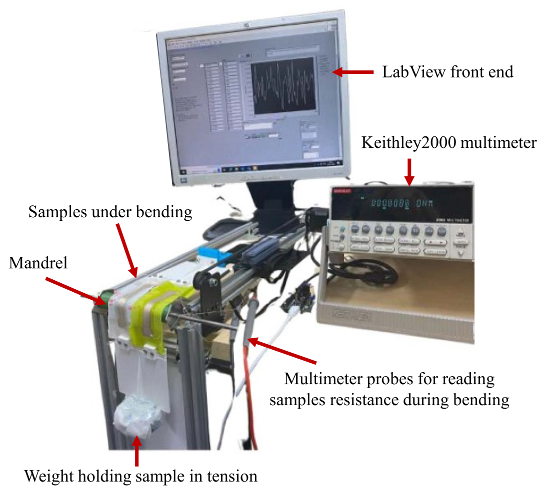


Figure 4. Cyclic bending test set-up for durability testing of printed samples.

Table 3. Washing parameters and values.

Parameters	Value
Spin cycle	1000 rpm
Time	1 h
Temperature	40 °C
Washing machine loading per wash	2 kg

3. Results and discussion

3.1. Reliability of printed conductors on the primed fabrics

Figure 6 illustrates the bending behaviour of the printed conductor on the primed fabrics during and after 1000 bending cycles. In general, the electrical resistance of the conductor increases gradually during bending but returns to a value close to its initial value after bending. The change in the electrical resistance of the conductor due to this bending action is described by the normalised resistance, R_N given by:

$$R_N = \frac{R_f}{R_i} \quad (1)$$

where R_i and R_f are the initial and final values of the electrical resistance.

The impact of repeated bending on the electrical resistance is illustrated by the magnitude of the degradation parameter, ΔR_N given by:

$$\Delta R_N = R_{Nmax} - R_{Nmin}. \quad (2)$$

The maximum change in electrical resistance, R_{Nmax} occurs when the conductor is fully bent around the mandrel with maximum tension from the applied load. When the sample reaches an unbent position, the electrical resistance reduces to a value, R_{Nmin} comparable to the electrical resistance of the pristine conductor before bending, as shown in figure 6(b).

With an increasing number of bending cycles, the size of ΔR_N grows as shown in figure 7. This highlights the deterioration in the electrical resistance of printed conductors under frequent or repetitive stress cycling.

3.2. Reparability of printed conductors on primed fabrics after bending

To reduce the impact of repetitive or regular stress cycles on the reliability as depicted in figure 7, printed conductors on IssacordPoly60 and Optic White fabrics were investigated again over 20 000 bending cycles as shown in figure 8. Although the electrical resistance of the printed conductors decreased significantly as expected when bent, results indicate that the printed conductor may self-repair when given a rest interval before reuse. For example, both encapsulated and unencapsulated conductors exhibited a decrease in their normalized electrical resistances, R_N, when allowed to rest. After 24 h, a significant drop is seen at 8000 and 15 000 bending cycles for the unencapsulated conductor in figure 8(a) and at 7000 and 20 000 cycles for the

Figure 5. Stitched samples on a T-shirt for washing.

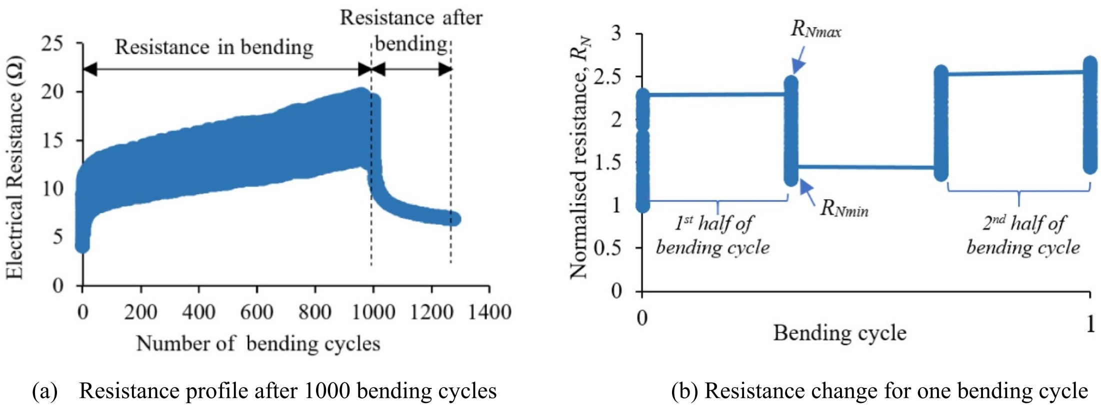


Figure 6. Real time measurement of the electrical resistance of printed conductor on primed fabric during bending.

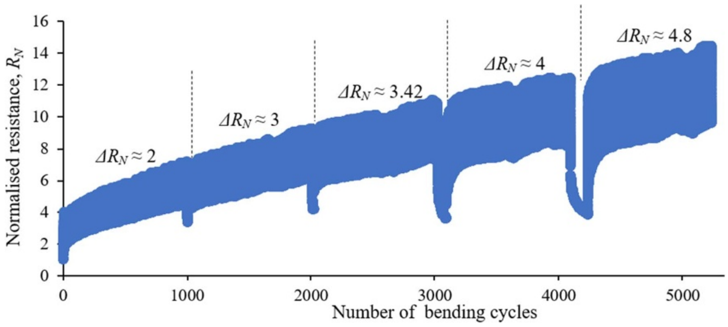
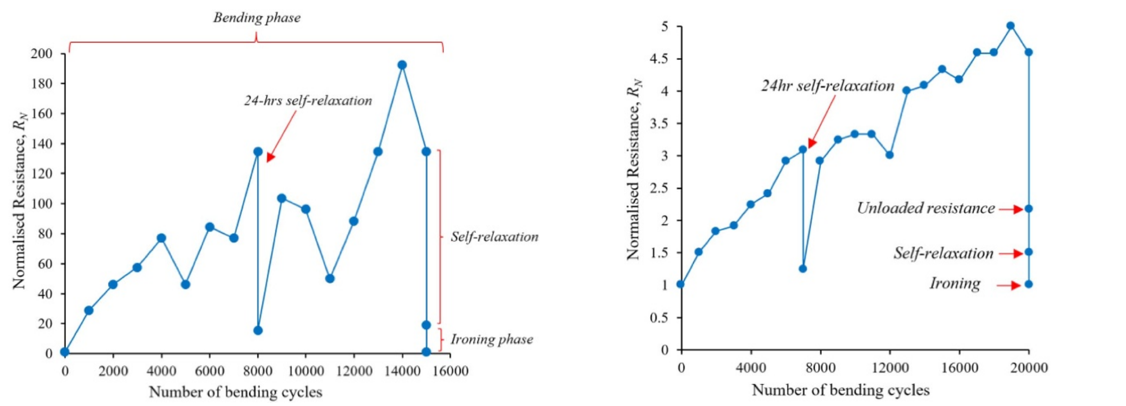


Figure 7. Effect of repeated bending cycles on the electrical resistance of printed conductors.

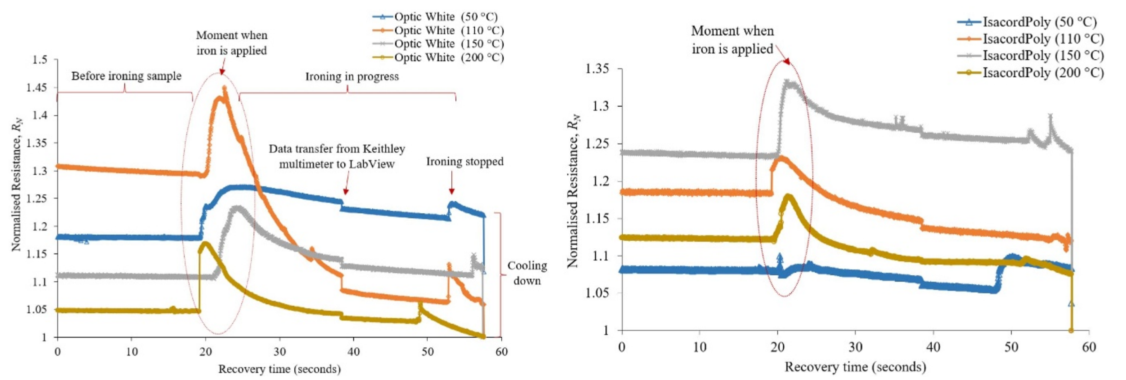
encapsulated conductor in figure 8(b). The normalized resistance for the unencapsulated conductor on IsacordPoly60 fabric (figure 8(a)) dropped from 135 (recorded immediately after bending) to 19 (recorded 24 h later). This translates to a 710% decrease after 15 000 bending cycles. Figure 8(b) demonstrates the protective effect of the encapsulation layer, reducing bending stress and consequently the magnitude of resistance change observed in the printed conductor.

The use of hot ironing to repair and anneal the printed tracks after repeated exposure to bending stress was also investigated. Figure 8(a) shows a further decrease in the normalised electrical resistance, R_N of the printed conductor from 19 to 1 after it was heat-pressed for 20 s using a household iron set to 200 °C. This finding shows that printed conductors on primed fabrics left for 'self-relaxation' for more than 24 h can recover to their original value. For future wearing applications of screen-printed

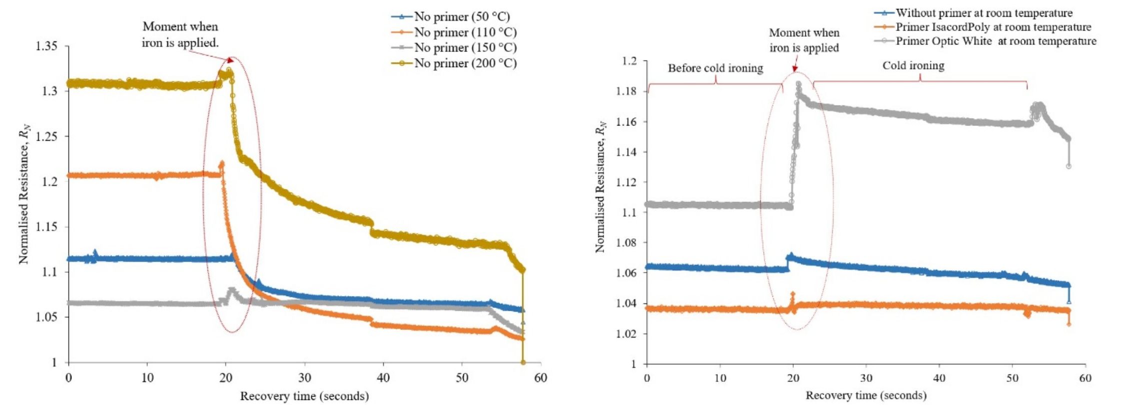


(a) Unencapsulated conductor on IsacordPoly60 (b) UV-IF-1004 Encapsulated conductor on Optic White fabric

Figure 8. Comparison of the reparability of printed conductors on primed fabrics through self-relaxation and ironing. The unloaded resistance is the electrical resistance when the applied tensile load was removed.



(a) Conductor response to ironing on printed primer layer on Optic White (left) and (b) IsacordPoly60 fabrics (right).



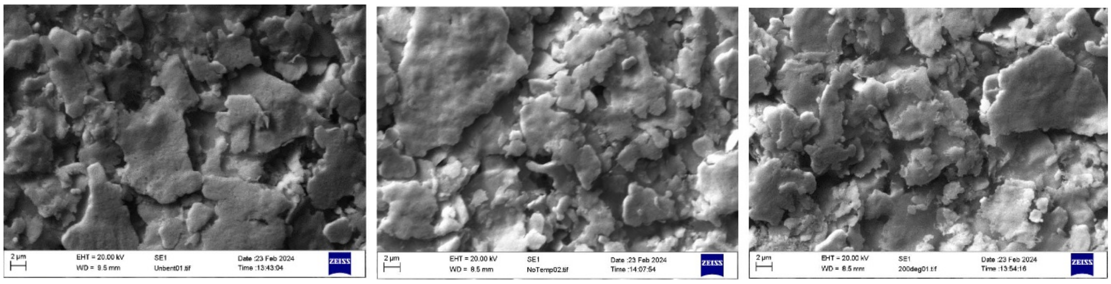
(c) Conductor response on fabrics without primer layer (d) Conductor response to cold ironing

Figure 9. Impact of ironing temperature on repairing printed conductor on fabrics with and without primer layer after 20 000 bending cycles.

e-textiles, either immediate ironing or storing the garment for a short period between uses could effectively 'repair' any bending damage.

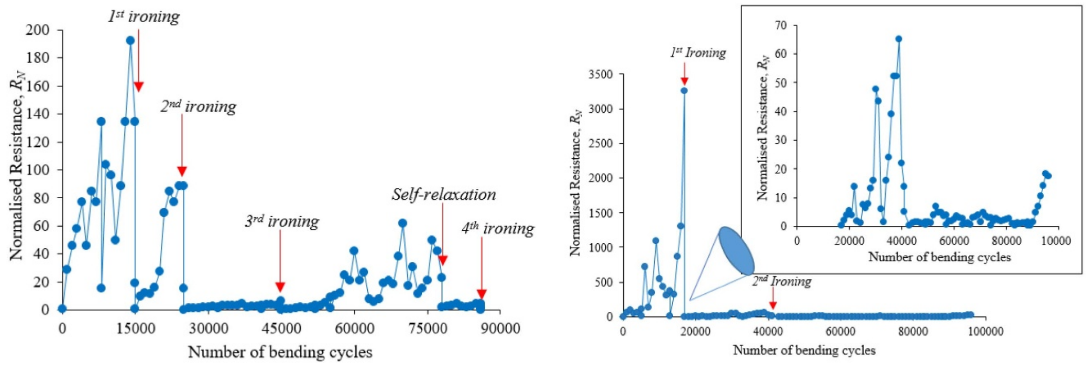
3.2.1. Effect of domestic iron temperature settings on repairing printed conductors

Domestic irons commonly correspond to ironing symbols on wash instructions where one dot signifies a low temperature appropriate for delicate materials like acrylic (approximately 110 °C), two dots represent a medium temperature for synthetic fabrics such as polyester and nylon (about 150 °C), and three dots denote a high temperature suitable for robust fabrics like cotton and linen (around 200 °C) [57]. To examine the effect of utilizing these standard temperatures for repairing strained conductors, nine samples were subjected to ironing for 25 s after undergoing 20 000 bending cycles, with three samples tested at each temperature. Figure 9 shows that the electrical resistance



(a) Before bending (b) After bending (c) After ironing

Figure 10. Micrographs of printed conductor before and after bending and after ironing showing overlap of sliver flakes.



(a) IsacordPoly60 (b) Optic White fabric

Figure 11. Normalised resistance of printed unencapsulated conductors on primed fabrics from intermittent bending and ironing routines.

of the annealed conductors returns to pristine value after ironing at all three temperatures.

The repair mechanism begins with an initial rise in electrical resistance as soon as the iron is applied. This occurs because the pressure from the iron flattens the fabric, inducing an initial strain on the conductor. This was verified through a cold ironing experiment on conductors printed with and without the primer layer, yielding an identical response as shown in figure 9(d).

Subsequently, the electrical resistance gradually decreases during hot ironing as shown in figures 9(a)–(c), and reverts to its original value after cooling down, typically within a minute. The thermal expansion and contraction process in polymers triggers a cooperative rearrangement of constituent molecules, especially near their glass transition temperatures [58]. For materials like PET and polyurethane films, the glass transition temperature typically falls within the range of 70 °C–160 °C [59, 60]. Figure 9 indicates that conductors ironed at 50 °C or room temperature did not fully repair. For example, the electrical resistances of printed conductors on the Optic White fabric after ironing at 50 °C in figure 9(a), and after cold ironing at room temperature in figure 9(d) were still 15% higher than the original value.

However, ironing the conductors at the three standard temperatures completely repaired them. Both the silver flakes/polymer matrix within the conductor shown in figure 10 and the printed primer layer experience thermal expansion at these ironing temperatures. Upon cooling, the polymers contract, allowing for increased overlap among the silver flakes. This behaviour facilitates repair and the recovery of electrical conductivity of the conductors after ironing.

Without the primer layer, conductors printed directly on the fabric were also fully repaired as shown in figure 9(c). However, micrographs of conductors before and after bending, as well as after ironing at all tested temperatures, showed no significant differences as depicted in figure 10.

3.2.2. Effect of occasional and regular ironing on the reliability of printed conductors on primed fabrics

Figure 11 shows how intermittent or occasional ironing can be utilised to correct or remedy any increase in electrical resistance of printed conductors induced by continuous exposure to bending stress. After 86 000 bending cycles and four ironing points, figure 11(a) depicts the electrical response of the printed conductor on the IsacordPoly60 fabric. The infrequent ironing process only raised the electrical resistance of the conductor by $R_N = 0.12$. The printed conductor on Optic-White fabric behaved identically after 96 000 bending cycles and two ironing points, as shown in figure 11(b). After the second ironing,

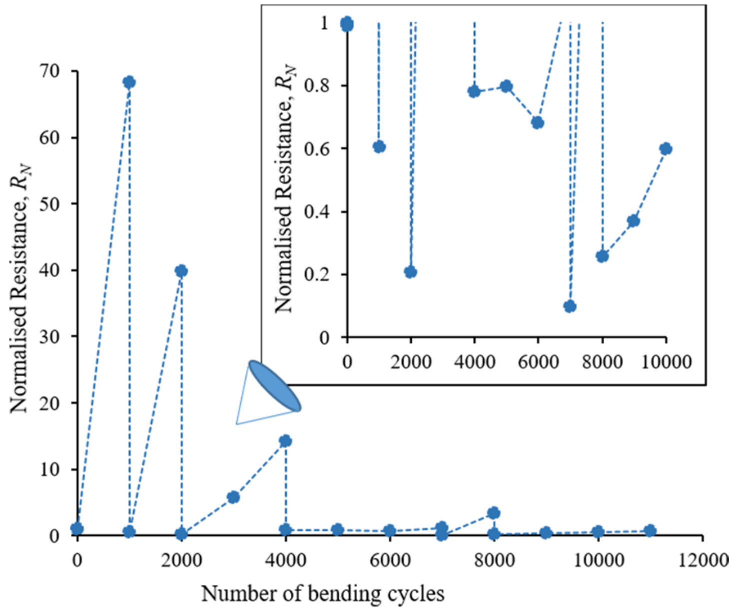


Figure 12. Resistance profile of printed conductor on IsacordPoly60 fabric due to regular ironing per 1000 bending cycles.

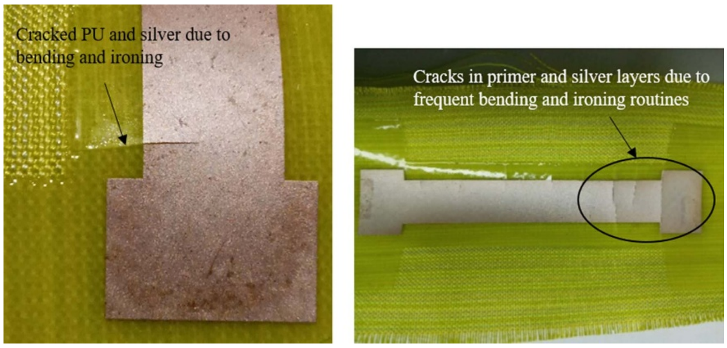


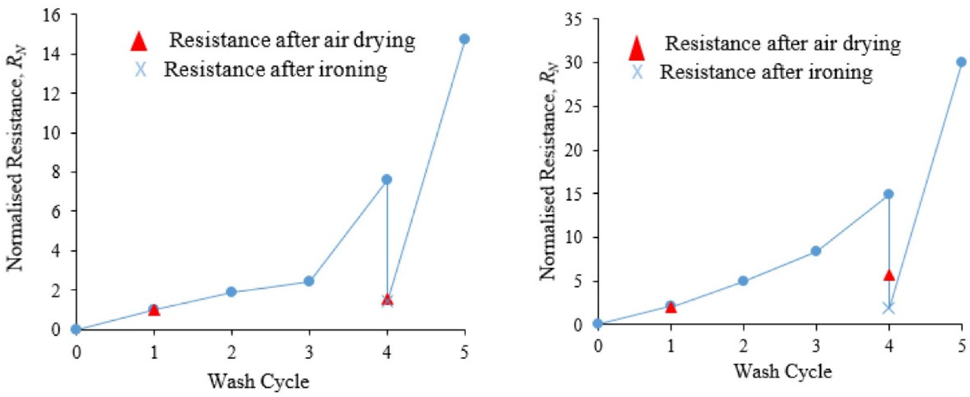
Figure 13. Crack formation on printed primer and silver layers due to frequent bending and ironing routines on IsacordPoly60 fabric.

the resistance change R_N only rose by a factor of 0.15 at the 43 000th bending cycle. Ironing significantly improved conductor performance and durability during bending by slowing the rate at which electrical resistance degraded during successive bending cycles, as shown in figure 11. As a result of these irregular ironing routines, neither sample displayed any apparent faults in the conductor or the printed primer layer.

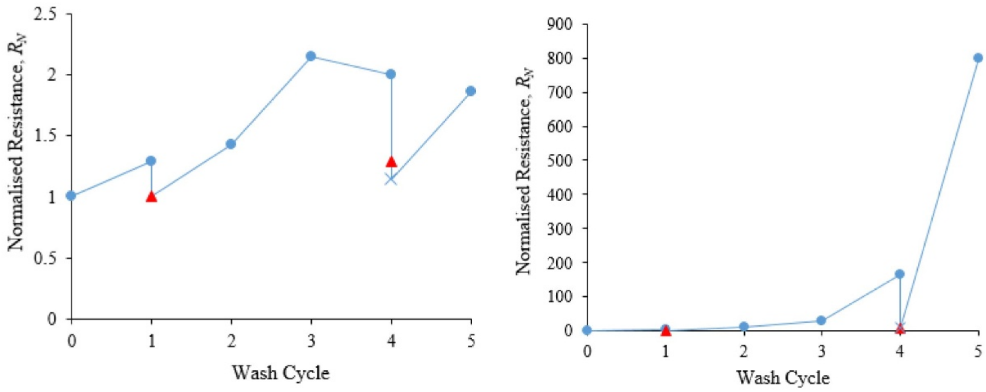
So far, it has been demonstrated that ironing improves the electrical performance of printed conductors subjected to bending stress. The effect of regular ironing on the printed conductors or the primer layer, on the other hand, is unknown. Figures 12 and 13 show the impact of frequent ironing of printed conductors on primed IsacordPoly60 fabric at 200 °C per 1000 bending cycles. As expected, ironing reduced the electrical resistance of the conductor, but the quality of the printed UV-IF-1004 PU primer layer deteriorated as the frequency of ironing increased, as illustrated in figure 13. This frequent ironing initially weakens the printed PU which then splits the printed silver as the PU beneath it cracks during bending, as shown in figure 13. It is hypothesised that the sample's ironing and cooling routine generates thermal fatigue in the primer layer, which then becomes the initial point of failure during the bending cycle. Figure 13 shows how the fracture length of the PU film develops into the silver layer and destroys it as the bending cycle increases. Reducing the ironing temperature will improve the lifetime of the primer layer while also aiding the repair of conductors as shown in figure 9.

3.2.3. Reparability of printed conductors on primed fabrics after washing

Initially, four IsacordPoly60 fabric samples and seven Optic-White fabric samples were washed. The four IsacordPoly60 samples comprised two pairs of UV-IF-1004 encapsulated and unencapsulated conductors sewn to the white T-shirt shown in figure 5. The



(a) Resistance change in encapsulated (left) and unencapsulated (right) printed conductors on IsacordPoly60 fabrics



(b) Resistance changes in encapsulated (left) and un-encapsulated (right) printed conductors on Optic White fabrics

Figure 14. Resistance change of printed conductors on primed fabrics after 5 washing cycles and ironing.

Optic-White samples included three encapsulated conductors and four unencapsulated conductors.

Figure 14 shows that encapsulated conductors outperform unencapsulated samples over the five washing cycles. The increase in electrical resistance of the unencapsulated conductors was more than double that of the encapsulated samples. Air-drying the samples at room temperature was adequate in both cases to temporarily repair the conductors without the requirement for ironing. Despite this, ironing was found to significantly lower electrical resistance after air drying in both encapsulated and unencapsulated samples. For example, the R_N of the unencapsulated conductor in figure 14(b) was lowered by more than 200% after ironing, from 5.6 after air-drying to 1.9 after ironing.

Curling of the samples after washing was a major issue in the first washing trial, as seen in figure 15. This was owing to the excessive water absorption of the screen-printed UV-IF-1004. As a result, a comparison test was performed using a more waterproof encapsulating material, UV-IF-1039. An additional 11 samples, five UV-IF-1004 and six UV-IF-1039 encapsulated samples on Optic White fabric, were washed. The wash test results in figure 16 reveal that the UV-IF-1004 encased conductors failed after three washes, causing considerable damage to the patterns. The more waterproof UV-IF-1039 withstood 10 washing cycles with a slight curl in the samples.

Figure 15. Curling of standalone printed conductors with UV-IF-1004 and UV-IF-1039 encapsulation.

Ironing was also found to be effective in minimising stress-induced changes in the electrical resistance of printed conductors during successive washing cycles. For example, after the sixth wash, the electrical resistance of the conductor represented by the green

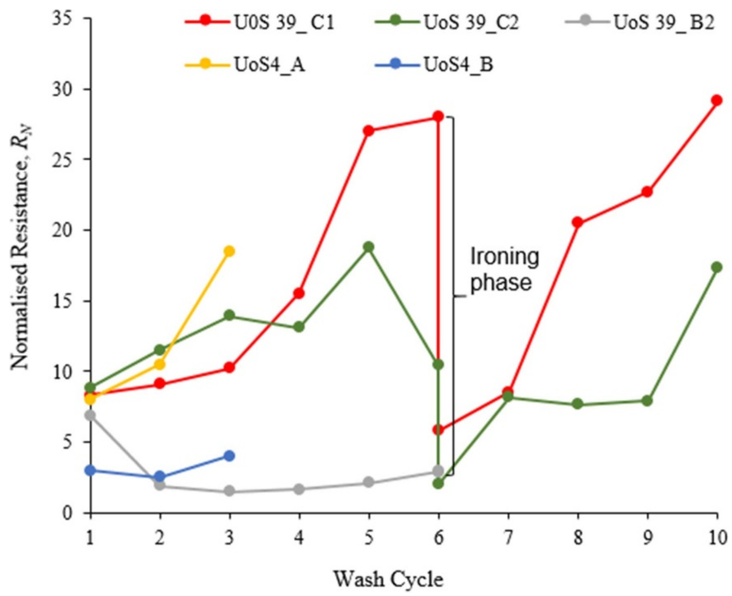
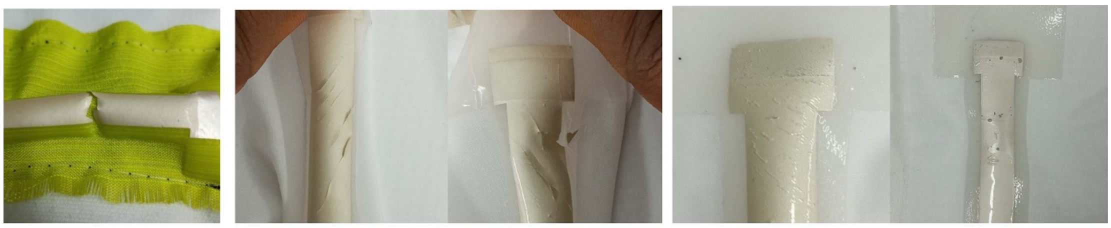


Figure 16. Resistance change of printed conductors with waterproof and non-waterproof encapsulation after washing and ironing.



(a) Peeled primer layer (b) Crack formation due to curling UV-IF-1004 layer (c) Defects in the UV-IF-1039 encapsulation

Figure 17. Failure modes resulting from washing of printed conductors on Optic White and IsacordPoly60 fabrics.

trace in figure 16 reduced by 500%, from a normalised resistance of $R_N = 10.4$ immediately after washing to a value of $R_N = 2$ after ironing. This fix allowed the sample to tolerate five additional washing cycles before increasing resistance by 17.4 after the tenth wash cycle.

3.2.4. Washing-induced failure modes in printed conductors on primed fabrics

One of the failure modes discovered after washing was the peeling of the screen-printed UV-IF-1004 priming layer off the IsacordPoly60 fabric, as shown in figure 17(a). This is due to inadequate adhesion between the fabric and the printed primer layer, which eventually broke down with repeated wash cycles and caused the conductor break illustrated in figure 17(a). The curling of the UV-IF-1004 primer and encapsulating layers also initiated cracks on the printed conductors, as seen in figure 17(b).

The wash test also caused stress in the UV-IF-1039 primer and encapsulating layers, resulting in ripples in the printed conductors. This also resulted in the encapsulation peeling away from the conductor after a few washing cycles, as illustrated in figure 18(c). However, by increasing the printed thickness of the printed encapsulation, peeling of the encapsulation material can be decreased or eliminated.

3.3. Encountered challenges—reliability of bonded joints

The unreliability of bonded joints formed when an external cable is attached to the printed conductors can impede real-time monitoring of printed conductors. These joints are prone to failure during bending, so they must be inspected. Many of the connectors proposed in the literature are still rigid [61], making them failure hotspots during testing and, invariably, during real-world usage.

Three adhesive joints were tested in this experiment [62], and the results show that epoxied connections are still more durable when bent. The failure modes, however, remain the same, with fracture formation occurring around the bonded joints [62].

3.4. Reliability of printed conductors on laminate sheets

After lamination to the fabrics using the bonding settings in table 3, the measured electrical resistance of the printed conductors on all of the laminate sheets

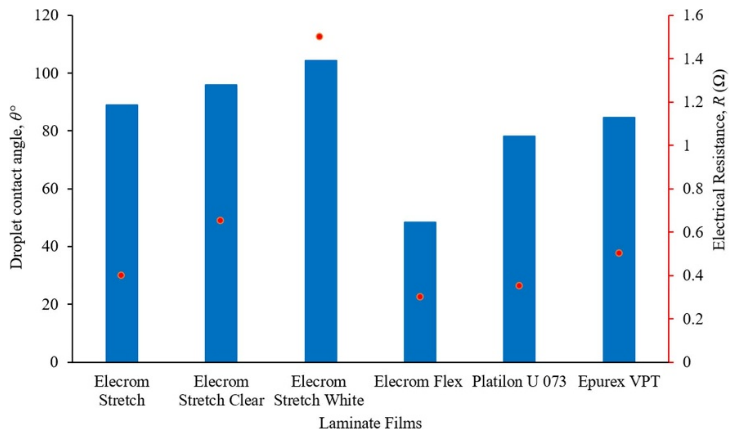


Figure 18. Impact of surface property of laminate films on the electrical resistance of printed conductors.

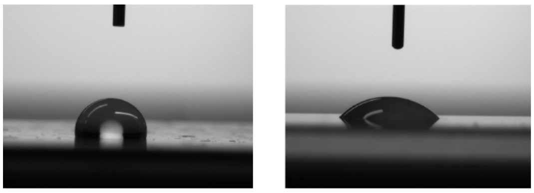


Figure 19. Contrast in the droplet shape on (a) hydrophobic and (b) hydrophilic laminate films.

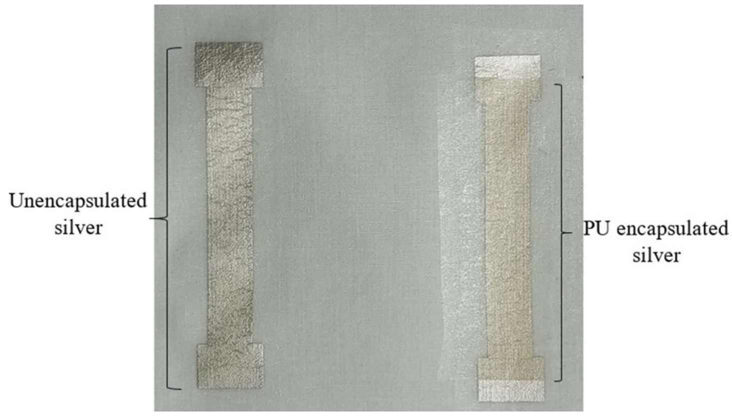


Figure 20. Laminated silver conductor on EPUREX sheet bonded to Optic White fabric.

ranged between 0.3 Ω and 1.5 Ω before bending or washing. Figure 18 compares the electrical resistance of printed conductors on laminate films to the surface energy of the films determined using drop shape analysis (DSA). The result shows that the Elecrom Flex laminate sheet attained the lowest electrical resistance of 0.3 Ω, which is 5 times less than the value recorded on the Elecrom Stretch White—the laminate with the largest contact angle depicted in figure 18. This demonstrates that laminates with high surface energy allow for the printing of superior conductors and, in this example, good wetting of silver conductive ink on the film. Figure 19 is an example DSA measurement that shows a clear difference in the form of the droplet on the hydrophobic and hydrophilic laminate sheets.

3.4.1. Reparability of printed conductors on laminate sheets after bending

The impact of bending on the electrical resistance of encapsulated and unencapsulated laminated conductors on optic-White fabric, as shown in figure 20, was initially tested over 20 000 bending cycles using the Epurex VPT sheet. Encapsulated conductors were created by laminating an additional layer of Epurex film on top of the unencapsulated conductor. Figure 21(a) depicts how the electrical resistance of

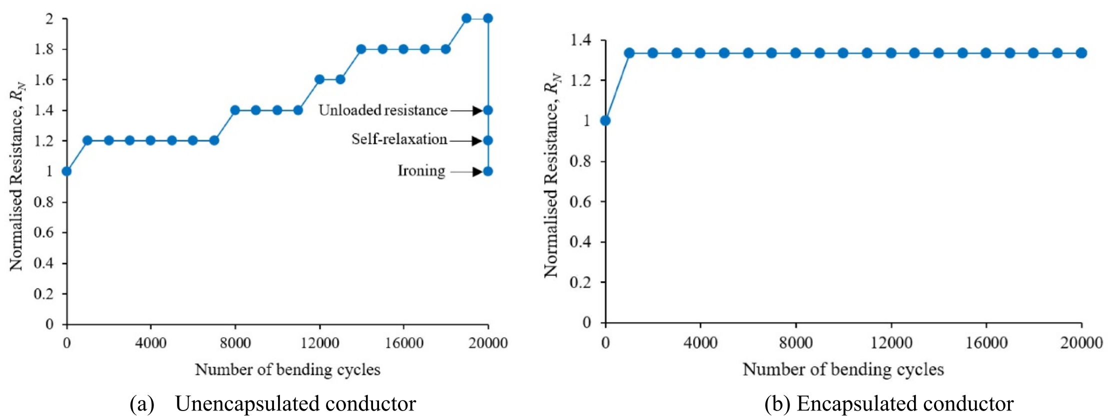


Figure 21. Effect of bending and ironing on printed conductors on Epurex sheets laminated onto Optic-White fabric. The unloaded resistance is the electrical resistance when the applied tensile load was removed.

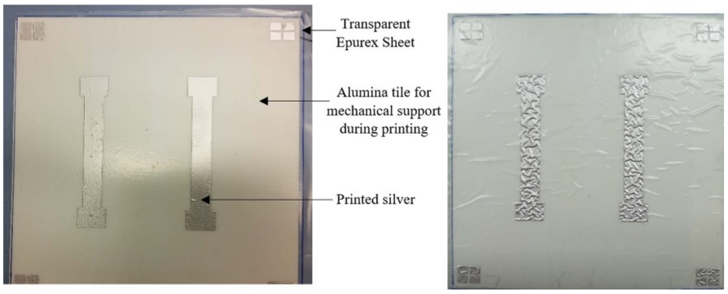


Figure 22. Warp of Epurex film (right) after printing conductor.

the unencapsulated conductor rapidly grew during the bending regime, eventually doubling its original value following the bending test. However, the encapsulated sample maintained the same electrical resistance throughout its bending regime after the initial increase to $R_N = 1.3$, as shown in figure 21(b).

The self-relaxation and ironing-repairability of laminated conductors were also examined. Self-relaxation of the unencapsulated conductor limited the resistance change to $R_N = 1.2$ (≈14%), and ironing restored the electrical resistance to its initial value, whereas no change was seen in the encapsulated sample for either self-relaxation or ironing. Because the increase in electrical resistance in the encapsulated conductor was so minor (0.1 Ω), it was assumed that the measurement was within the error margin, resulting in no discernible change after ironing. However, one drawback of using the Epurex VPT sheet is that is it only suitable for printing single-layer devices. The VPT sheet warps as the printed silver dries up at room temperature even before the sample is cured in an oven as shown in figure 22. As a result, the other laminates listed in table 3 were explored to suit the multilayer printing requirements of complicated printed e-textile devices.

Figure 23 shows that the electrical resistance of the conductors printed on the other laminate sheets increases after 1000 cycles of bending. The Elecrom Stretch Clear performed the worst of all printed films, with a tenfold increase in electrical resistance after bending (i.e. $R_N = 10$). The Elecrom Flex had the best performance, showing no change in resistance until the 10 000th cycle when a slight change of $R_N = 1.3$ was observed, which is comparable to the resistance change reported with the Epurex film. This resistance change is also nearly ten times less than the resistance change obtained with the Elecrom Stretch Clear laminate sheet.

The best performance was obtained with Elecrom Flex, showing very comparable results with the Epurex VPT sheet as shown in figure 23. Consequently, the reliability and reparability of printed conductors on Elecrom Flex were further examined through extended bending cycles up to 400 000 and ironing. Results shown in figure 24 indicate that the encapsulated conductors show up to a 50% increase in normalised resistance after 400 000 bending cycles without ironing. This change in resistance is easily repaired through ironing which restored the conductor to its pristine condition. Unencapsulated conductors had a sharp increase of up to 300% in their electrical resistance after 200 000 bending cycles but the ironing process restored its electrical resistance to the initial value. This result indicates the electrical resistance of printed conductors on laminate sheets is easily repairable using a

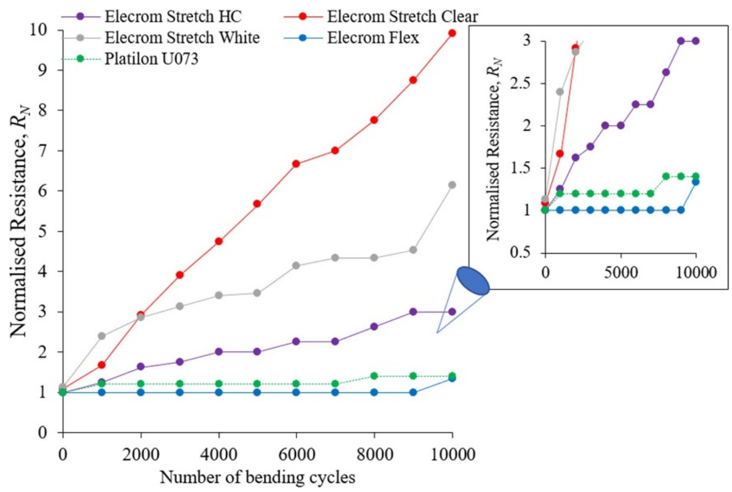


Figure 23. Electrical resistance of printed conductors on laminate sheets after 10 000 bending cycles.

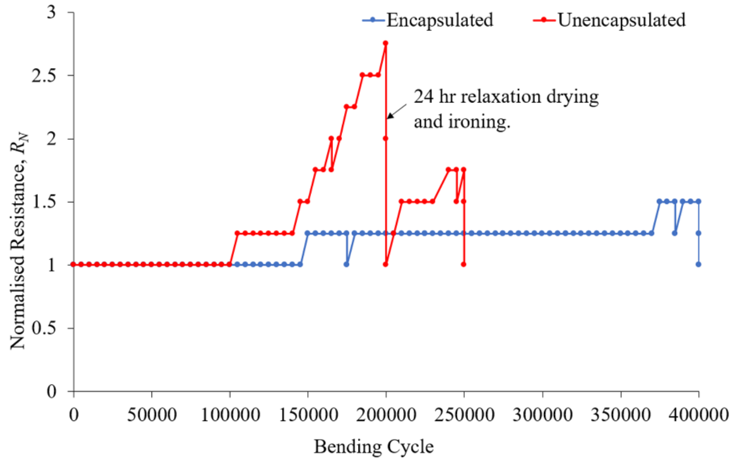


Figure 24. Electrical resistance of printed conductors on Elecrom Flex after extended bending cycles and ironing.

domestic ironing routine which will improve their lifetime.

3.4.2. Reparability of printed conductors on laminate sheets after washing

Five washing cycles were initially used to evaluate the printed conductors on each laminate sheet sewn to a T-shirt. The samples all withstood at least five wash cycles, as shown in figure 25. Printed conductors on the Elecrom Stretch Clear laminate sheet performed the worst upon washing, with a maximum resistance increase of $R_N = 360$. This poor performance can be attributed to its hydrophobic surface, which resulted in poor print quality and silver conductor wetting. Because of the inadequate wetting, the silver particles had large interspaces that expanded when the film was bent or washed. Printed conductors on the Elecrom Flex and Platilon U073 provided the best performance, with a maximum resistance increase of $R_N = 3$. The best performance was demonstrated by printed conductors on the Elecrom Flex and Platilon U073, with a maximum resistance increase of $R_N = 3$. This is good because the samples are unencapsulated and could therefore be significantly improved upon.

The ironability of conductors was also evaluated after washing. The electrical resistance of all printed conductors decreased after ironing, as seen in figure 24. For example, the resistance change of printed conductors on the Platilon film U073 dropped from $R_N \approx 2.8$ by 23% after ironing. In contrast, Elecrom Flex saw a 60% drop in electrical resistance from $R_N = 3$ after washing to $R_N = 1.2$ after ironing. Although printed conductors on the Elecrom Stretch Clear laminate showed the most improvement after ironing, with a 98% reduction in electrical resistance, they remain unreliable due to the low surface energy of the sheet. This finding implies that laminate material selection should be carefully considered to improve the reliability and reparability of printed conductors.

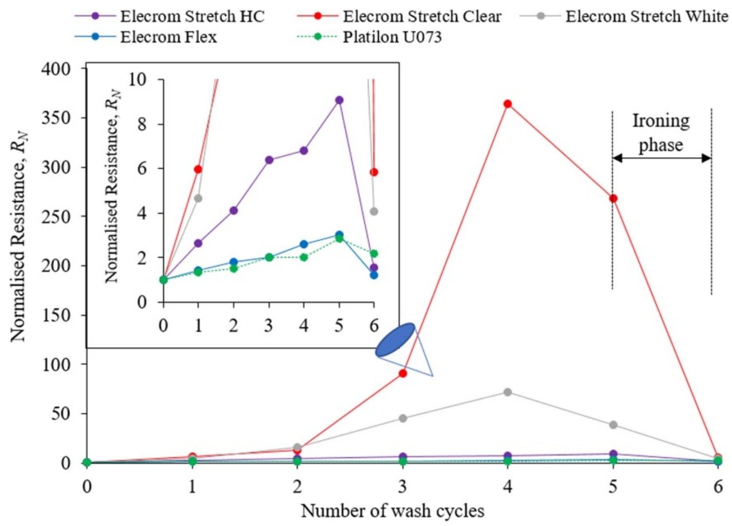


Figure 25. Effect of ironing on washed printed conductors on laminate sheets.

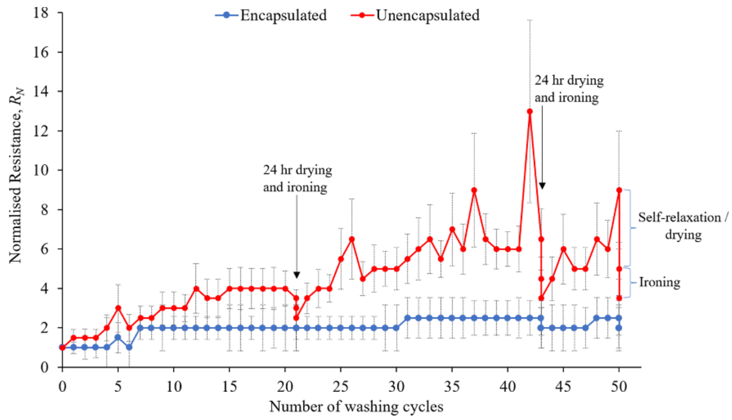


Figure 26. Electrical resistance of printed conductors on Elecrom Flex laminate sheets after 50 wash cycles and intermittent drying and ironing.

In general, the printed conductors on the Elecrom Flex exhibited the best performance among all the laminate sheets.

As a result, six conductors, including three encapsulated and three unencapsulated samples, underwent additional wash tests to better understand the degradation rate for extended washing cycles. Following 50 wash cycles and intermittent ironing as depicted in figure 26, the normalized resistance, R_N averaged across all number of samples for both encapsulated and unencapsulated conductors increased to 2.12 (i.e. 112% increase) and 2.39 (139% increase) respectively with final electrical resistances just under 1 ohm. The results also indicate that unencapsulated conductors are more susceptible to washing stresses but are easily repaired through ironing.

3.5. Comparing the reliability of printed conductors on printed primer layer and laminate sheets

The findings show that in response to dynamic stress, the electrical resistance of printed conductors on laminate sheets and primed fabrics increases. Ironing can be used to restore electrical resistance in both materials. However, the bending and washing tests strongly suggest that printed conductors on laminate sheets are more reliable than conductors on primed fabrics. After 20 000 bending cycles, unencapsulated conductors on primed fabrics exhibit a maximum resistance change of up to $R_N = 3260$, which is significantly greater than the resistance change, $R_N = 1.8$, reported for conductors on laminate sheets in figures 11 and 21, respectively. In addition, the best result from encapsulated printed conductors on primed fabrics, as shown in figure 8(b), is 250% worse than the performance from unencapsulated conductors on laminate sheets after the same number of bending cycles. Moreover, conductors on the best laminate sheets (Elecrom Flex, Platilon U073 and Epurex) showed little to no change in electrical resistance throughout the first 10000 bending cycles and survived 400 000 bending cycles with no change in resistance after ironing.

Similarly in the wash test, the maximum resistance change recorded for conductors on laminate sheets after 50 wash cycles and ironing is significantly lower (i.e. 230%) than the measured resistance change for conductors on primed fabrics (i.e. 3000%) only after 10 wash cycles. When compared to conductors on primed fabrics, encapsulated conductors on the best laminate films show no obvious cracks or damage from the reliability tests, as illustrated in figure 17.

4. Conclusions

The durability of screen-printed conductors on textiles is a challenge. To increase durability, the reparability of screen-printed conductors using a home ironing process was investigated. The results show that conductors printed on laminate films and then heat-pressed or laminated onto textiles are more resilient under mechanical stress than printed conductors on fabrics with and without a primer layer. Although the electrical resistance of both types of screen-printed conductors will eventually degrade when subjected to frequent washing and bending stresses, the results show that prime performance can be restored with immediate ironing at standard ironing temperatures between 110 °C and 200 °C or by allowing the printed conductor to self-relax between uses. Through this process, printed conductors were able to withstand 400 000 bending cycles and endure 50 washing cycles with a change in resistance of less than 20%, while keeping the actual electrical resistance below 2 ohms.

The findings of this paper indicate that the lifetime of e-textile products based on printed conductors would significantly increase if degradation due to practical stresses is periodically repaired using normal ironing and at a minimum temperature of 110 °C. This necessitates the involvement of e-textile wearers and users in the active care of their e-textile products. Manufacturers will also need a care label to accompany their e-textile products, detailing the safe ironing regime and frequency required for repair on different textiles. This will help users know when they need to iron their e-textile without waiting until the e-textile completely loses functionality.

To optimise durability, it is essential that designers carefully select the materials used in planarizing the textile surface. Introducing a printed primer layer onto the textile may increase the conductor's sensitivity to mechanical stress, benefiting sensing applications but greatly reducing the durability of the printed conductor. While the use of laminate sheets significantly enhances durability, their surface energy must be evaluated to optimise the printing quality of conductors on them.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5258/SOTON/D2976.

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