

Investigating the Mechanical Failures at the Bonded Joints of Screen-Printed E-Textile Circuits [†]

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Abstract: It is often necessary to connect e-textile devices with power supplies and other peripherals using electrical wires. This connection is usually achieved with the use of wires that are consequently bonded to the e-textile circuit using conductive epoxies or solders. This paper reports the mechanical failures that arise from this bonded joint during bending by considering the connection of textile-based Litz wires to screen-printed silver conductors using a combination of conductive epoxies and tapes as bonding adhesives. Cyclic bending results of the conductors around a 5 mm bending diameter rod show that conductors with bonded joints degrade after 3500 cycles with the formation of cracks and fractures around the bonded joints. Conductors without bonded joints achieve more than 10,000 bending cycles without the formation of cracks in the conductors.

Keywords: e-textiles; bonded joints; cyclic bending; mechanical failures; connectors; screen printing



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1. Introduction

E-textiles combine electronic and textile materials to achieve electronic solutions that are more integrated into human life. Such solutions include health monitoring and rehabilitation [1], aesthetic augmentation [2], and sustainable energy solutions for low power wearable devices [3]. However, the transition of e-textiles from research prototypes to commercial devices significantly hinges on the reliability and robustness of the e-textile in real consumer environments [4]. One such reliability concern centres on achieving durable wired connections between e-textile circuits and their power supplies and/or external peripheral devices. Most of the reliability research on e-textiles has focused on preventing fatigue failures along the embedded conductors under practical stresses. Different methods for improving the durability of conductors that have been reported include the optimization of conductor design with serpentine structures [5], locating the conductors on the neutral axis of the printed e-textile [6], and using mechanically resilient functional materials to enhance the lifetime of the e-textile [7,8]. However, the first point of mechanical failure typically occurs at the bonded joints where electronic components are bonded to the embedded conductors [9] or where the wires connect the e-textiles to external devices and power supplies [6]. For a typical printed e-textile construction, shown in Figure 1, wired connections are unavoidable, hence it is imperative to find solutions that mitigate these failures through robust bonding methods.

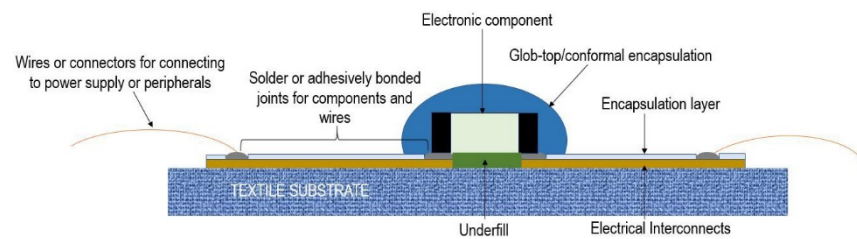


Figure 1. A typical construction of printed e-textiles.

This paper evaluates three different methods for joining textile-based Litz wires to screen printed silver conductors on a polyester fabric, as shown in Figure 2. The bonded joints shown in Figure 2 consist of rigid, flexible and intermediate joints implemented by using conductive films and adhesives. The durability of these joints is assessed through the real-time acquisition and logging of the resistance change of the printed conductor under repeated cyclic bending. This approach simulates the practical bending stresses associated with the use of textiles and examines the behaviour of the bonded joints under mechanical stress. This study is useful for understanding the challenges associated with interfacing e-textile circuits and devices with required peripherals.

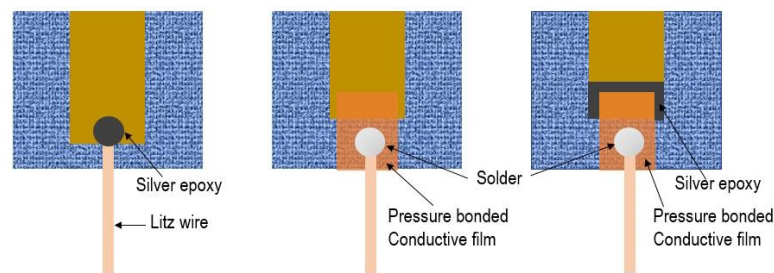


Figure 2. Bonding methods for wired connections on screen printed e-textiles showing (from left to right) rigid, flexible, and intermediate bonded joints.

2. Materials and Methods

The screen-printed e-textile shown in Figure 3 uses a dumbbell-shaped interface and conductor layer pattern and was fabricated on a DEK 248 semi-automatic screen printer based on the printing process described in [10]. The non-planar surface of textiles often necessitates the printing of an interface layer to smooth and planarize the textile before any functional layers can be printed. Consequently, in this work a custom-made polyester fabric, IsacordPoly60, with an average thickness of 207 μm was used as the textile substrate [11]. The textile was selected to limit the printed thickness of the interface layer to 50 μm with a surface roughness of $<2 \mu\text{m}$, which currently represents the state of the art. The interface and conductor layers were realized using screen printable UV cured polyurethane ink, Fabink UV-IF1004, and thermally cured silver paste, Fabinks TC-C4007, from Smart Fabric Inks Ltd. These inks were chosen for their printability, flexibility, and strong adhesion to textiles [12]. The achieved thickness for the silver conductor was 5 μm .

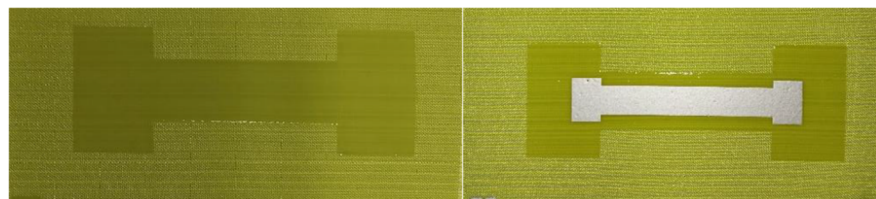


Figure 3. Screen-printed dumb-bell interface (left) and silver conductor (right) patterns on a bespoke woven Isacord Polyester 60 thread count (IsacordPoly60) fabric.

Silver loaded epoxy, conductive copper film, and low-temperature solders were used to attach textile-based Litz wire to the printed conductor based on the three bonding methods shown in Figure 2. The silver epoxy was cured for 10 min at 120 °C while the copper film was pressure-bonded onto the conductor after the Litz wires were soldered. Since the silver-loaded epoxy becomes stiff and rigid when fully cured, the conductive copper film was chosen to increase the flexibility of the bonded joints and minimize the stiffness gradient between the bonding material and the printed conductor.

Test Setup for Monitoring Bonded Joint during Cyclic Bending

Three samples of each of the bonding methods were subjected to 90° cyclic bending around a 5 mm bending radius under a bending tensile load of 1.5 N as described in [13]. The cyclic bending is driven by a stepper motor. Real-time monitoring and assessment of the performance of these bonded joints under cyclic bending stress was achieved by continuously measuring and recording the electrical resistance of the screen-printed conductor using a LabView controlled Keithley multimeter, as shown in Figure 4. The durability of the samples containing any of the bonding methods was compared with that of samples without any bonding material.

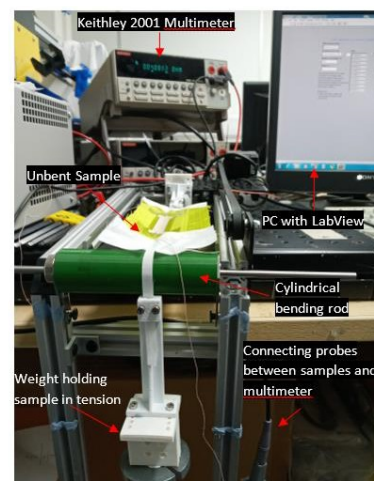


Figure 4. Bending test setup for real-time monitoring of bonded joints under cyclic bending.

3. Results and Discussion

The result showed that the presence of the bonded joints generally induced more stress on the silver conductors during bending and generated the fractures shown in Figure 5. Whilst samples without the bonded joints survived more than 10,000 cycles before crack formation, samples with bonded joints only survived 3500 cycles, after which the electrical resistance of the samples could not be measured by the Keithley multimeter. These fractures introduced poor contact between the contact pad of the conductor and the bonding materials. The poor contact triggered high contact resistance between the wire and the silver conductor and introduced noise into the electrical resistance measurement of the printed conductor, as shown in Figure 6. Figure 6a shows the actual change in the normalised electrical resistance (i.e., the ratio of the electrical resistance in bending to the measured resistance before bending) of the printed conductor over 3000 bending cycles before any noticeable failure at the bonded joint of the conductive epoxy was detected. As soon as the bonded joint began to fail, an upsurge of almost 1000 was initially noticed in the normalised resistance. This eventually deteriorated with an increase in the normalized resistance of up to 7000 within 1000 bending cycles, as shown in Figure 6b.



Figure 5. Crack formation on samples with bonded joints conductive epoxy (**left**), pressure bonded conductive film (**middle**) and epoxy + conductive film (**right**).

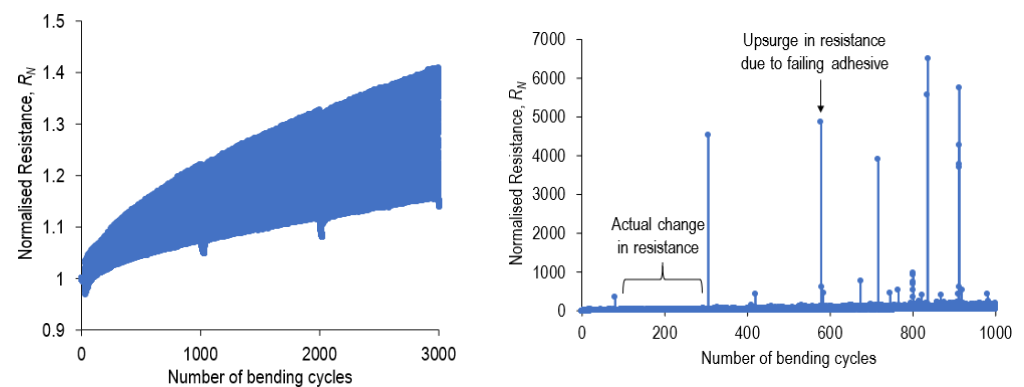


Figure 6. Normalised resistance changes of samples using conductive epoxy before sudden spike resistance measurement (**left**) and during the failure of the bonded joint (**right**).

Figure 7 compares the performance of the flexible bonded joints created from electrically conductive film, and the intermediate joints formed by combining conductive epoxy with the conductive film. The results indicate that the flexible joints quickly degraded under cyclic stress as shown in Figure 7a and introduced sudden peaks and fluctuations to the measurement within the first 1000 bending cycles due to intermittent contact. The magnitude of this generated noise reduced with the intermediate joints, which used the conductive epoxy to increase the bonding strength of the conductive film as shown in Figure 7b. This result was expected since the epoxy-based bonded joint showed more resilience under bending. In all the tested samples, the failure point always occurred at the interface between the bonding material and the printed conductor, as shown in Figure 5. The crack length propagated through the printed conductor when the sample was repeatedly loaded with bending stress.

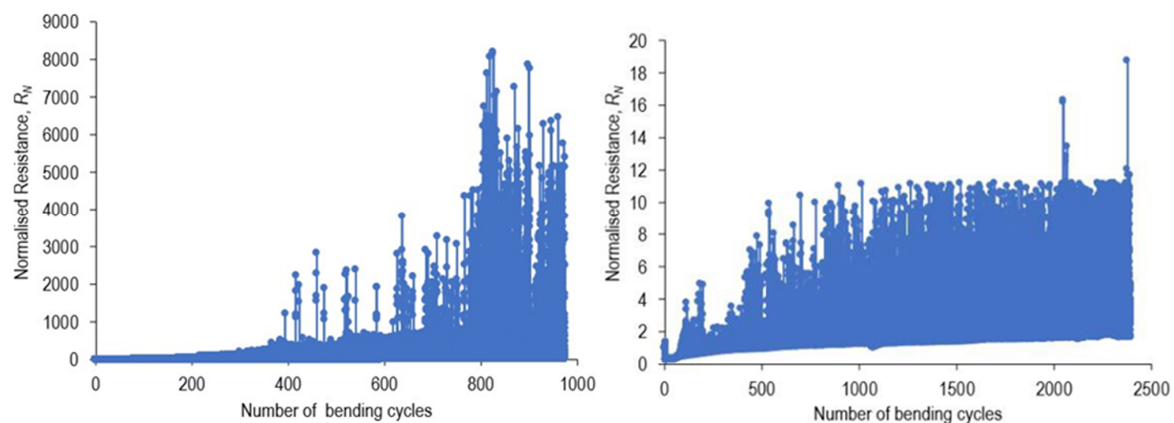


Figure 7. Normalised resistance changes of samples using pressure-bonded conductive film (**left**) and conductive epoxy + conductive film (**right**).

4. Conclusions

Bonded joints are currently unavoidable for e-textile design because they are useful for interconnecting devices on the textile and for wiring/connecting e-textiles to power supplies and peripherals. This paper reports the durability of three different bonded joints of varied degrees of flexibility. The results show that bonded joints remain a critical failure point for e-textile interconnections. The reported results show that rigid epoxied joints produce the best results but ultimately result in the cracking of the conductive patterns. Flexible connectors with better adhesion than currently available pressure-bonded conductive films are still required to minimise the stiffness mismatch created by epoxy joints. It is recommended that the durability of the printed e-textiles could be improved by minimizing the number of bonded joints where possible during e-textile design and manufacture; this can be achieved by integrating more of the electronics into or onto the textile, thus reducing the need for interconnections.

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Conflicts of Interest: The authors declare no conflict of interest.

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