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Finite-Element Analysis of the Mechanical Stresses on the Core Structure of Electronically Functional Yarns †

Mohamad Nour Nashed, Arash M. Shahidi, Theodore Hughes-Riley * and Tilak Dias

Advanced Textiles Research Group, Nottingham School of Art and Design, Nottingham Trent University, Dryden Street, Nottingham NG1 4GG, UK; m-nour.nashed@ntu.ac.uk (M.N.N.); arash.shahidi@ntu.ac.uk (A.M.S.); tilak.dias@ntu.ac.uk (T.D.)

* Correspondence: theodore.hughesriley@ntu.ac.uk; Tel.: +44-(0)1158-488178

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Abstract: Electronic yarns (E-yarns) are a type of electronic textile where the electronics are embedded within the yarn structure, resulting in a yarn with normal textile properties. This is achieved by soldering thin copper wires onto electronic components, encapsulating the component within a UV-curable resin micro-pod, and covering the component with reinforcing yarns. The resin micro-pod protects both the component and the solder joints, providing the final yarn strength along its main axis: this is critical for its reliability after post-processing and during use. This work explored the use of Finite-Element Analysis to evaluate the mechanical stresses at the soldered joints of the core structure of E-yarns under axial loading before and after the encapsulation of the component. The results of this analysis were compared to the tensile test results of the core structure of the E-yarn.

Keywords: electronic textiles; smart textiles; electronic yarns; E-textiles; E-yarn; finite element analysis; electronically functional yarn; wearable electronics

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1. Introduction

Developments in recent years have led to the miniaturization of the electronic devices that can be used in electronic textiles (E-Textiles) [1]. However, despite these advances, the reliability of the embedded electronics has proven to be a challenge for many E-textile innovations [1–3]. Textile garments are designed to be worn, washed, and dried, resulting in significant mechanical loads being applied to the fibres that form them [4]. The applied force can reach a few thousand Newtons per meter, which for E-textile garments can influence the reliability of any embedded electronic [5]. This lack of reliability is often due to contact failures or an increase in the resistance of the connections [2].

Electronic yarns (E-yarns) are a type of E-textile where small electronic components are embedded into the core of the yarns that make up the garment. The technology integrates the electronics by soldering the components onto copper wires. The functional part is then encapsulated within a rigid resin micro-pod to make it washable and increase the robustness of the solder joints [6]. This core structure (Figure 1a) is then inserted into a knitted or braided structure to provide the appearance of a normal textile yarn (Figure 1b). The process to manufacture E-yarns has been discussed in earlier publications [6,7].

Examining the failure mode of E-textiles is complicated, as stretching, bending, and indentation are all present in the life-cycle of a garment [8]. In the case of E-yarns, wash tests showed that the mode of failure was the breakage of the copper wire due to mechanical stresses [9]. The breakage of the copper wire was observed to occur at the interface between the rigid resin micro-pod and the conductive wire, as shown in Figure 1c. Significant damage to the copper wire may also lead to electrical failure prior to breakage. Thus, the E-yarn structure must be designed appropriately to avoid any premature failures.

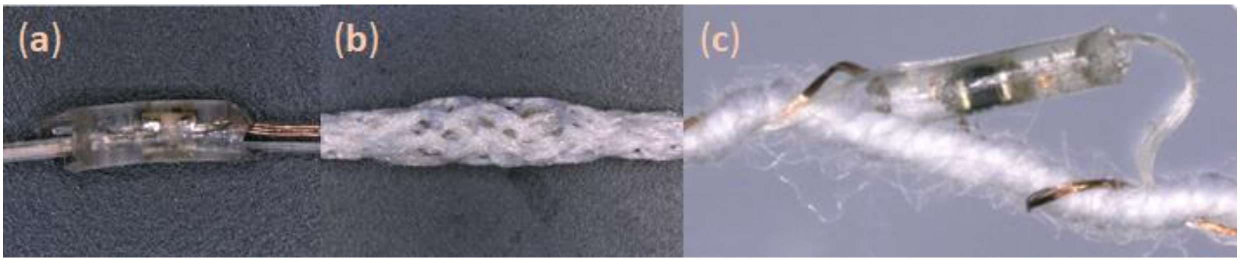

Figure 1. Microscope images of E-yarns. (**a**) The core structure of the E-yarn, including the conductive wire, the soldered component, and the supporting yarn. (**b**) The final E-yarn. (**c**) Image showing the failure of the conductive wire at the micro-pod interface after a wash test.

Different designs of E-yarn will use components with different geometries and the number and locations of the conductive wires in the core structure of the E-yarn depend on the component's connections. A different layout would lead to a different distribution of mechanical stresses and influence the failure mode. This study assessed the single lap joint soldering structure used to solder two-terminal surface mount devices such as LEDs and thermistors [6,7,9].

To understand the stresses on the core of the E-yarn, the structure was modelled using Finite-Element Analysis (FEA). A single-lap joint structure was used to assess the shear strength of the adhesives [10,11]. The mechanical loads transferred into the solder joints due to axial loading would result in shear stresses and bending moments that would result in the debonding of the solder pads of the component [12,13].

Understanding the distribution of mechanical stress within the core structure would help to improve the encapsulation process for the E-yarn and increase the reliability of the resulting yarn. This study will discuss the effect of adding the resin micro-pod around the electronic component on the mechanical stresses transferred into the solder joints of the core structure of the E-yarn.

2. Materials and Methods

2.1. Tensile Tests

The tensile results of the core structure were obtained using Zwick/Roell 2.5 tensile tester (Ulm, Germany) to evaluate the physical properties of the core structure before and after encapsulation (3 mm length micro-pod using Dymax 9001v3.5; Torrington, CT, USA). The tests were conducted using LEDs (Kingbright KPHHS-1005SURCK: New Taipei City, Taiwan) soldered onto copper wire (7-strand copper wire, 50 µm wire diameter: Knight Wire, Potters Bar, UK); 50 mm copper wire lengths and a test speed of 200 mm/min were used. The tests were conducted without a supporting yarn to evaluate the effect of adding only the micro-pod.

2.2. Computer Model of the Core E-Yarn Structure

A simplified 3D geometry was designed using Autodesk Inventor (Autodesk, Mill Valley, CA, USA). Models were prepared to simulate a $0.5 \times 0.5 \times 1.0$ mm component that was soldered onto a copper wire with a diameter of 0.15 mm. A second model represented the same soldered component encapsulated in a resin micro-pod. The 3D models were then used for finite-element static analysis using 'Ansys workbench 2021R1' (Ansys, Inc., Canonsburg, PA, USA). A static analysis was conducted to analyze the stress distribution in the single-lap joint of the electronic component soldered onto the copper wires. The analysis calculated the overall stresses at each element based on the von-mises criterion, shear stresses in the XZ (the plane parallel to the axis of the copper wire) direction, the highest stress in one of the principal directions at each element, and the highest shear stress at each element by plotting Mohr's circles at each element, using the principal stresses.

The following assumption was implemented to simplify the model:

- The solder joints' thickness was negligible.
- The copper wire was uniform and the physical properties of both the wire and the electronic component were homogenous.
- The applied load was axial to the wire's long axis, with deformation restricted in all other direction.
- Bonding between the conductive wire, the resin, and the contact was assumed to be perfect. No separation was assumed to occur under loading.
- The axial displacement of the fiber was assumed to be independent of the radius of the fiber.

3. Results

These tensile results showed that failure occurred 3.0 N before encapsulation, while after encapsulation failure occurred at 3.5 N, showing an improvement in the tensile strength after adding the resin micro-pod. Figure 2 shows tensile testing results for soldered LEDs before and after encapsulation.

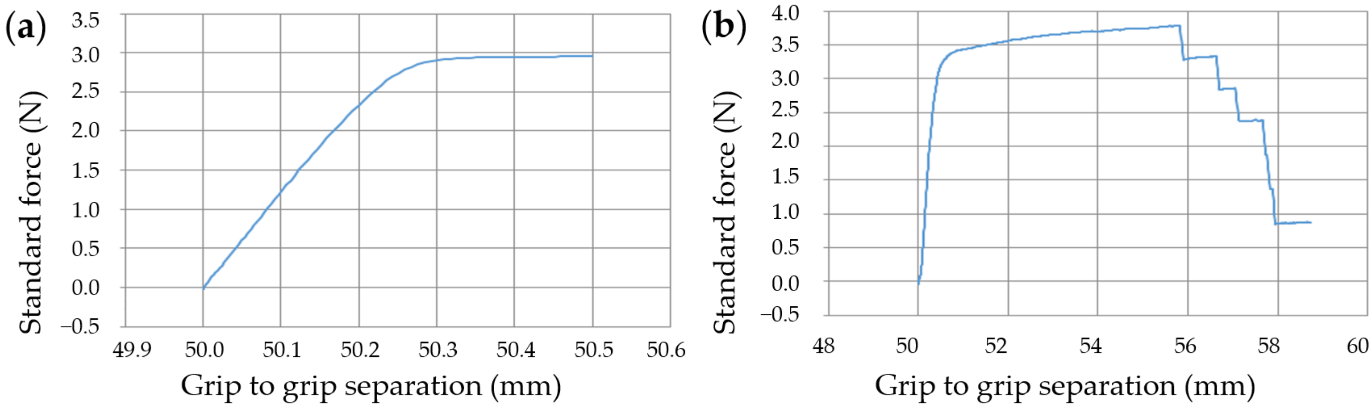

Figure 2. Tensile test results of the core structure of the E-yarn: (**a**) before encapsulation; (**b**) after encapsulation.

The results of Finite-Element Analysis are shown in Figure 3.

Results from the model showed that adding the resin micro-pod reduced the maximum stress to which the wire and soldered components were subjected. Moreover, it can be seen from the analysis that adding the resin micro-pod would reduce the equivalent stresses transferred to the solder joints by 5.8%, in comparison to the stresses before encapsulation, while the maximum shear stresses were similarly reduced by 6.8%. These results are in line with empirical testing, which showed an increase in the total strength after adding the micro-pod to the core structure of the E-yarn.

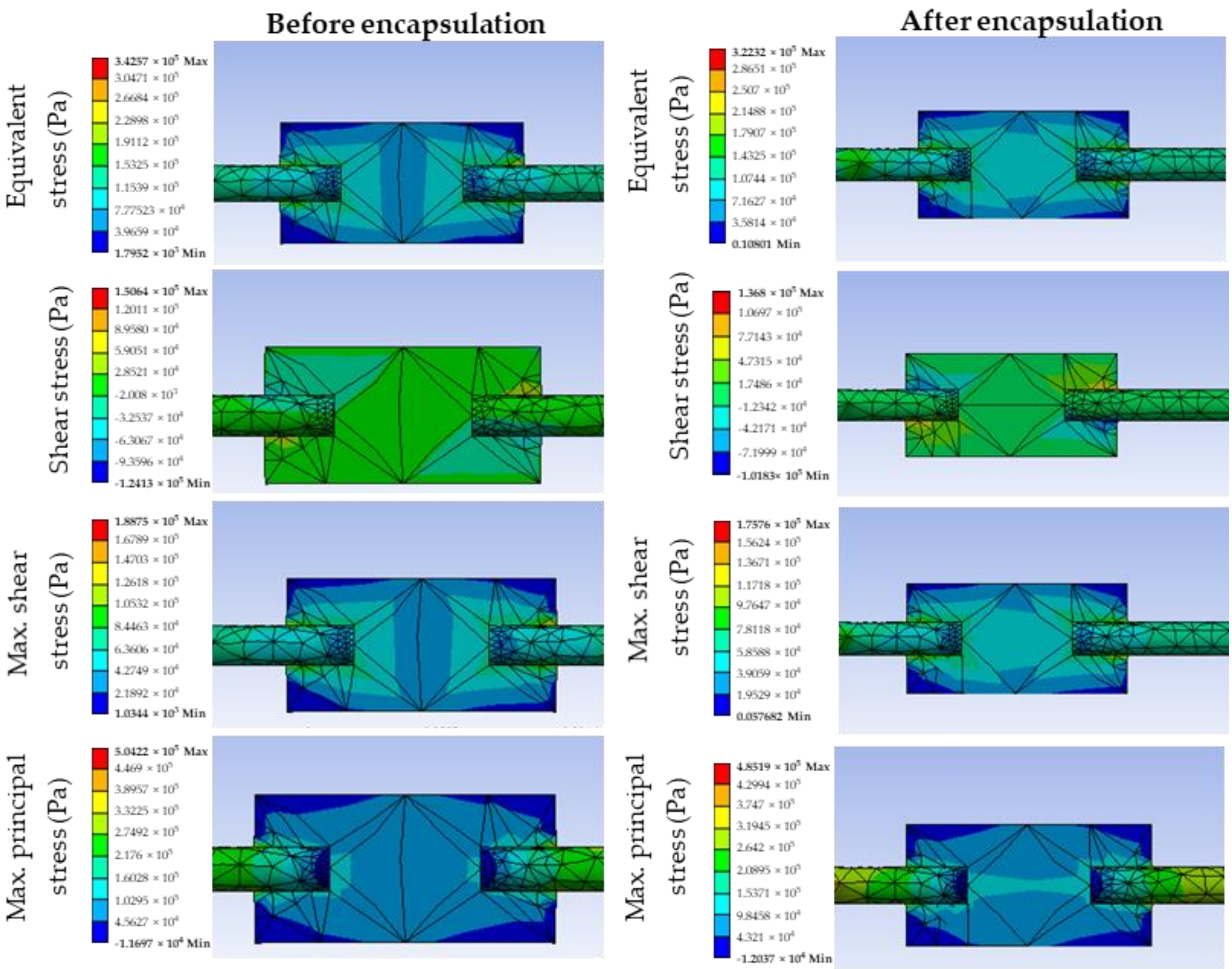

Figure 3. The results of the FEA for the core structure of the E-yarn. The figure shows the bottom view of the soldered components. Note that the micro-pod has been hidden for clarity.

4. Discussion and Conclusions

Adding a resin micro-pod to the single-lap joint structure resulting from the process of soldering a copper wire onto a component changed the distribution of stresses in the matrix. Failure of the interfacial bonds occurred when the shear strength of the structure, or the tenacity of the wire, are reached. The analysis showed that the maximum shear stress was near the ends of the solder joints. The tensile results showed an increase in the strength of the core structure by 16% in comparison to that before encapsulation. The FEA analysis results supported this.

FEA analysis is suitable for predicting the mechanical failure in E-yarns and can be extended for different arrangements and sizes of the component. It can also be used to evaluate different types of resin.

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