Laundering Electrically Conductive Fabrics for E Textile Applications

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Outline

Part I (by Weifeng Liu, Flex):
- Introduction to E Textiles
- Challenges with E Textiles
- Project Objectives
- Test Set up and Sample Preparation
- Test Results and Analysis
- Summary

Part II (by Jeffrey Lee, IST):
- Further Test Setup
- Test Results and Analysis
- Summary and Conclusions
- Future Work
Part I

Laundersing Test at Flex

Presenter: Weifeng Liu, PhD
E-textiles, also known as intelligent textiles, smart textiles, smart fabrics, smart garments, or smart clothing, are fabrics with electronics, sensors, and power sources embedded in them which provide electronics functionality and at the same time maintain textile characteristics.
Market for E Textiles

Cumulative Wearable Device Shipments by Device Category, World Markets: 2013-2020

*Smart Clothing Market Analysis, UC Berkley
Challenging for E Textiles Adoption

- Lack of obvious use cases
- Lack of awareness for consumers

*Smart Clothing Market Analysis, UC Berkley*
Technical Challenges with E Textiles

- **Business**: Infrastructure and eco system, Integration of industries...
- **Electronics design**: Performance and functionality...
- **Component**: Miniaturization, power consumption...
- **Power supply**: Energy density and capacity, energy harvesting...
- **Component integration**: Process, invisibility...
- **Reliability**: Flexibility, stretchability, *Washability (launderability)*...
- **Comfort**: Thermal, mechanical, psychological...
- **Health and safety**: Fire, radiation, biocompatibility...
- **Environment**: Recyclability...
- **Standardization**: Evaluation and testing...
Challenges on Launderability of E Textiles

- **Chemical**
  - Water
  - Impurities
  - Detergent
  - Bleach
  - Softener
- **Mechanical**
  - Water flow
  - Abrasion
  - Agitation
  - Tumbling
  - Crumpling
  - Torsion
  - Bending/folding
- **Thermal**
  - Temperature
  - Temp. swing
Further Challenges with E-Textile Launderability

- Limited studies on e textile launderability

- Lack of knowledge on e textile behavior during washing and drying cycles
  - What are the factors affecting the e textile launderability performance?
  - What are the mechanisms causing the degradation of e textile materials during laundry (e.g. metal leach into water)
  - What are the design rules to make e textiles robust and laundry proof?

- Lack of standardization (test coupon design, test conditions, cycles, acceptance criteria)
  - New requirements on e textiles as compared to traditional textiles
Project Objective and Plan

- **Project Objective**
  - Obtain first hand understanding of the behavior and performance of conductive materials, coatings and encapsulants of e-textiles during laundry

- **Project Plan**
  - Select conductive materials, coatings and encapsulation materials
  - Design and fabricate the test vehicles
  - Perform the washability testing
  - Perform electrical resistance measurement before and after laundry cycles
  - Perform material inspection and failure analysis
Materials Evaluated

- Conductive material
  - Conductive yarn
  - **Conductive fabric**
  - Conductive ink
- Encapsulation and coating
  - Water resistant coating
  - Dielectric ink printing
  - Thermoplastic urethane (TPU) lamination
- Material characterization
  - Electrical resistance measurement: 4 wire Kelvin method (before and after each laundry cycle)
  - Electrical measurement directly on fabric/yarn/ink or mechanical fastener (like snap button) or conductive adhesive
  - Optical and SEM inspection
Laundry Equipment and Conditions

Washing Condition (Normal, tap cold water, 50 minutes per cycle)

Drying Condition (Normal, 30 minutes per cycle)

Liquid detergent

Laundry bag
Launderability of Conductive Fabrics

Evaluated four types of conductive fabrics:
- Ripstop silver fabric (woven fabric, silver coated nylon yarn)
- Ni-Co conductive fabric (woven fabric, Multiple layer metal coated polyester yarn)
- Copper polyester taffeta fabric (woven fabric, copper coated polyester yarn)
- Nickel ripstop fabric (woven fabric, copper/nickel coated polyester yarn)
Launderability of Conductive Fabrics

- **Sample preparation**
  - Fraying or loosening of edge of fabrics during laundry
    - Conductive fabrics laminated to TPU with glue applied to secure the fabric edges
  - Four configurations of samples
    - Lamination to Denim (semi flex cloth patch): with/without water resistance coatings
    - Laminated to Spandex (soft cloth): uncoated fabrics
    - Lamination to denim with TPU as encapsulant: uncoated fabrics
    - Lamination to denim then clamped to rigid board: uncoated fabrics
Analysis of Launderability Study

- 10 cycles of washing and drying performed

- Resistance of the conductive fabrics shows increase with laundry cycles. The level of increase depends on the type of fabric:

- With water resistance coatings, resistance of the conductive fabrics continue to show increase with laundry cycles
  - Coating#2 shows certain improvement, especially with Ni-Co and copper fabrics
Copper conductive fabric laminated to semi-flex substrate (Denim) after 10 laundry cycles
SEM Inspection after Laundry

Nickel/Cobalt conductive fabric laminated to semi-flex substrate (Denim) after 10 laundry cycles

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<tr>
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<td>Cu</td>
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<td>P</td>
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<tr>
<td>Ni</td>
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<td>25.46</td>
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<tr>
<td>Cu</td>
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</table>
SEM Inspection after Laundry

Nickel conductive fabric laminated to semi-flex substrate (Denim) after 10 laundry cycles

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<td>O K</td>
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<td>Al K</td>
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<tr>
<td>Cl K</td>
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<td>Ni K</td>
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<td>Cu K</td>
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<tr>
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<tr>
<td>O K</td>
<td>27.69</td>
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<td>Totals</td>
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SEM Inspection after Laundry

Silver conductive fabric laminated to semi-flex substrate (Denim) after 10 laundry cycles

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<tr>
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<td>48.57</td>
<td>68.31</td>
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<tr>
<td>N K</td>
<td>22.38</td>
<td>26.99</td>
</tr>
<tr>
<td>Cl K</td>
<td>0.48</td>
<td>0.23</td>
</tr>
<tr>
<td>Ag L</td>
<td>28.57</td>
<td>4.47</td>
</tr>
<tr>
<td>Totals</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight%</th>
<th>Atomic%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C K</td>
<td>50.02</td>
<td>70.15</td>
</tr>
<tr>
<td>N K</td>
<td>17.94</td>
<td>21.57</td>
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<tr>
<td>O K</td>
<td>3.65</td>
<td>3.84</td>
</tr>
<tr>
<td>Ag L</td>
<td>28.39</td>
<td>4.43</td>
</tr>
<tr>
<td>Totals</td>
<td>100.00</td>
<td></td>
</tr>
</tbody>
</table>
Analysis of Launderability Study

- Based on the test results and SEM inspection, a hypothesis was gradually formed: the increase in electrical resistance of the conductive fabric is mainly caused by fracture and loss of metal coatings on the yarn fibers, which is caused by the dynamic mechanical stresses during washing and drying.

- If the mechanical stresses are minimized, what will happen to the conductive fabrics?

Conductive Fabrics Laminated to Different Substrates
(Spandex, Denim with TPU encapsulation, Rigid board)
Analysis of Launderability Study

- **Performance ranking in general:**
  - Fabric clamped to rigid board > Fabric laminated to soft substrate > Fabric laminated to semi-flex substrate

- The results confirm our initial hypothesis that mechanical stresses during laundry cause fracture and loss of metal coatings on the yarn fibers, leading to increase in electrical resistance
  - When there is no mechanical stress to fold or bend the conductive fabrics, their resistances remain stable
Analysis of Conductive Fabrics after Laundry

- No evidence of metal coating fracture and corrosion observed for the Ni-Co, copper and nickel conductive fabrics clamped to the rigid boards
- Some damage observed on the silver conductive fabrics clamped to the rigid board, however, it has not caused an obvious increase in resistance.
Launderability of Conductive Yarns

- Evaluated three types of conductive yarns
  - #1: silver coated nylon yarn
  - #2: copper/nickel/silver coated LCP yarn
  - #3: silver coated aramid yarn
- Sample preparation
  - Three types of water resistant coatings (yarns dipped in coating solutions and heat treated at 115°C)
  - The yarns permanently secured to denim patches through lamination of TPU strips or TPU lamination as encapsulant (laminated at 160°C)
  - Silver conductive adhesives dispensed on the ends of yarns to make test points
Launderability of Conductive Yarns

- In general, resistance of the yarns increases with washing/drying cycles
  - Yarn#1 performs the best, yarn#2 performs similar to Yarn#1 with exception of one yarn, yarn#3 shows an excessive increase in resistance
- Resistance continues to show increase even with water resistance coatings and TPU lamination
  - No consistent improvement observed as compared to untreated yarns
Launderability of Conductive Yarns

The resistance performance of the yarns depends on the mechanical integrity of the yarns during launder: the yarn with fibers maintaining bundled state shows stable resistance.
Launderability of Conductive Ink

• **Materials evaluated**
  - Silver conductive ink and AgCl electrode printed on TPU film
  - A dielectric ink printed over the silver conductive ink

• **Test vehicles**
  - Conductive ink printed on TPU then laminated on spandex
  - Conductive ink printed on TPU, laminated to denim patch and then clamped on a rigid board
Launderability of Conductive Ink

- The conductive ink with minimal mechanical stress during laundry shows stable resistance.
Summary

• Laundry testing performed on conductive materials for e-textile applications, including conductive yarns, conductive fabrics and conductive ink
  ▪ Effect of water resistant coatings and TPU lamination on the conductive materials evaluated.

• In general, the conductive materials show increase of resistance with laundry cycles. The extent of the increase depends on the material type, metal coating, the substrates to which fabrics are attached.
  • It is hypothesized and confirmed that mechanical stresses experienced by the conductive materials during laundry play a dominant role causing the damages to the metal coating layers of the fabric fibers, leading to resistance increase or even open circuit.
  • The substrates to which the conductive materials are attached significantly impact the performance of the conductive materials during laundry. A substrate that can minimize the mechanical stresses imposed on the conductive materials will ensure the integrity of the materials and stability of their electrical resistances.
  • No obvious evidence of metal corrosion/leach caused by the current household detergent observed for the current laundry conditions.

• Water resistance coatings and TPU lamination do not show a consistent improvement, since they may not provide adequate mechanical reinforcement to the conductive materials.
Part II

Laundering Test at IST: Independent Lab

Presenter: Jeffrey Lee
Project Objectives

• Confirmation of prior test results through independent lab

• Further examination of certain factors on the conductive fabric launderability
  ▪ Test equipment (use of AATCC certified washer and dryer)
  ▪ Detergent (use of AATCC certified detergent)
  ▪ Metal coating metallurgy
Test Flow

Sample Preparation → Resistance Measurement → Laundering Test → Resistance Measurement

Material Analysis

SEM

X-S (metal thickness)

Low Scan Angle XRD

Summary & Conclusion
Test Equipment and Conditions

• Washer: SDL Atlas Vortex M6
• Washing parameters
  – Temperature: 30°C
  – Water level: 19 gal
  – Agitation/Spin speed: 120 spm
  – Duration: 33 mins. (whole cycle from water filling to finish spinning)

• Dryer: SDL Atlas Vortex M6D (designed to pair with washer)
• Drying parameters
  – Temperature: 68°C
  – Duration: 30 mins

• Detergent: AATCC 1993 Standard Reference Detergent without brightener
  – Contains Sodium Aluminosilicate, Sodium Sulfate, Sodium Alkylbenzene Sulfonate, Sodium Carbonate, Sodium Polyacrylate
  – Amount: 66g, as prescribed by AATCC methods
Sample Preparation

- Conductive materials procured from lessemf
- TPU (Bemis 3206) used to laminate conductive materials to supporting fabrics
- Three types of supporting fabrics (from left to right in the picture): Nylon (soft), Spandex (soft), Denim (semi rigid)
Sample Description: Conductive Fabrics

- Four types of conductive fabrics (Same as in Part I)
- Sample dimension: 3 x 10 (cm)

<table>
<thead>
<tr>
<th>Conductive Fabric Product name (Less EMF)</th>
<th>Nickel/Copper Ripstop Fabric (Ni)</th>
<th>Cobaltex (NiCo)</th>
<th>Ripstop Silver Fabric (Ag)</th>
<th>Pure Copper Polyester Taffeta (Cu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>Polyester</td>
<td>Polyester</td>
<td>Nylon</td>
<td>Polyester</td>
</tr>
<tr>
<td>Conductor</td>
<td>Nickel/Copper coating</td>
<td>Nickel- Cobalt/Nickel/Copper coated</td>
<td>Silver plated</td>
<td>Copper plated</td>
</tr>
<tr>
<td>Resistivity</td>
<td>0.03 Ohm/sq</td>
<td>&lt; 0.1 Ohm/sq</td>
<td>&lt;0.25 Ohm/sq</td>
<td>0.05 Ohm/sq</td>
</tr>
<tr>
<td>Metal Thickness</td>
<td>0.08mm (3 mil)</td>
<td>0.08 mm (3 mil)</td>
<td>0.05 mm (2 mil)</td>
<td>0.08mm (3 mil)</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-40°C to 150°C, up to 200°C short term</td>
<td>N/A</td>
<td>-30°C to 90°C temperature range</td>
<td>-40°C to 150°C, up to 200°C short term</td>
</tr>
<tr>
<td>Manufacturer recommendation</td>
<td>Do not wash or dry clean. Dry brush or wipe only. Do not iron</td>
<td>N/A</td>
<td>Hand washable</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Sample Description – Supporting Fabrics

- Three types of supporting fabrics
- Supporting fabric dimension: 10 x 12 (cm)

| Fabric Type   | Spandex                  | Nylon  
(Spandex 18%) | Denim  |
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>Black</td>
<td>Light blue</td>
<td>Blue</td>
</tr>
<tr>
<td>Texture</td>
<td>Soft</td>
<td>Soft</td>
<td>Hard</td>
</tr>
<tr>
<td>Elasticity</td>
<td>Elastic (10cm→17cm)</td>
<td>Very Elastic (10cm→19cm)</td>
<td>Inelastic (almost no change)</td>
</tr>
</tbody>
</table>

![Spandex](image1)
![Nylon](image2)
![Denim](image3)
Sample Description – TPU

- Tested different TPU from Bemis to confirm the best option for laminating conductive fabrics to supporting fabrics

<table>
<thead>
<tr>
<th>TPU Number</th>
<th>3206 (final choice)</th>
<th>3412</th>
<th>3829</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer</td>
<td>Single layer</td>
<td>Single layer</td>
<td>Single layer</td>
</tr>
<tr>
<td>Brand</td>
<td>Sewfree</td>
<td>Sewfree</td>
<td></td>
</tr>
<tr>
<td>Fabrics (Woven, nonwoven, knits, felts)</td>
<td>Denim (Cotton)</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td></td>
<td>Nylon</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Spandex (Nylon/Lycra)</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Glue line temperature range</td>
<td>120°C~130°C</td>
<td>150°C~170°C</td>
<td></td>
</tr>
<tr>
<td>Softening point</td>
<td>75°C</td>
<td>115°C</td>
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</tr>
<tr>
<td>Recovery</td>
<td>90%</td>
<td>99%</td>
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</tr>
<tr>
<td>Home Laundering</td>
<td>Up to 40°C</td>
<td>Up to 60°C</td>
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</table>
TPU Test Results

• TPU adhesion starts to show difference after two times of laundering and drying

• Bemis 3206 showed the best performance among the fabrics, does not detach from either Spandex or Denim fabrics

3206 shows strong bonding with supporting fabrics

3412 on Spandex fabric can be peeled off by hand

3829 detached from Denim fabric after washing and can be peeled off by hand from Spandex fabric
# Sample Test Matrix

<table>
<thead>
<tr>
<th>Conductive Fabric</th>
<th>Support Material</th>
<th>Sample size</th>
<th>Wash (X1, X3, X5, X7, X10)</th>
<th>OM + Resistance</th>
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<tbody>
<tr>
<td>Ni</td>
<td>Spandex</td>
<td>1</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Ni</td>
<td>Nylon</td>
<td>1</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Ni</td>
<td>Denim</td>
<td>1</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Ni-Co</td>
<td>Spandex</td>
<td>1</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Ni-Co</td>
<td>Nylon</td>
<td>1</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Ni-Co</td>
<td>Denim</td>
<td>1</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Ag</td>
<td>Spandex</td>
<td>1</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Ag</td>
<td>Nylon</td>
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<td>√</td>
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<tr>
<td>Ag</td>
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<td>Cu</td>
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<td>Cu</td>
<td>Nylon</td>
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<td>√</td>
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<tr>
<td>Cu</td>
<td>Denim</td>
<td>1</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>
Resistance Measurement

• After taking sample out from the drying machine, leave the sample for one night before monitoring the resistance.
• Test probes are placed perpendicular to the sample surface.
  – HioKi Ohmmeter RM3544 was used for the measurement with 1 μΩ max. resolution.
  – Four point Kevin method for resistance measurement.
• After the probes are contacted to the sample surface, wait for 10 seconds before reading the resistance; if the resistance is not stable, record the range of resistance in the first 10 seconds.
Resistance Measurement

Length of conductive fabrics: 10 cm
Length of supporting fabrics: 12 cm

Width of supporting fabrics: 5 cm
Width of conductive fabrics: 3 cm

- Each sample has two measurement positions, one is diagonal (red circle), the other one is horizontal (yellow circle)
- Resistance measurement for both measurement positions are recorded
## Summary Of Test Results

<table>
<thead>
<tr>
<th>Number</th>
<th>Conductive Fabric</th>
<th>Support Material</th>
<th>Resistance before Washing</th>
<th>Resistance after 1st Washing</th>
<th>Resistance after 3rd Washing</th>
<th>Resistance after 5th Washing</th>
<th>Resistance after 7th Washing</th>
<th>Resistance after 10th Washing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ni</td>
<td>Spandex</td>
<td>Diagonal 170 mΩ</td>
<td>221mΩ</td>
<td>360mΩ</td>
<td>1.24Ω</td>
<td>1.08~1.1Ω</td>
<td>4~4.5Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal 154.5 mΩ</td>
<td>170mΩ</td>
<td>282mΩ</td>
<td>1Ω</td>
<td>1.02~1.03Ω</td>
<td>11.3~12Ω</td>
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<tr>
<td>2</td>
<td>Ni</td>
<td>Nylon</td>
<td>Diagonal 175 mΩ</td>
<td>208mΩ</td>
<td>280mΩ</td>
<td>421mΩ</td>
<td>840~860 mΩ</td>
<td>7Ω</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal 140 mΩ</td>
<td>179mΩ</td>
<td>256mΩ</td>
<td>394mΩ</td>
<td>915~935mΩ</td>
<td>8~8.2Ω</td>
</tr>
<tr>
<td>3</td>
<td>Ni</td>
<td>Denim</td>
<td>Diagonal 180 mΩ</td>
<td>220mΩ</td>
<td>1.38Ω</td>
<td>23~28Ω</td>
<td>42~47Ω</td>
<td>820Ω~1Ω</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal 162 mΩ</td>
<td>172mΩ</td>
<td>1.24Ω</td>
<td>21.8~22Ω</td>
<td>45~51Ω</td>
<td>980~840Ω</td>
</tr>
<tr>
<td>4</td>
<td>Ni-Co</td>
<td>Spandex</td>
<td>Diagonal 252 mΩ</td>
<td>359mΩ</td>
<td>557mΩ</td>
<td>678mΩ</td>
<td>1~1.2 Ω</td>
<td>1.07Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal 247 mΩ</td>
<td>298mΩ</td>
<td>465mΩ</td>
<td>548mΩ</td>
<td>670 mΩ</td>
<td>980mΩ~1Ω</td>
</tr>
<tr>
<td>5</td>
<td>Ni-o</td>
<td>Nylon</td>
<td>Diagonal 229 mΩ</td>
<td>404mΩ</td>
<td>561mΩ</td>
<td>1.41Ω</td>
<td>1.92Ω</td>
<td>4.6Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal 210 mΩ</td>
<td>360mΩ</td>
<td>580mΩ</td>
<td>1.47Ω</td>
<td>1.57Ω</td>
<td>2.2Ω</td>
</tr>
<tr>
<td>6</td>
<td>Ni-Co</td>
<td>Denim</td>
<td>Diagonal 250 mΩ</td>
<td>500mΩ</td>
<td>1.08Ω</td>
<td>16.3Ω</td>
<td>28~30Ω</td>
<td>57~60Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal 210 mΩ</td>
<td>470mΩ</td>
<td>954mΩ</td>
<td>15~15.4Ω</td>
<td>23.5Ω</td>
<td>66~70Ω</td>
</tr>
<tr>
<td>7</td>
<td>Ag</td>
<td>Spandex</td>
<td>Diagonal 1.69Ω</td>
<td>1.67Ω</td>
<td>2.097Ω</td>
<td>2.11Ω</td>
<td>2.35Ω</td>
<td>2.54Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal 1.29 Ω</td>
<td>1.39Ω</td>
<td>1.74Ω</td>
<td>1.8Ω</td>
<td>2.01Ω</td>
<td>2.14Ω</td>
</tr>
<tr>
<td>8</td>
<td>Ag</td>
<td>Nylon</td>
<td>Diagonal 1.65 Ω</td>
<td>1.76Ω</td>
<td>2.17Ω</td>
<td>2.24Ω</td>
<td>2.5Ω</td>
<td>2.6Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal 1.35 Ω</td>
<td>1.38Ω</td>
<td>1.81Ω</td>
<td>1.86Ω</td>
<td>2.02Ω</td>
<td>2.07Ω</td>
</tr>
<tr>
<td>9</td>
<td>Ag</td>
<td>Denim</td>
<td>Diagonal 1.59 Ω</td>
<td>1.69Ω</td>
<td>2.48Ω</td>
<td>3.18Ω</td>
<td>4.05Ω</td>
<td>3.11Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal 1.23 Ω</td>
<td>1.43Ω</td>
<td>2.04Ω</td>
<td>2.65Ω</td>
<td>3.1Ω</td>
<td>3.04Ω</td>
</tr>
<tr>
<td>10</td>
<td>Cu</td>
<td>Spandex</td>
<td>Diagonal 213 mΩ</td>
<td>635mΩ</td>
<td>316Ω</td>
<td>1.55 KΩ</td>
<td>900 mΩ~1Ω</td>
<td>960~980Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal 193 mΩ</td>
<td>576mΩ</td>
<td>380Ω</td>
<td>680~720Ω</td>
<td>590~730Ω</td>
<td>1.1~1.3KΩ</td>
</tr>
<tr>
<td>11</td>
<td>Cu</td>
<td>Nylon</td>
<td>Diagonal 209 mΩ</td>
<td>322mΩ</td>
<td>149Ω</td>
<td>680~730Ω</td>
<td>620~720Ω</td>
<td>1.2~1.23KΩ</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal 167 mΩ</td>
<td>315mΩ</td>
<td>178Ω</td>
<td>235.5Ω</td>
<td>550~600Ω</td>
<td>1.8KΩ</td>
</tr>
<tr>
<td>12</td>
<td>Cu</td>
<td>Denim</td>
<td>Diagonal 232 mΩ</td>
<td>452mΩ</td>
<td>1.16kΩ</td>
<td>2.4~2.7KΩ</td>
<td>4.2KΩ</td>
<td>6.3KΩ</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal 171 mΩ</td>
<td>405mΩ</td>
<td>1.1kΩ</td>
<td>3.5~3.7KΩ</td>
<td>3.2KΩ</td>
<td>4.3KΩ</td>
</tr>
</tbody>
</table>
Resistance Change during Laundry

**Ni Fabrics**

<table>
<thead>
<tr>
<th>Resistance before Washing</th>
<th>Resistance after 1st Washing</th>
<th>Resistance after 3rd Washing</th>
<th>Resistance after 5th Washing</th>
<th>Resistance after 7th Washing</th>
<th>Resistance after 10th Washing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Resistance (mΩ)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Spandex-Diagonal**
- **Spandex-Horizontal**
- **Nylon-Diagonal**
- **Nylon-Horizontal**
- **Denim-Diagonal**
- **Denim-Horizontal**

Denim Supporting fabric
Resistance Change during Laundry

Ni-Co Fabrics

Electrical Resistance (mΩ)

Resistance before Washing
Resistance after 1st Washing
Resistance after 3rd Washing
Resistance after 5th Washing
Resistance after 7th Washing
Resistance after 10th Washing

Denim Supporting fabric

Spandex-Diagonal
Spandex-Horizontal
Nylon-Diagonal
Nylon-Horizontal
Denim-Diagonal
Denim-Horizontal

Spandex-Diagonal
Spandex-Horizontal
Nylon-Diagonal
Nylon-Horizontal
Denim-Diagonal
Denim-Horizontal

0
1000
2000
3000
4000
5000
6000
Resistance Change during Laundry

Ag Fabrics

Electrical Resistance (mΩ)

- Spandex-Diagonal
- Spandex-Horizontal
- Nylon-Diagonal
- Nylon-Horizontal
- Denim-Diagonal
- Denim-Horizontal

Resistance before Washing
Resistance after 1st Washing
Resistance after 3rd Washing
Resistance after 5th Washing
Resistance after 7th Washing
Resistance after 10th Washing

Denim Supporting fabric
Resistance Change during Laundry

Cu Fabrics

Electrical Resistance (mΩ)

- Spandex-Diagonal
- Spandex-Horizontal
- Nylon-Diagonal
- Nylon-Horizontal
- Denim-Diagonal
- Denim-Horizontal

Denim Supporting fabric
Comparison between Conductive Fabrics

![Comparison of Conductive Fabrics](image)
Comparison between Supporting Fabrics

![Comparison of Substrate (Ag Fabric) graph](chart.png)

- Spandex
- Nylon
- Denim

Normalized Resistance vs. Laundry Cycle
Comparison between Supporting Fabrics

![Graph showing comparison of substrate (Ni-Co fabric) with normalized resistance across laundry cycles for Spandex, Nylon, and Denim.](image)
Comparison between Supporting Fabrics

![Graph showing comparison of substrate (Cu Fabric) over laundry cycles. The graph compares Spandex, Nylon, and Denim, with Spandex having the highest normalized resistance.](image)
Comparison between Supporting Fabrics

![Comparison of Substrate (Ni Fabric)](image-url)
Material Analysis: OM and SEM

- **3-D Optimal Microscope (OM)**

  **KEYENCE VHX-5000**
  - Magnification: 20X～1000X
  - Tilt Angle: 0°～60°
  - Rotation Angle: 180°
  - Size measurement

- **Scanning Electron Microscope (SEM)**

  **HITACHI Reglus 8240**
  - Electro Gun: Cold FE
  - Resolution: 0.7 nm (Accelerating Voltage 15 kV), 0.9 nm (Accelerating Voltage 1 kV)
  - Magnification: 20～1000k
  - Accelerating Voltage: 0.01～30kV
SEM Inspection (Before/After Laundry)

Before Laundry Test

After 10th Laundry Cycle

Magnification: x 500 times
Supporting material: Spandex
SEM Evaluation: metal coating thickness

Before Laundry Test

Cu
Thickness: 2.12~2.31um

Ag
Thickness: 139~218nm

Ni
Thickness: 0.992~1.32um

Ni-Co
Thickness: 0.661~1.06um

After 10th Laundry Cycle

Cu
Thickness: 1.92~1.98um

Ag
Thickness: 238~298nm

Ni
Thickness: 1.26~1.72um

Ni-Co
Thickness: 0.86~0.992um

• No obvious reduction of metal coating thickness after 10th laundry
Factors Affecting Fracture of Metal Coatings

- Laundry conditions
  - Method, Temp., water impurities, detergent, bleach, time...
- Supporting fabric/substrate
  - Semi rigid (Denim) versus soft (Spandex, Nylon)
- Metal coating thickness
<table>
<thead>
<tr>
<th>Metal Coating</th>
<th>Thickness (um)</th>
<th>Rf/R0 aft 10th Laundry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>0.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Cu</td>
<td>2</td>
<td>13300</td>
</tr>
<tr>
<td>Ni</td>
<td>1.5</td>
<td>1784</td>
</tr>
<tr>
<td>Ni-Co</td>
<td>1</td>
<td>96</td>
</tr>
</tbody>
</table>

- Metal material

<table>
<thead>
<tr>
<th>Metal</th>
<th>Modulus (Gpa)</th>
<th>Vickers Hardness (Mpa)</th>
<th>tensile strength(MPa)</th>
<th>Relative ductivity (Gold=1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>83</td>
<td>251</td>
<td>125</td>
<td>0.73</td>
</tr>
<tr>
<td>Cu</td>
<td>110</td>
<td>343</td>
<td>200</td>
<td>0.62</td>
</tr>
<tr>
<td>Ni</td>
<td>200</td>
<td>638</td>
<td>450</td>
<td>0.5</td>
</tr>
<tr>
<td>Co</td>
<td>209</td>
<td>1043</td>
<td>675</td>
<td>0.5</td>
</tr>
</tbody>
</table>

- Fiber polymer
- Bonding between metal and fiber
- Conductive fiber manufacturing process
  - Plating, coating, sputtering...
Conclusion and Summary

- Laundry test was performed at IST: an independent lab, to confirm the test results at Flex
  - Four conductive fabrics with different metal coatings (Ag, Ni, Cu and Ni-Co)
  - Three supporting fabrics: Nylon, Spandex and Denim
  - AATCC standard test equipment and detergent were used

- The IST test further confirms the test results and analysis by Flex
  - All the conductive fabrics see increase in electrical resistance during the laundry cycles
  - Conductive fabric metal coating:
    - Conductive fabric with silver coated fibers shows most stable resistance
    - Conductive fabric with copper coated fibers shows the worst performance
    - Metal coating fracture due to mechanical stresses during laundry are observed to cause the increase of resistance
    - No obvious metal coating thickness reduction observed, ruling out metal leach as a factor during laundry
  - Supporting fabric effect:
    - Conductive fabrics laminated to semi-rigid denim substrate show highest resistance increase as compared to soft substrate (nylon and spandex)
    - This further confirms the hypothesis in Part I that the substrates to which the conductive materials are attached significantly impact their performance during laundry
Future Work

• Continue launderability studies and understand effects of a variety of test parameters
  ▪ Test conditions: Temperature, detergent, bleach, softener, pH level……
  ▪ Effect of washing versus drying

• Continue the evaluation of different conductive materials and obtain deeper understanding of their performance and behavior
  ▪ Fiber materials and metal coatings
  ▪ Manufacturing processes: woven, knitting, embroidering, plating, printing

• Hope our work will help the e textile industries in:
  ▪ Better understanding the fundamentals of e textile launderability
  ▪ Guidance how to design more robust e textiles
  ▪ Standardization of e textile launderability testing
Acknowledgment

The authors would like to acknowledge the contributions from:

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• Bemis for TPU sample and hot press process guidelines
• Textile and Material Industrial Research Center, Feng Chia University Taiwan - for providing fabric samples
Thank You