Laundering Electrically Conductive Fabrics for E Textile Applications

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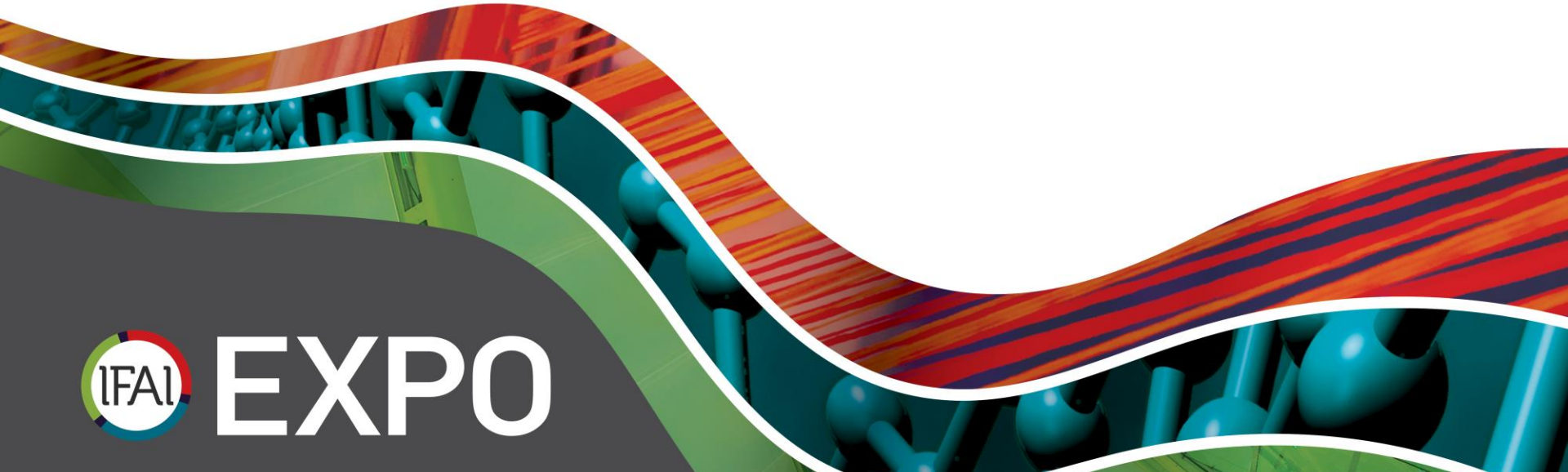


Outline

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

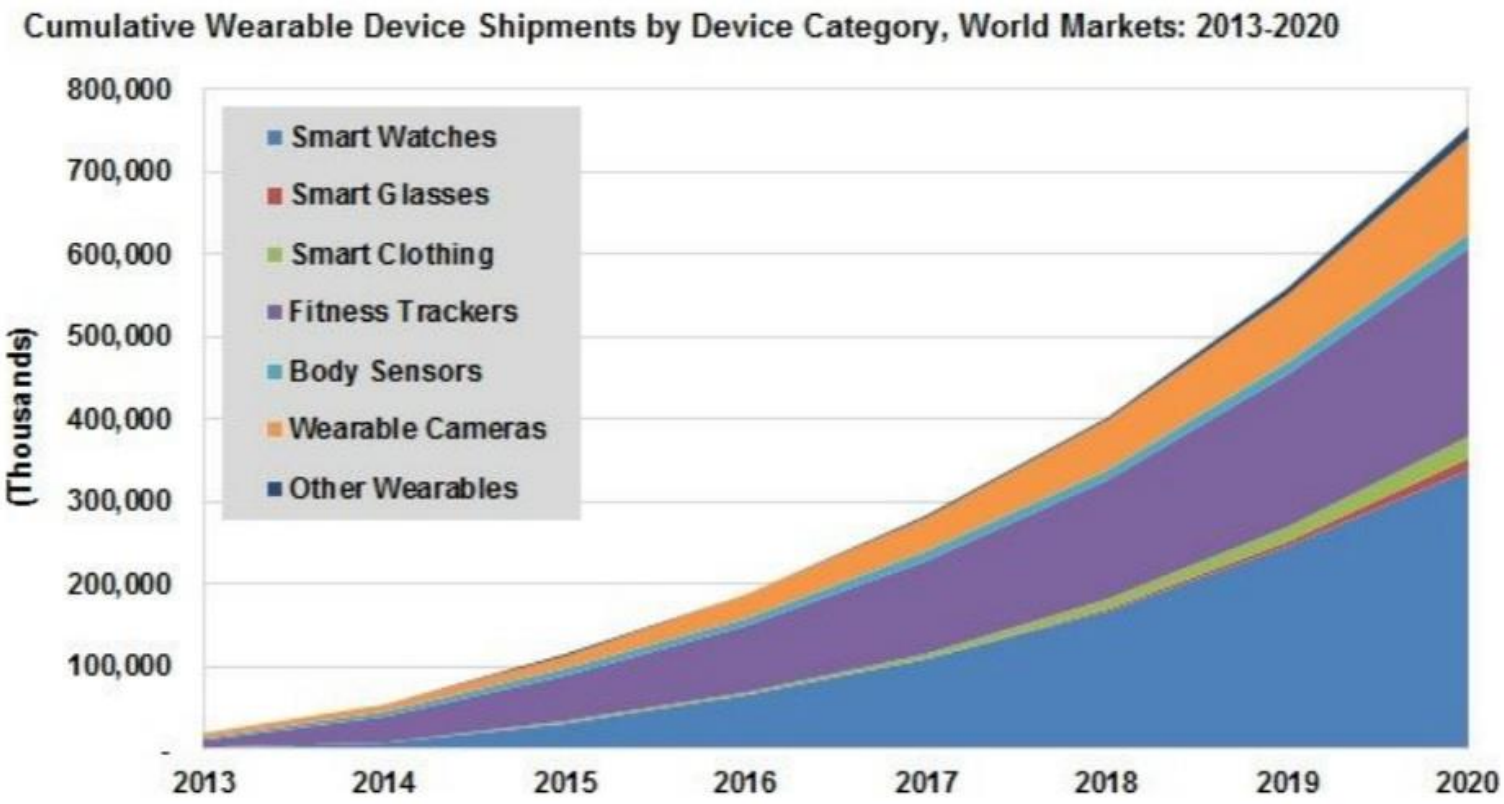
Laundering Test at Flex

Presenter: Weifeng Liu, PhD

Introduction to E Textiles

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

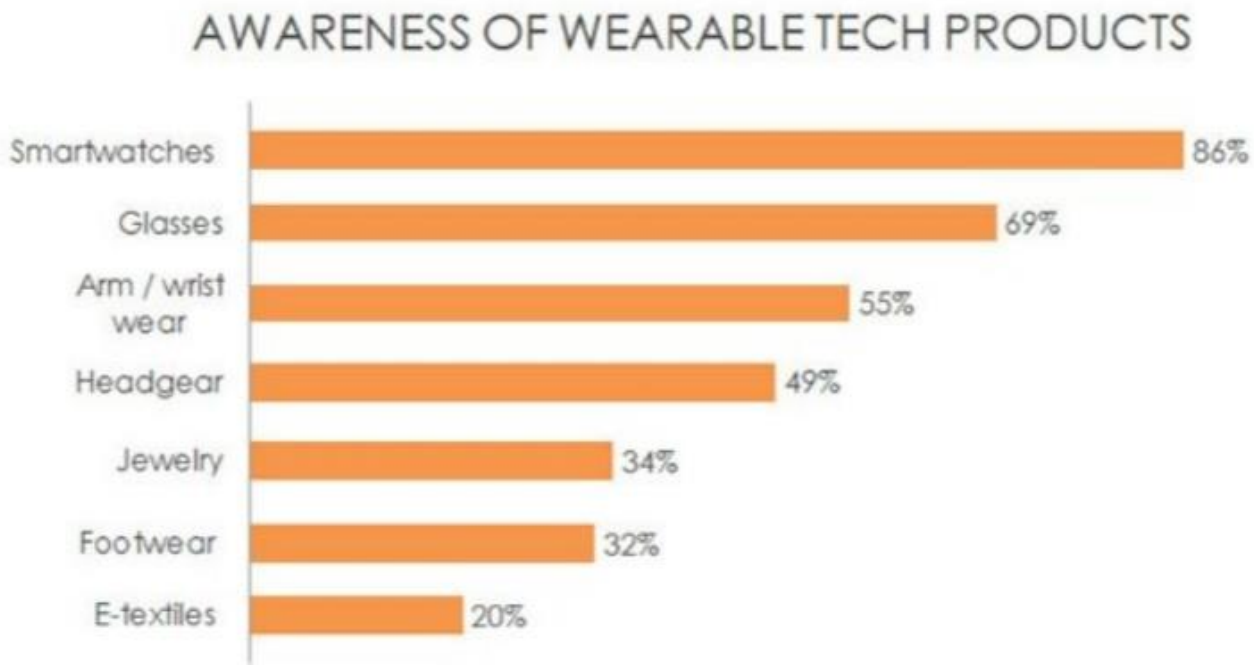
Market for E Textiles



*Smart Clothing Market Analysis, UC Berkley

Challenging for E Textiles Adoption

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



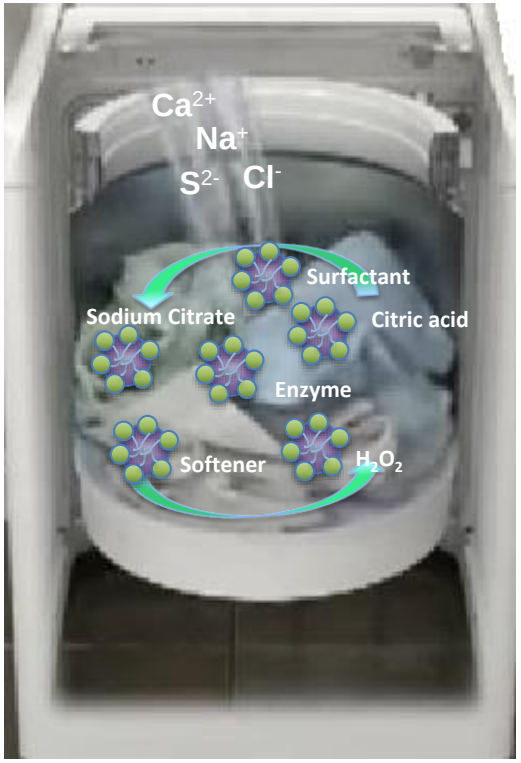
*Smart Clothing Market Analysis, UC Berkley

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)

Liquid detergent

Drying Condition (Normal, 30 minutes per cycle)

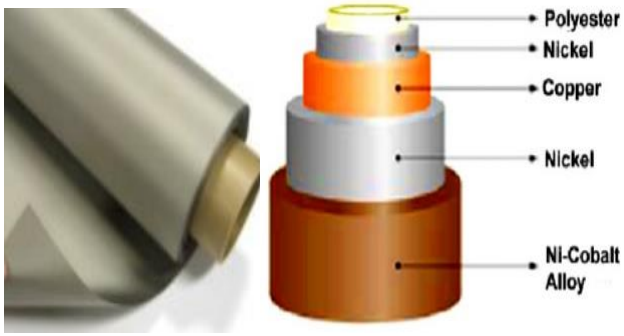
Laundry bag

Launderability of Conductive Fabrics

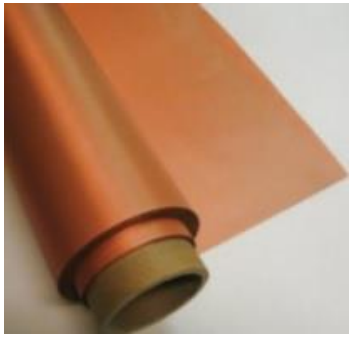
Evaluated four types of conductive fabrics:

- 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)

Silver fabric



NiCo fabric



Copper fabric

Nickel fabric

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

Conductive fabric laminated to denim patch

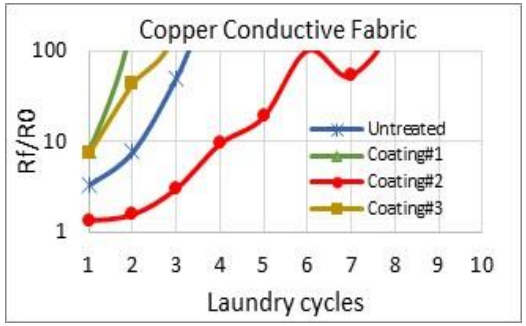
Conductive fabric laminated to denim patch with TPU film laminated as encapsulant

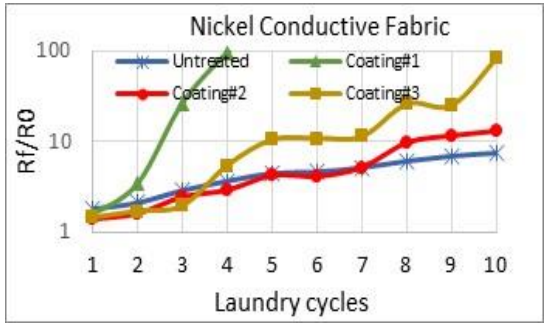
Conductive fabric laminated to denim patch then clamped on rigid board

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:
  - Performance ranking: Silver fabric>nickel fabric~cobalt fabric>copper 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

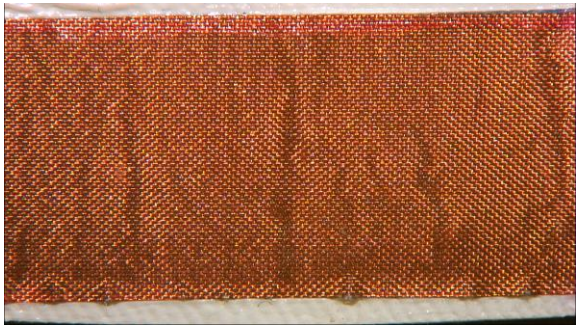
Conductive Fabrics Laminated to Semi-Flex Denim Substrates

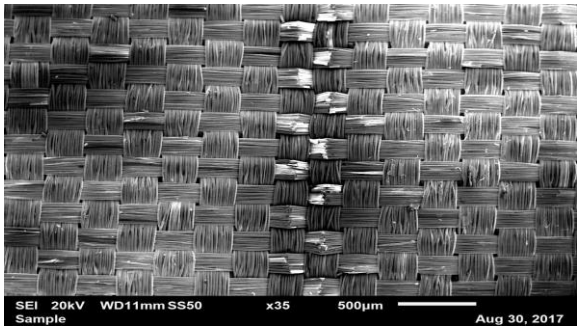


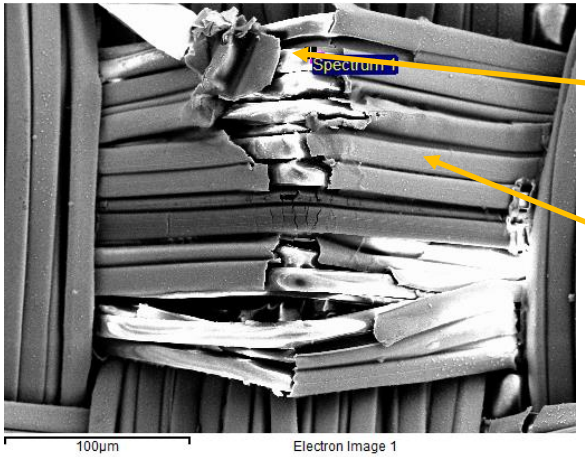


SEM Inspection after Laundry

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





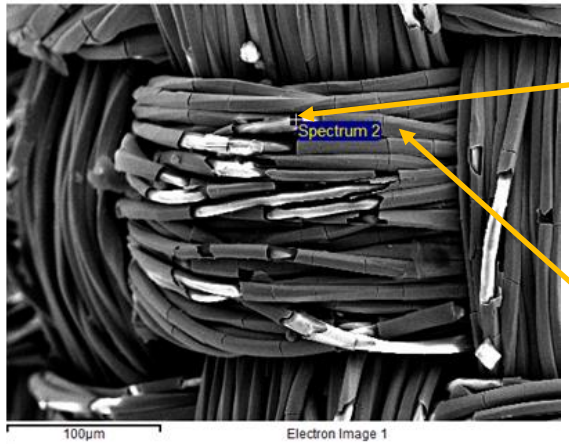


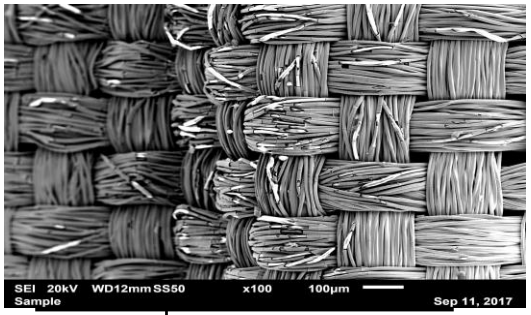
Element	Weight%	Atomic%
C K	67.46	73.84
O K	31.61	25.97
Cu K	0.93	0.19

Element	Weight%	Atomic%
C K	35.61	70.93
O K	4.25	6.35
Cl K	0.27	0.18
Cu K	59.87	22.54

SEM Inspection after Laundry

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





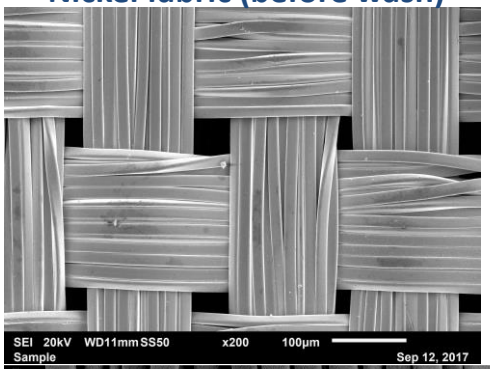
Element	Weight%	Atomic%
C K	74.13	80.43
O K	23.36	19.02
Ti K	0.21	0.06
Fe K	0.16	0.04
Ni K	1.01	0.22
Cu K	1.15	0.24
Totals	100.00	

Element	Weight%	Atomic%
C K	5.68	22.13
O K	1.72	5.02
P K	2.59	3.90
Fe K	7.47	6.25
Ni K	31.96	25.46
Cu K	50.58	37.23
Totals	100.00	

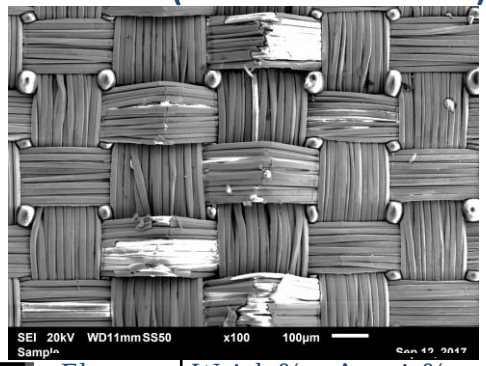
SEM Inspection after Laundry

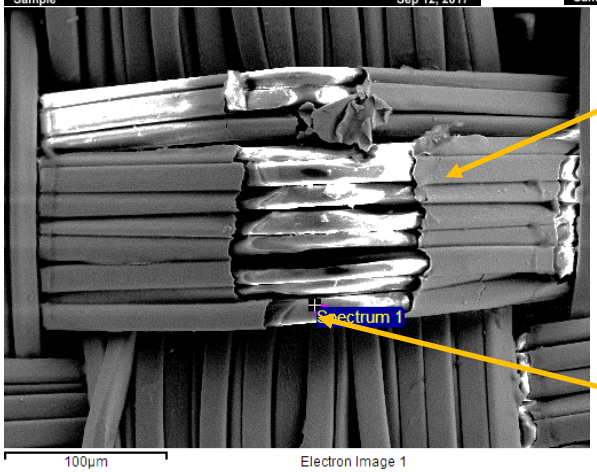
Nickel conductive fabric laminated to semi-flex substrate (Denim) after 10 laundry cycles

Nickel fabric (before wash)



After wash (laminated to denim)





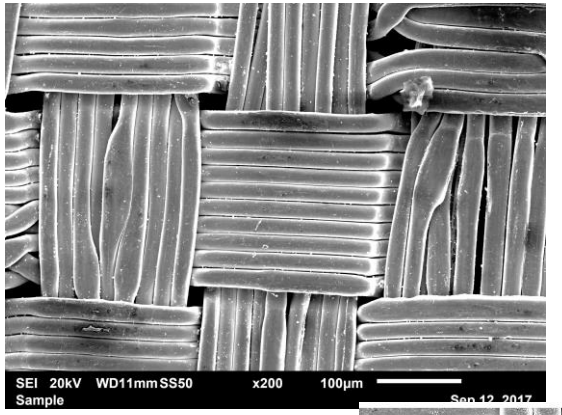
Element	Weight%	Atomic%
C K	31.04	67.41
O K	2.22	3.62
Al K	0.61	0.59
Cl K	0.83	0.61
Ni K	28.47	12.65
Cu K	36.82	15.12
Totals	100.00	

Element	Weight%	Atomic%
C K	72.31	77.67
O K	27.69	22.33
Totals	100.00	

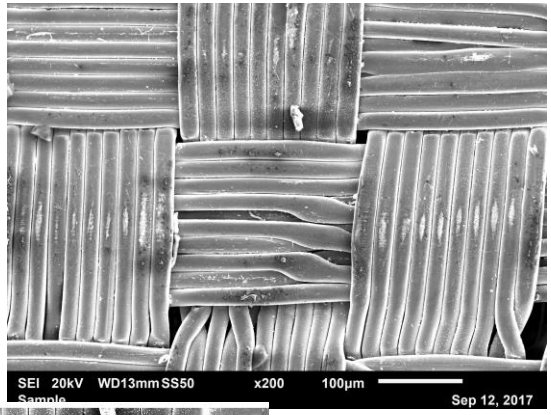
SEM Inspection after Laundry

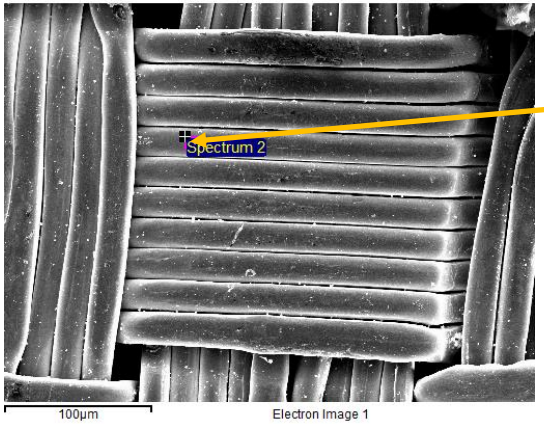
Silver conductive fabric laminated to semi-flex substrate (Denim) after 10 laundry cycles

Before wash

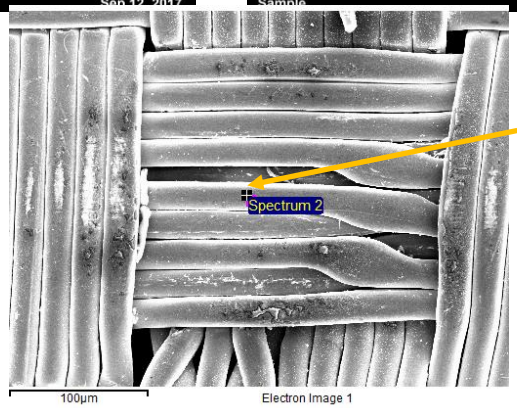


After wash





Element	Weight%	Atomic%
C K	48.57	68.31
N K	22.38	26.99
Cl K	0.48	0.23
Ag L	28.57	4.47
Totals	100.00	



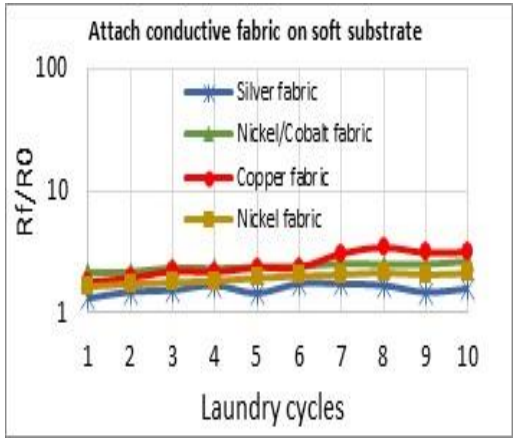
Element	Weight %	Atomic %
C K	50.02	70.15
N K	17.94	21.57
O K	3.65	3.84
Ag L	28.39	4.43
Totals	100.00	

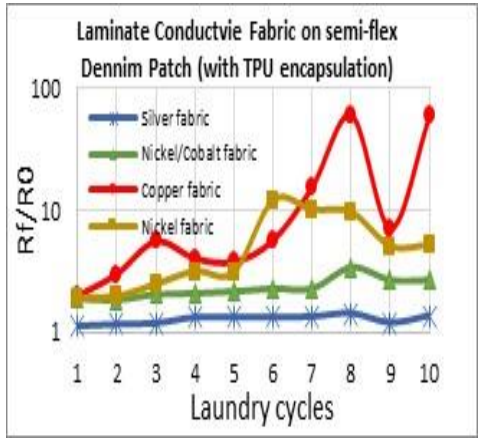
Analysis of Launderability Study

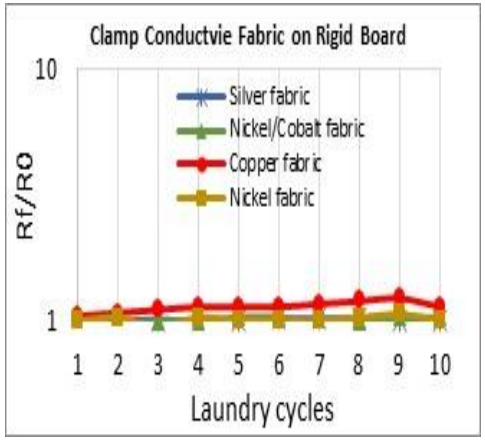
- Based on the test results and SEM inspection, a hypothesis was gradually formed: the increase in electrical resistance of the conductive fabric is mainly caused by fracture and loss of metal coatings on the yarn fibers, which is caused by the dynamic mechanical stresses during washing and drying

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

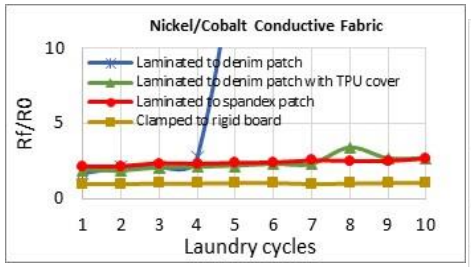
Conductive Fabrics Laminated to Different Substrates
(Spandex, Denim with TPU encapsulation, Rigid board)

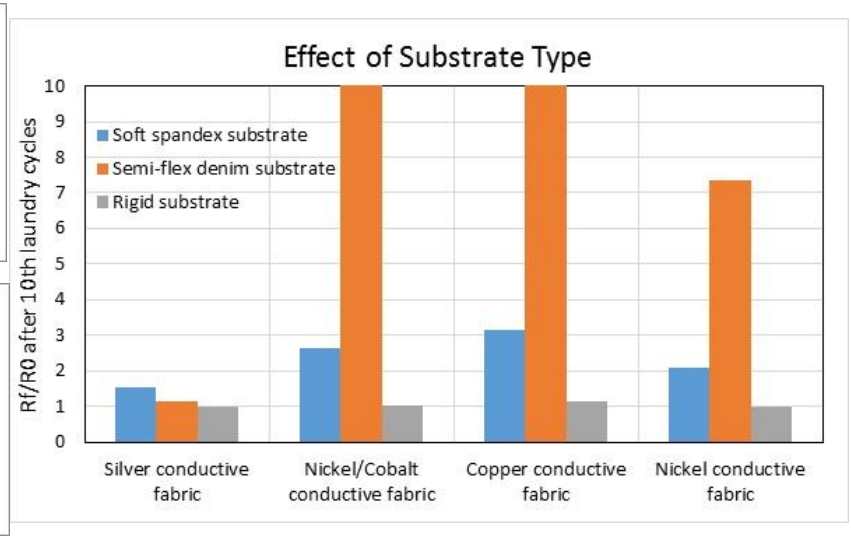


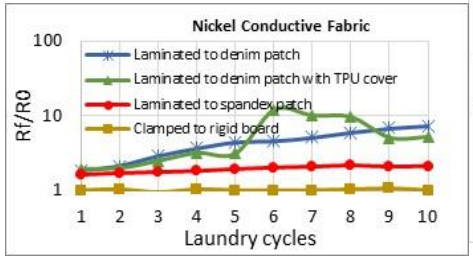




Analysis of Launderability Study



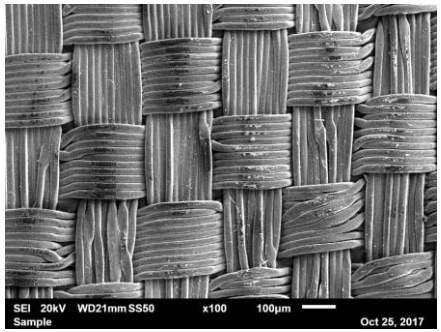


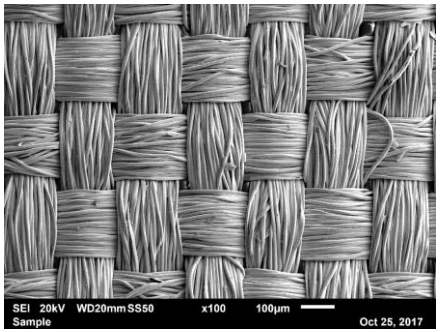


- Performance ranking in general:
  - Fabric clamped to rigid board > Fabric laminated to soft substrate > Fabric laminated to semi-flex substrate
- The results confirm our initial hypothesis that mechanical stresses during laundry cause fracture and loss of metal coatings on the yarn fibers, leading 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

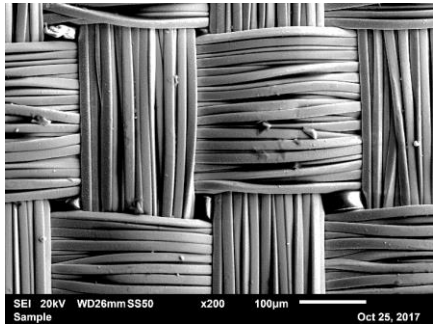
Silver conductive fabric clamped to rigid board after 10 laundry cycles

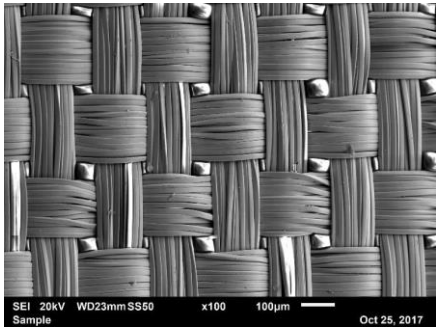




Nickel-cobalt conductive fabric clamped to rigid board after 10 laundry cycles

Copper conductive fabric clamped to rigid board after 10 laundry cycles



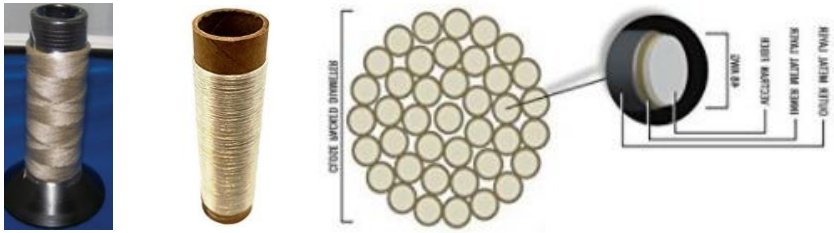


Nickel conductive fabric clamped to rigid board after 10 laundry cycles

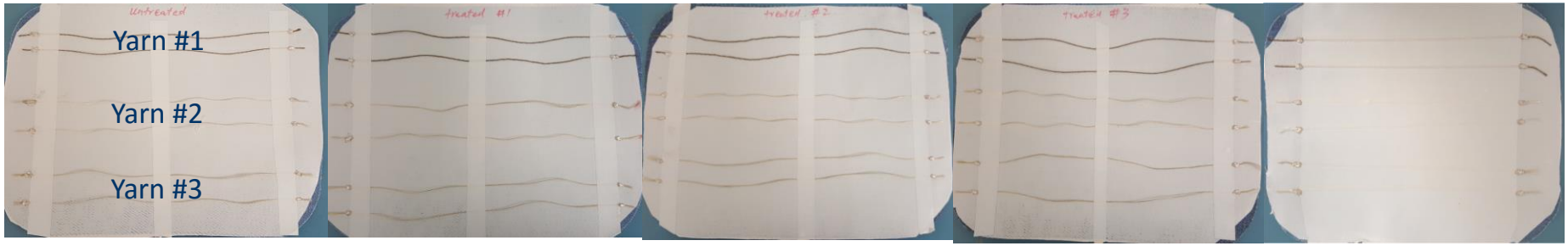
- No evidence of metal coating fracture and corrosion observed for the Ni-Co, copper and nickel conductive fabrics clamped to the rigid boards
- Some damage observed on the silver conductive fabrics clamped to the rigid board, however, it has not caused an obvious increase in resistance.

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

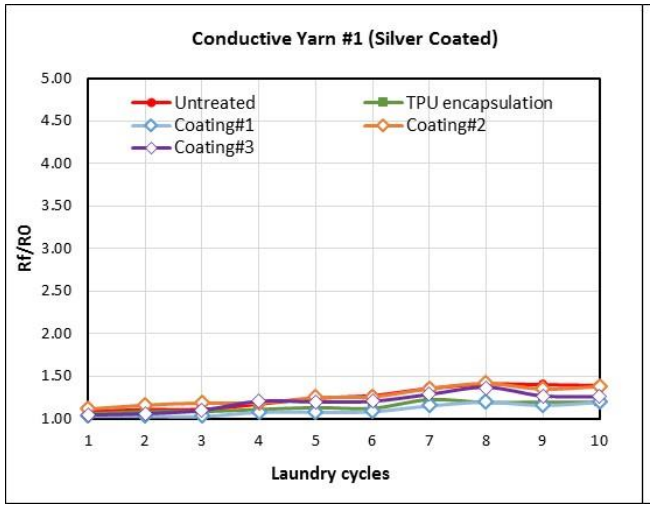


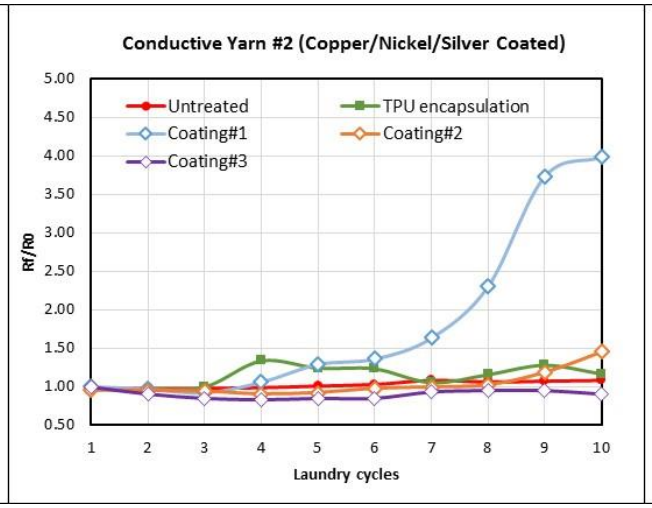
Untreated samples | **WR Coating #1** | **WR Coating #2** | **WR Coating #3** | **TPU Laminated**

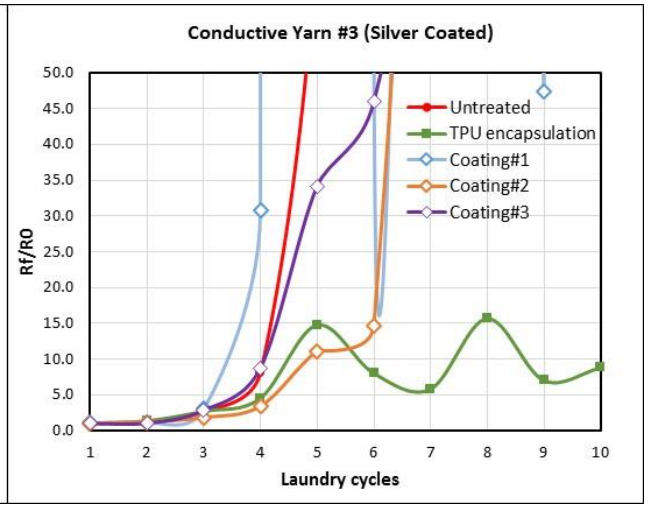


Launderability of Conductive Yarns

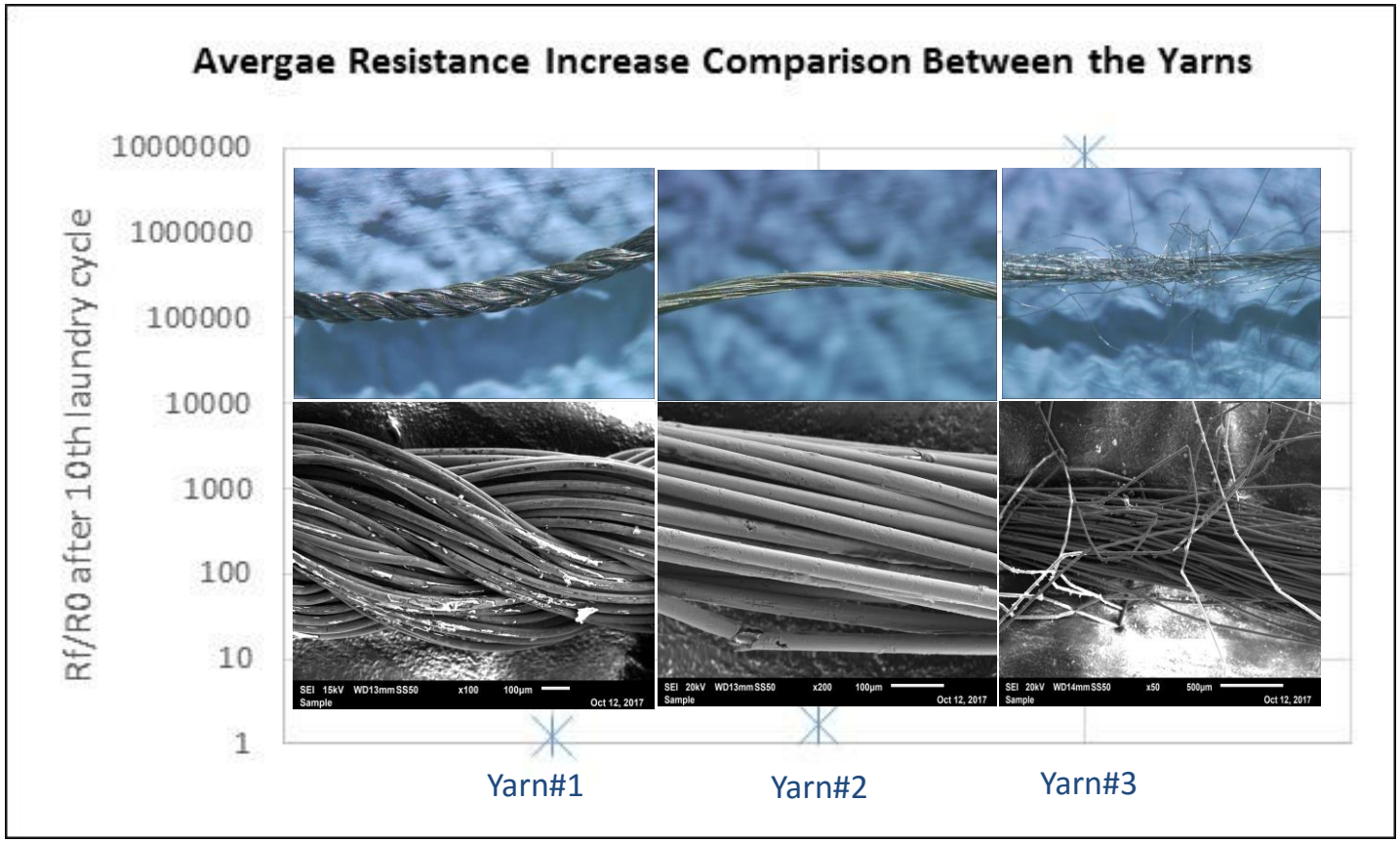
- In general resistance of the yarns increases with washing/drying cycles
  - Yarn#1 performs the best, yarn#2 performs similar to Yarn#1 with exception of one yarn, yarn#3 shows an excessive increase in resistance
- Resistance continues to show increase even with water resistance coatings and TPU lamination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







Launderability of Conductive Yarns

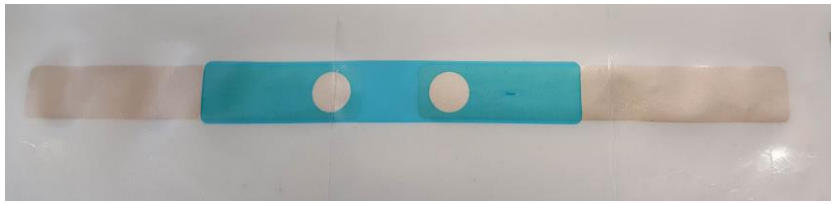


- The resistance performance of the yarns depends on the mechanical integrity of the yarns during launder: the yarn with fibers maintaining bundled state shows stable resistance.

Launderability of Conductive Ink

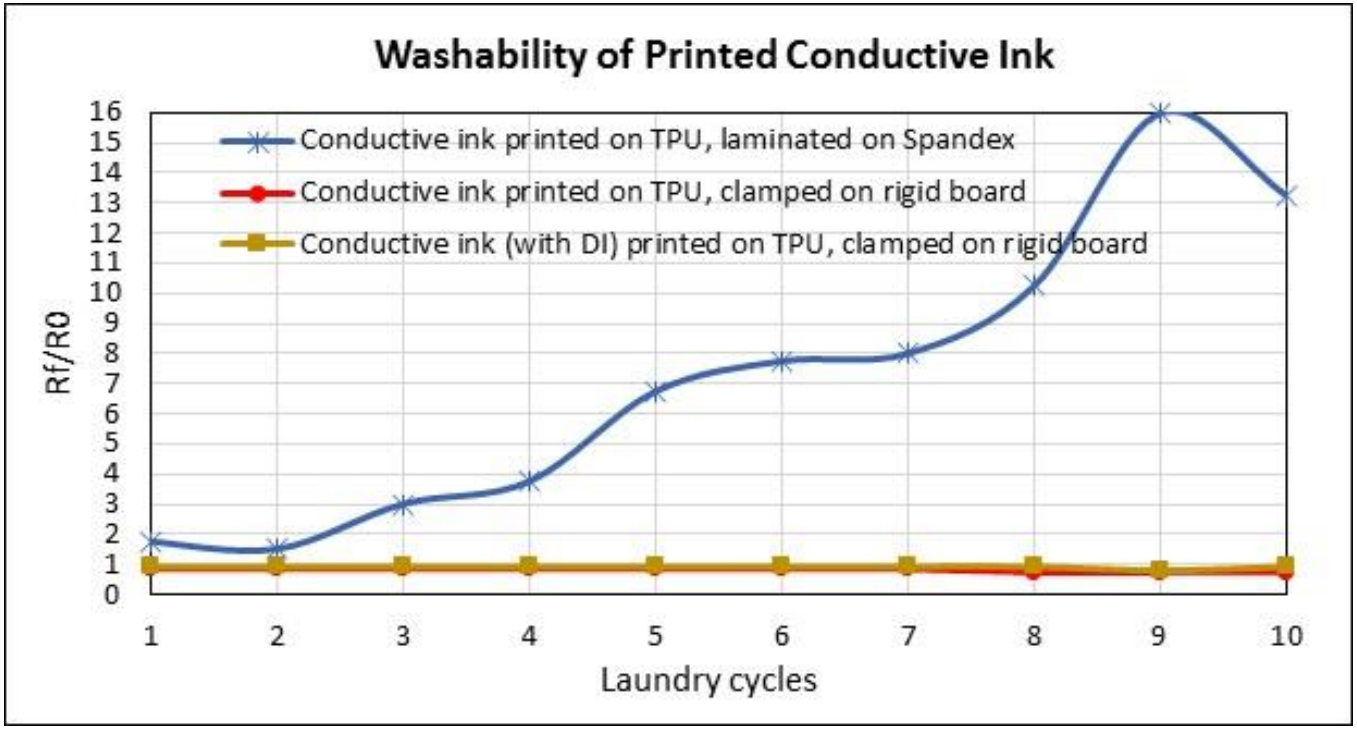
- **Materials evaluated**
  - Silver conductive ink and AgCl electrode printed on TPU film
  - A dielectric ink printed over the silver conductive ink
- **Test vehicles**
  - Conductive ink printed on TPU then laminated on spandex
  - Conductive ink printed on TPU, laminated to denim patch and then clamped on a rigid board

Conductive ink printed on TPU/laminated on spandex



Conductive ink printed on TPU/laminated on denim, clamped on 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

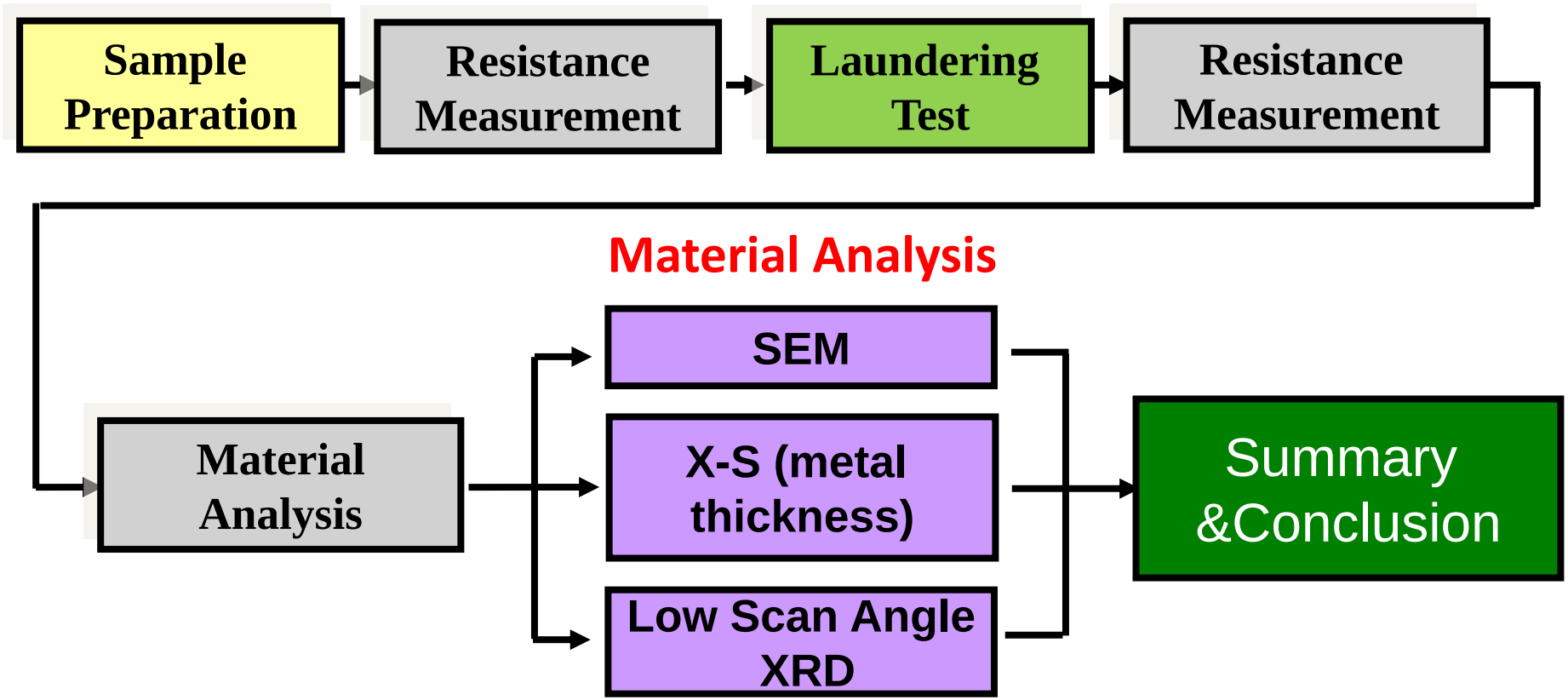
IFAI EXPO

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
Material Analysis
SEM
X-S (metal thickness)
Low Scan Angle XRD
Summary &Conclusion

Test Equipment and Conditions

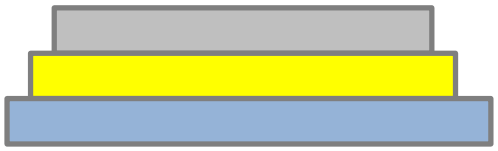
- Washer: SDL Atlas Vortex M6
- Washing parameters
  - Temperature: 30°C
  - Water level: 19 gal
  - Agitation/Spin speed: 120 spm
  - Duration: 33 mins. (whole cycle from water filling to finish spinning)

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

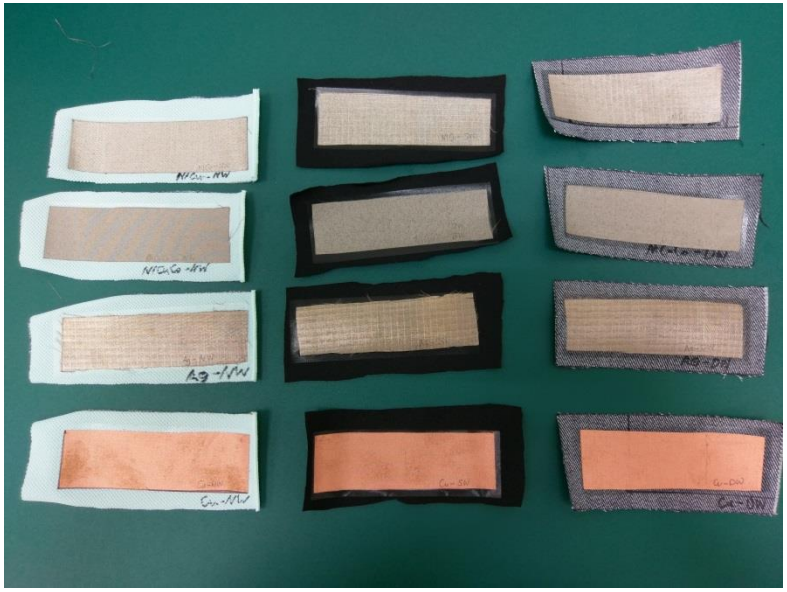
- Detergent: AATCC 1993 Standard Reference Detergent without brightener
  - ContainsL Sodium Aluminosilicate, Sodium Solfate, Sodium Alkylbenezene Sulfonate, Sodium Carbonate, Sodium Polyacrylate
  - Amount: 66g, as prescribed by AATCC methods

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)



Test sample illustration (side view)



Sample Description: Conductive Fabrics

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

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

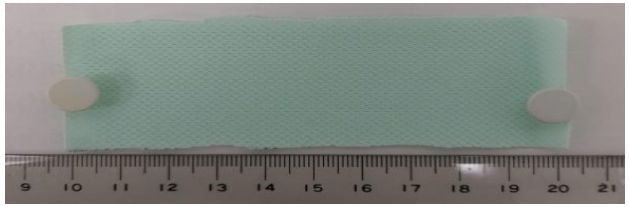
Sample Description – Supporting Fabrics

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

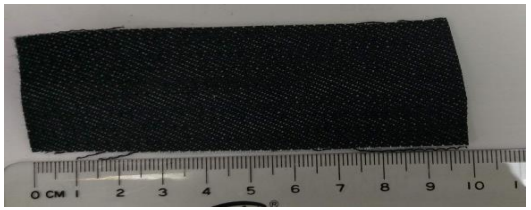
Fabric Type	Spandex	Nylon (Spandex 18%)	Denim
Color	Black	Light blue	Blue
Texture	Soft	Soft	Hard
Elasticity (Length change after elongation)	Elastic (10cm→17cm)	Very Elastic (10cm→19cm)	Inelastic (almost no change)

Spandex

Nylon



Denim



Sample Description – TPU

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

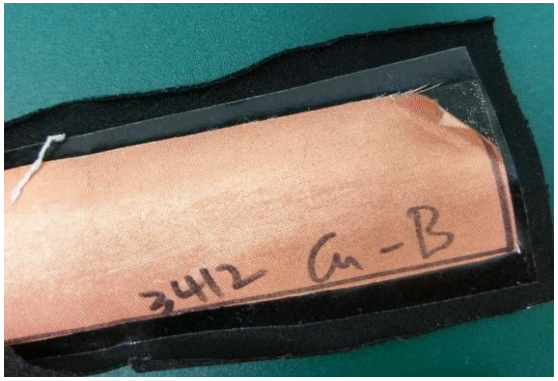
TPU Number		3206 (final choice)	3412	3829
Layer		Single layer	Single layer	Single layer
Brand		Sewfree	Sewfree	
Fabrics (Woven, nonwoven, knits, felts)	Denim (Cotton)	Excellent	Excellent	
	Nylon	Good	Good	
	Spandex (Nylon/Lycra)	Excellent	Excellent	
Glue line temperature range		120°C~130°C	150°C~170°C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

TPU Test Results

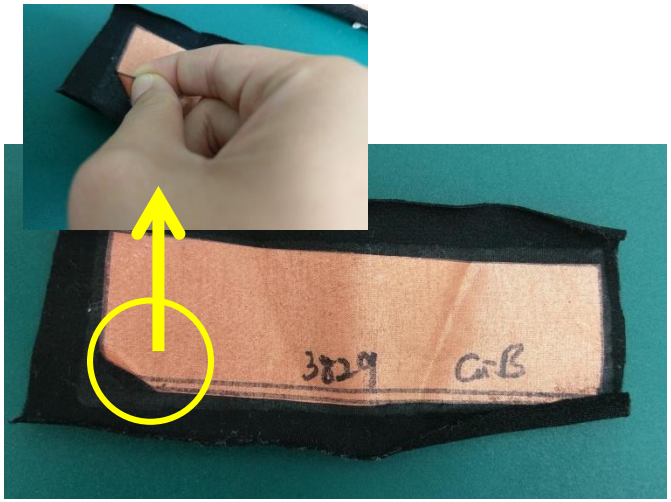
- TPU adhesion starts to show difference after two times of laundering and drying
- Bemis 3206 showed the best performance among the fabrics, does not detach from either Spandex or Denim fabrics

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

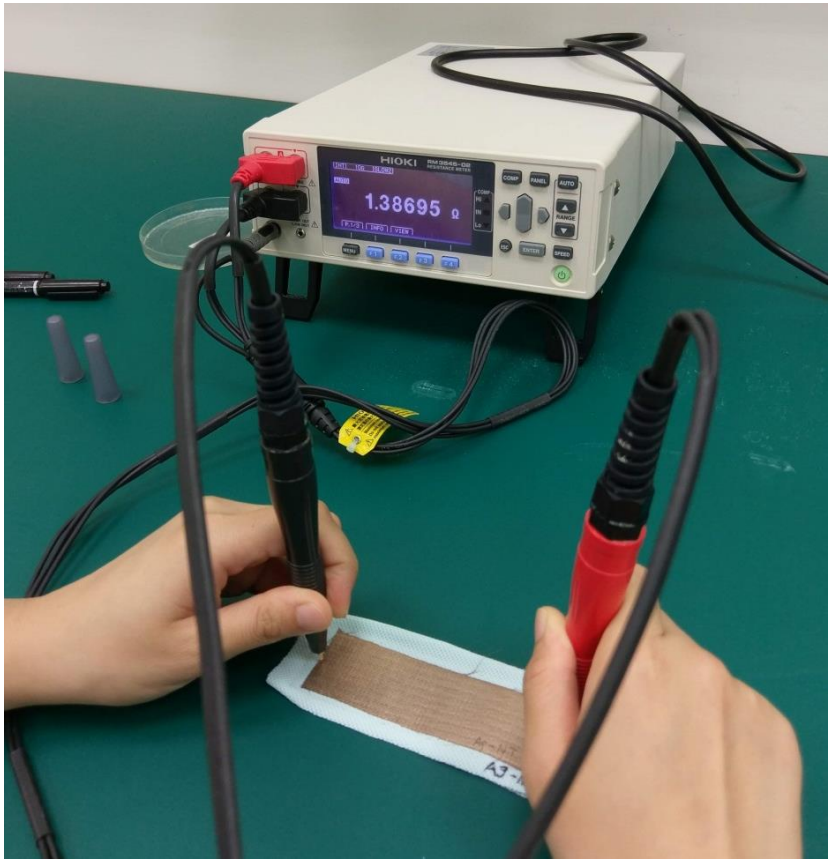


Sample Test Matrix

Conductive Fabric	Support Material	Sample size	Wash (X1, X3, X5, X7, X10)	OM + Resistance
Ni	Spandex	1	√	√
Ni	Nylon	1	√	√
Ni	Denim	1	√	√
Ni-Co	Spandex	1	√	√
Ni-Co	Nylon	1	√	√
Ni-Co	Denim	1	√	√
Ag	Spandex	1	√	√
Ag	Nylon	1	√	√
Ag	Denim	1	√	√
Cu	Spandex	1	√	√
Cu	Nylon	1	√	√
Cu	Denim	1	√	√

Resistance Measurement

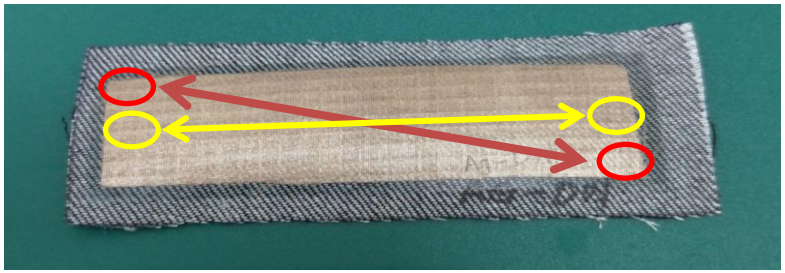
- After taking sample out from the drying machine, leave the sample for one night before monitoring the resistance
- Test probes are placed perpendicular to the sample surface
  - HioKi Ohmmeter RM3544 was used for the measurement with 1 μΩ max. resolution
  - Four point Kevin method for resistance measurement
- 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

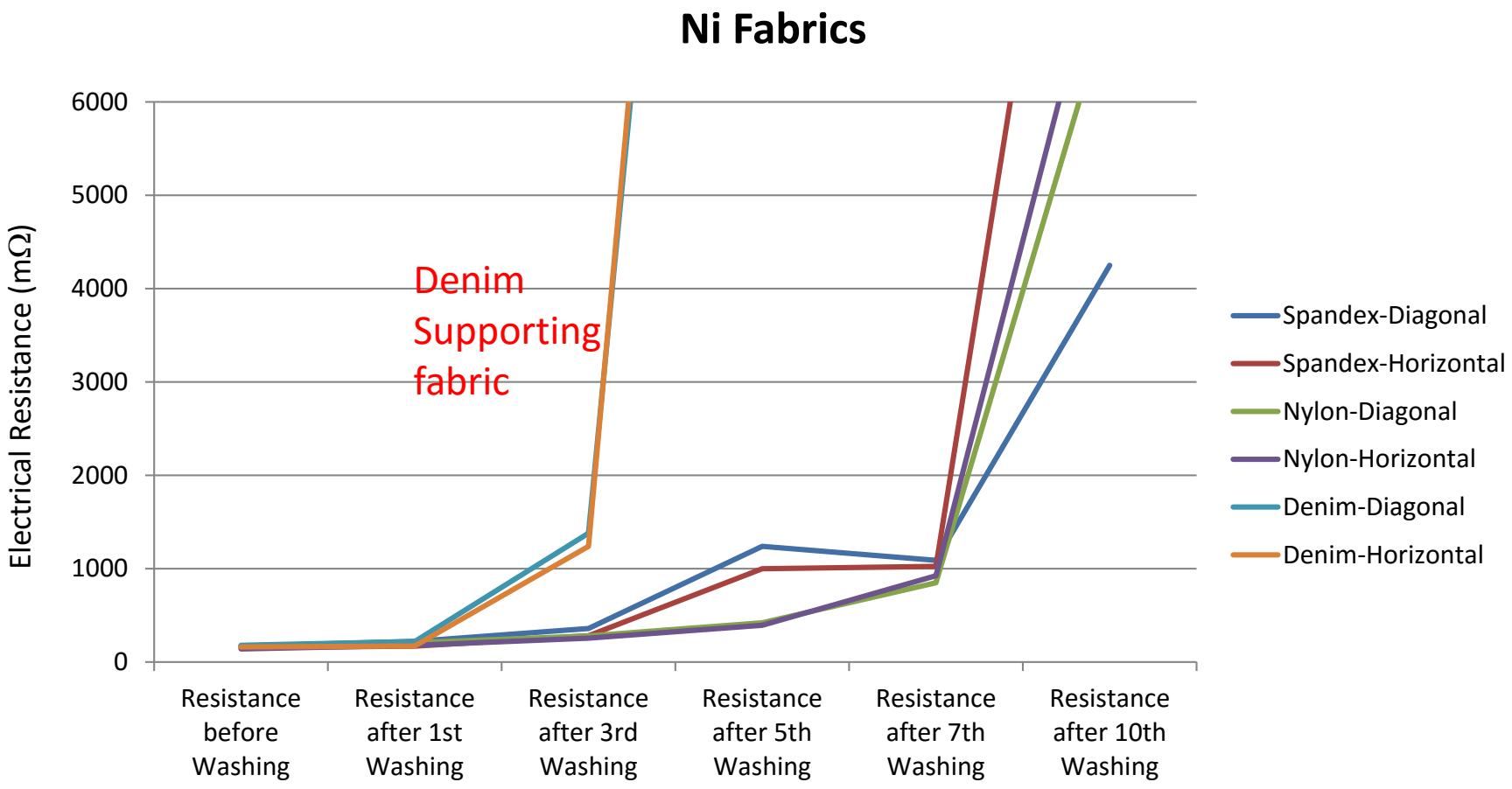


- Each sample has two measurement positions, one is diagonal (red circle), the other one is horizontal (yellow circle)
- Resistance measurement for both measurement positions are recorded

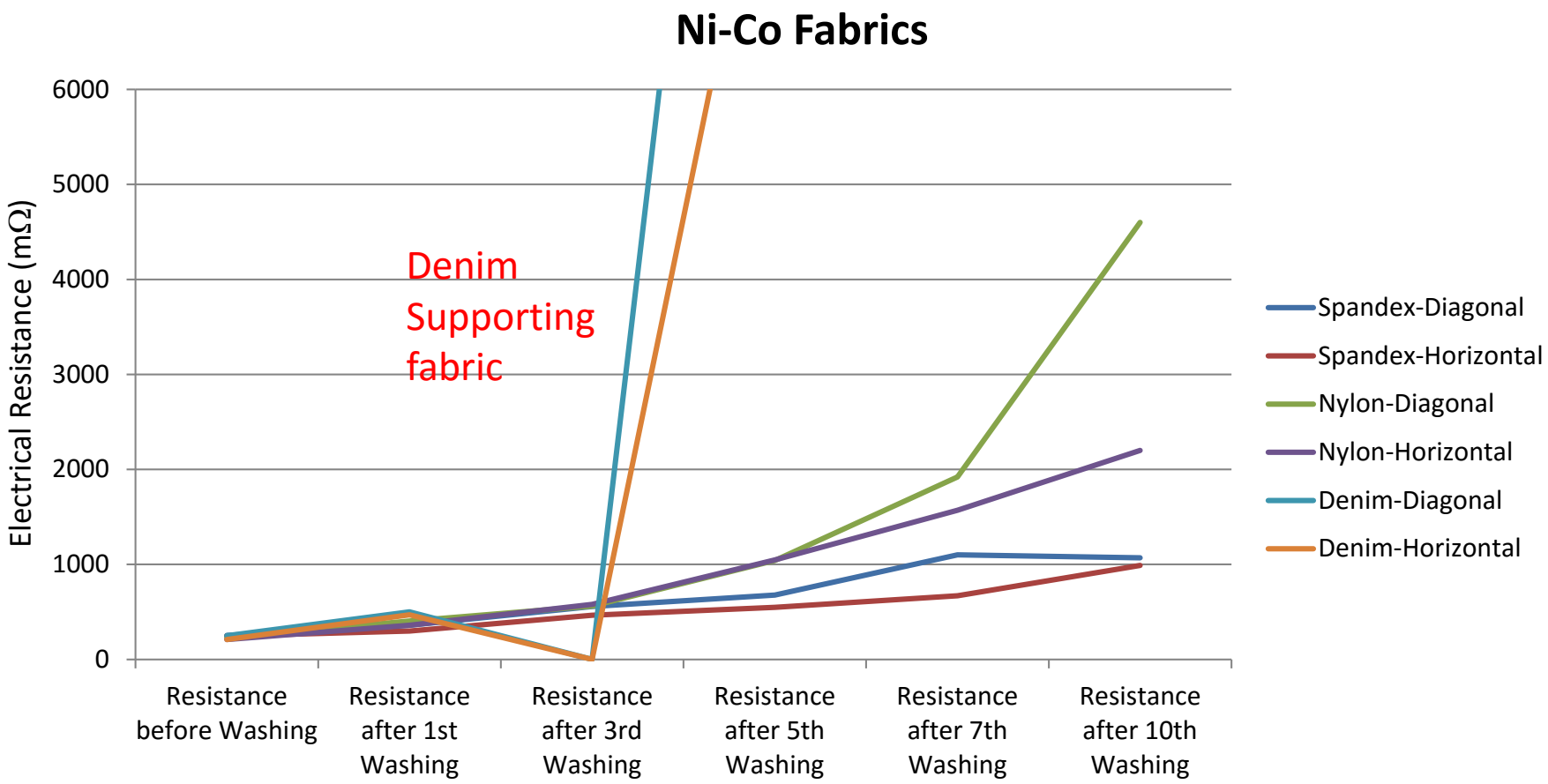
Summary Of Test Results

Number	Conductive Fabric	Support Material	Resistance before Washing		Resistance after 1st Washing	Resistance after 3rd Washing	Resistance after 5th Washing	Resistance after 7th Washing	Resistance after 10th Washing
1	Ni	Spandex	Diagonal	170 mΩ	221mΩ	360mΩ	1.24Ω	1.08~1.1Ω	4~4.5Ω
			Horizontal	154.5 mΩ	170mΩ	282mΩ	1Ω	1.02~1.03Ω	11.3~12Ω
2	Ni	Nylon	Diagonal	175 mΩ	208mΩ	280mΩ	421mΩ	840~860 mΩ	7.1Ω
			Horizontal	140 mΩ	179mΩ	256mΩ	394mΩ	915~935mΩ	8~8.2Ω
3	Ni	Denim	Diagonal	180 mΩ	220mΩ	1.38Ω	23~28Ω	42~47Ω	820Ω~1Ω
			Horizontal	162 mΩ	172mΩ	1.24Ω	21.8~22Ω	45~51Ω	980~840Ω
4	Ni-Co	Spandex	Diagonal	252 mΩ	359mΩ	557mΩ	678mΩ	1~1.2 Ω	1.07Ω
			Horizontal	247 mΩ	298mΩ	465mΩ	548mΩ	670 mΩ	980mΩ~1Ω
5	Ni-o	Nylon	Diagonal	229 mΩ	404mΩ	561mΩ	1.41Ω	1.92Ω	4.6Ω
			Horizontal	210 mΩ	360mΩ	580mΩ	1.47Ω	1.57Ω	2.2Ω
6	Ni-Co	Denim	Diagonal	250 mΩ	500mΩ	1.08Ω	16.3Ω	28~30Ω	57~60Ω
			Horizontal	210 mΩ	470mΩ	954mΩ	15~15.4Ω	23.5Ω	66~70Ω
7	Ag	Spandex	Diagonal	1.69Ω	1.67Ω	2.097Ω	2.11Ω	2.35Ω	2.54Ω
			Horizontal	1.29 Ω	1.39Ω	1.74Ω	1.8Ω	2.01Ω	2.14Ω
8	Ag	Nylon	Diagonal	1.65 Ω	1.76Ω	2.17Ω	2.24Ω	2.5Ω	2.6Ω
			Horizontal	1.35 Ω	1.38Ω	1.81Ω	1.86Ω	2.02Ω	2.07Ω
9	Ag	Denim	Diagonal	1.59 Ω	1.69Ω	2.48Ω	3.18Ω	4.05Ω	3.11Ω
			Horizontal	1.23 Ω	1.43Ω	2.04Ω	2.65Ω	3.1Ω	3.04Ω
10	Cu	Spandex	Diagonal	213 mΩ	635mΩ	316Ω	1.55 KΩ	900 mΩ~1Ω	960~980Ω
			Horizontal	193 mΩ	576mΩ	380Ω	680~720Ω	590~730Ω	1.1~1.3KΩ
11	Cu	Nylon	Diagonal	209 mΩ	322mΩ	149Ω	680~730Ω	620~720Ω	1.2~1.23KΩ
			Horizontal	167 mΩ	315mΩ	178Ω	235.5Ω	550~600Ω	1.8KΩ
12	Cu	Denim	Diagonal	232 mΩ	452mΩ	1.16kΩ	2.4~2.7KΩ	4.2KΩ	6.3KΩ
			Horizontal	171 mΩ	405mΩ	1.1kΩ	3.5~3.7KΩ	3.2KΩ	4.3KΩ

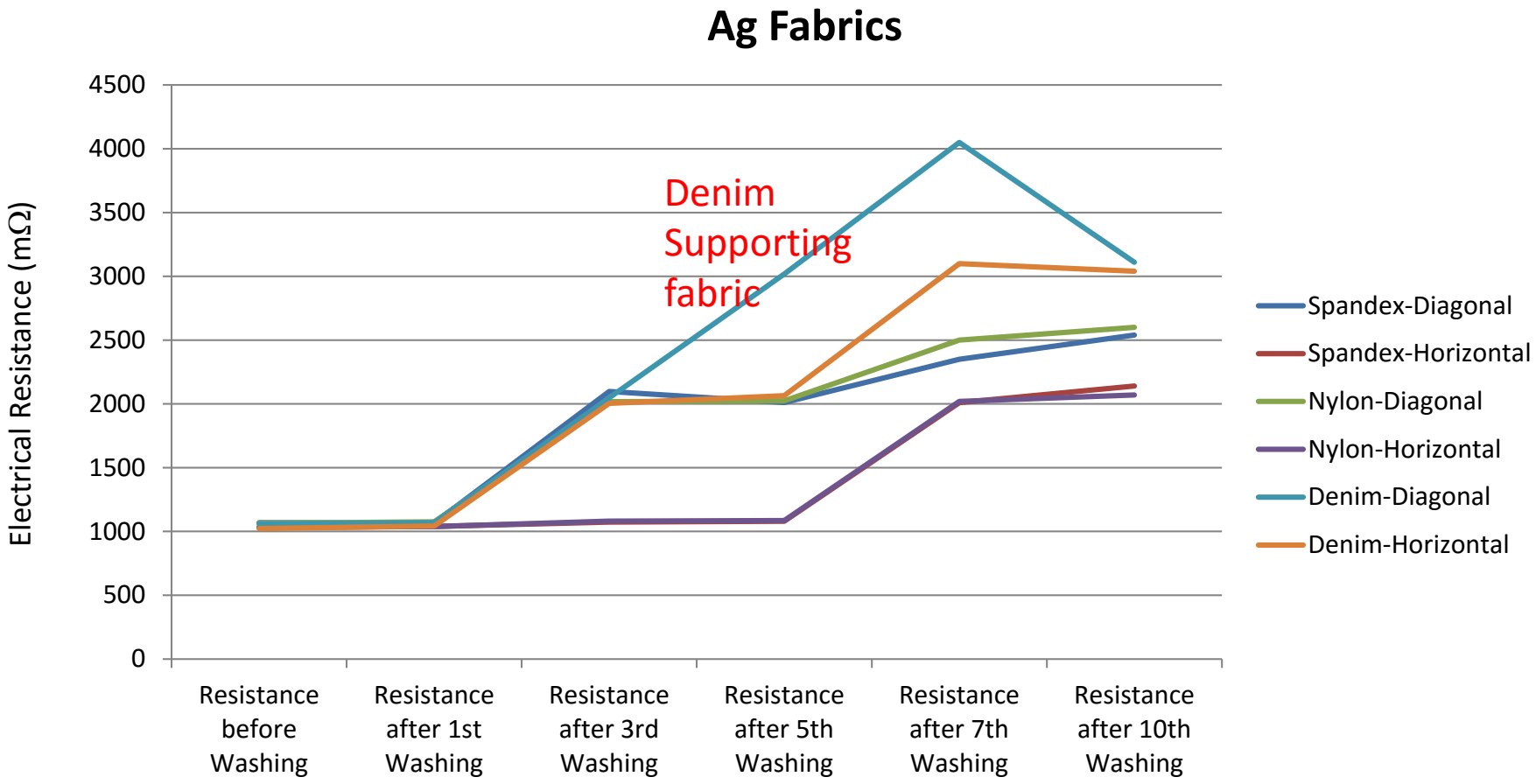
Resistance Change during Laundry



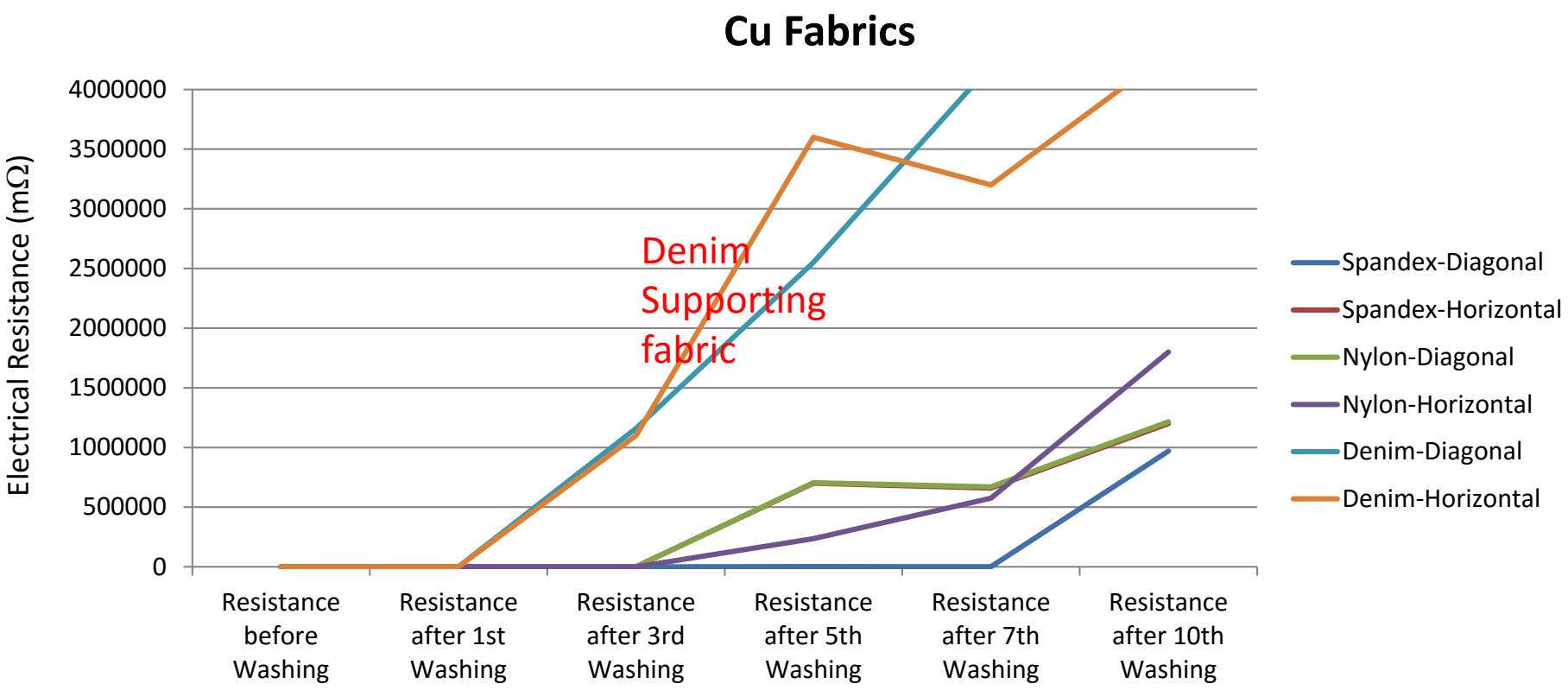
Resistance Change during Laundry



Resistance Change during Laundry

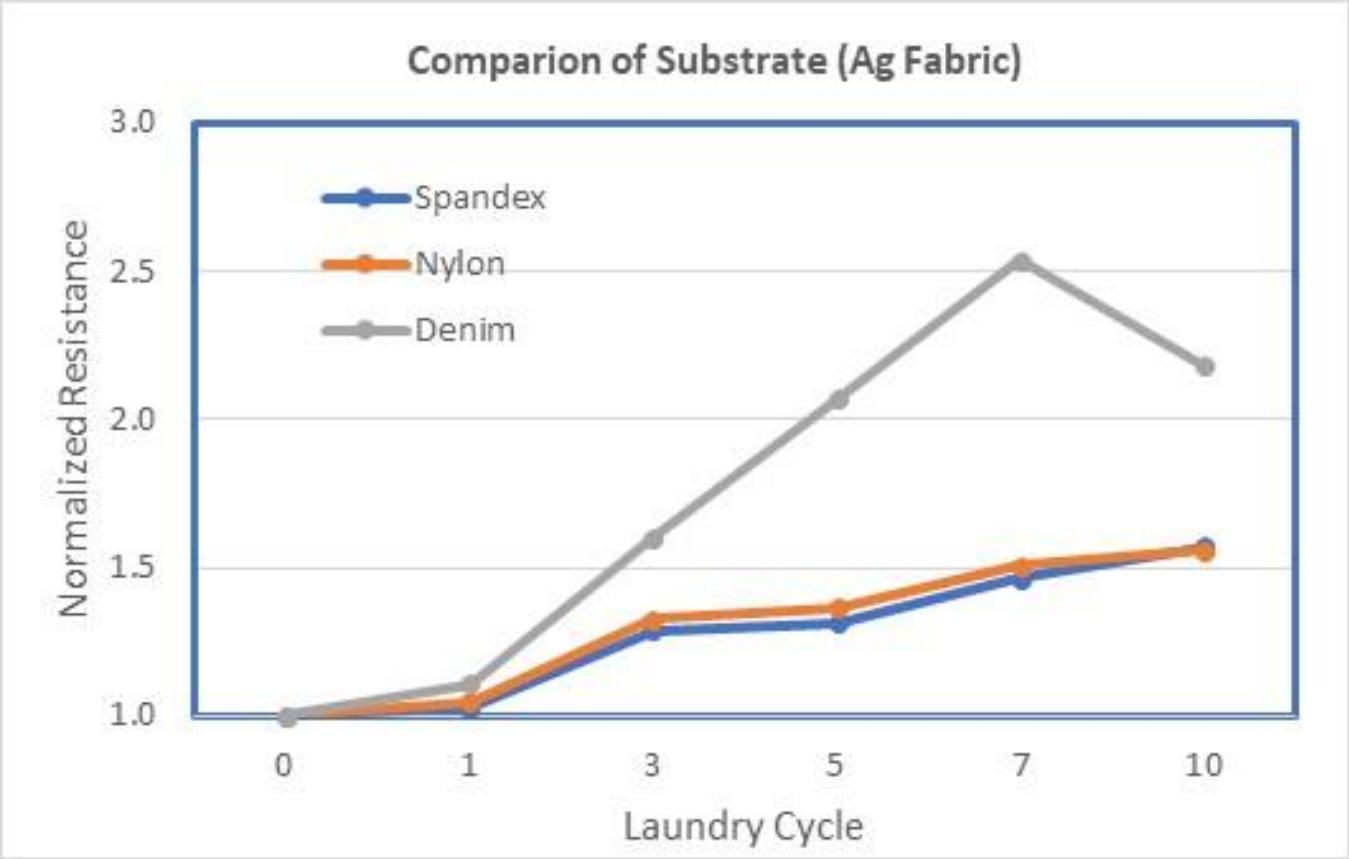


Resistance Change during Laundry

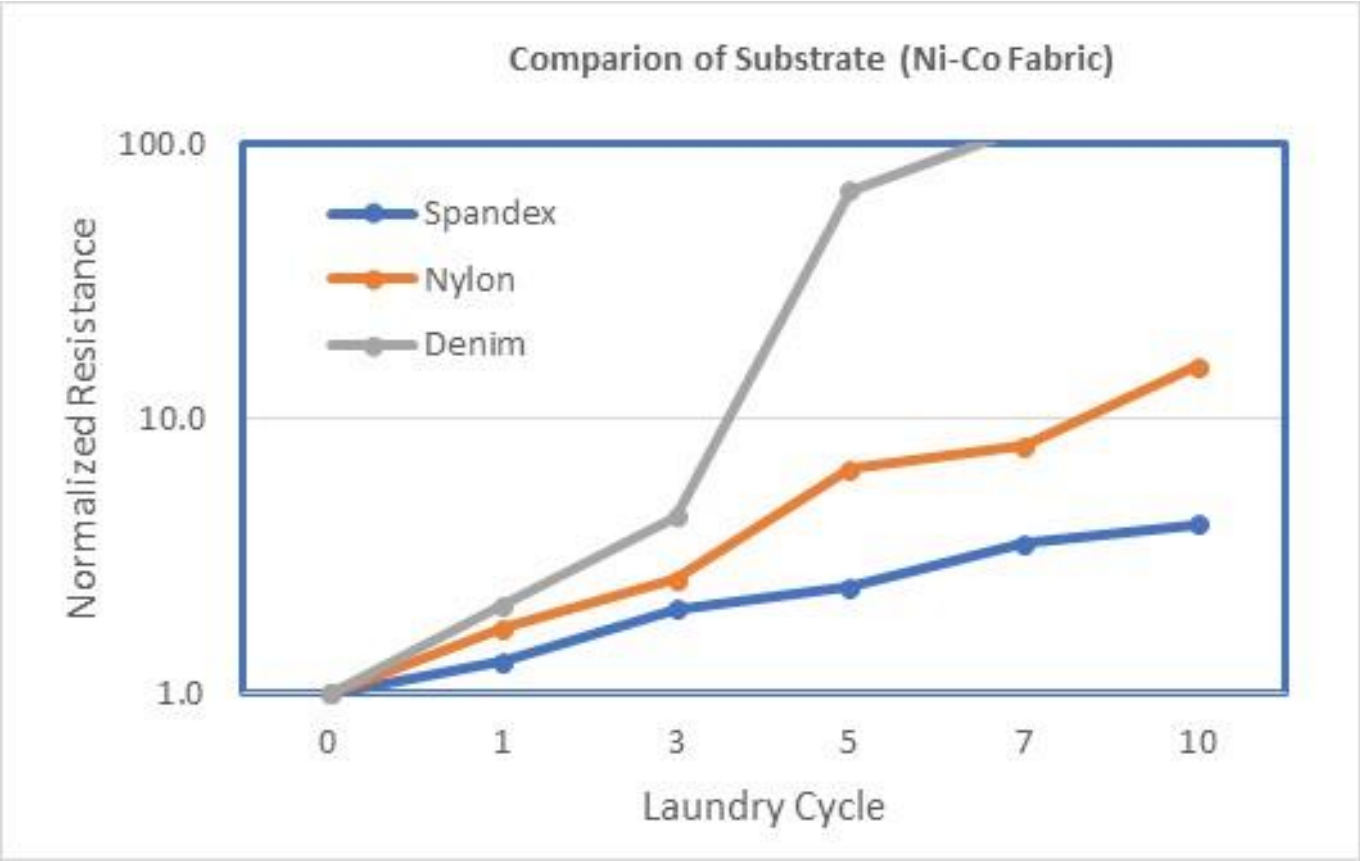


Comparison between Conductive Fabrics

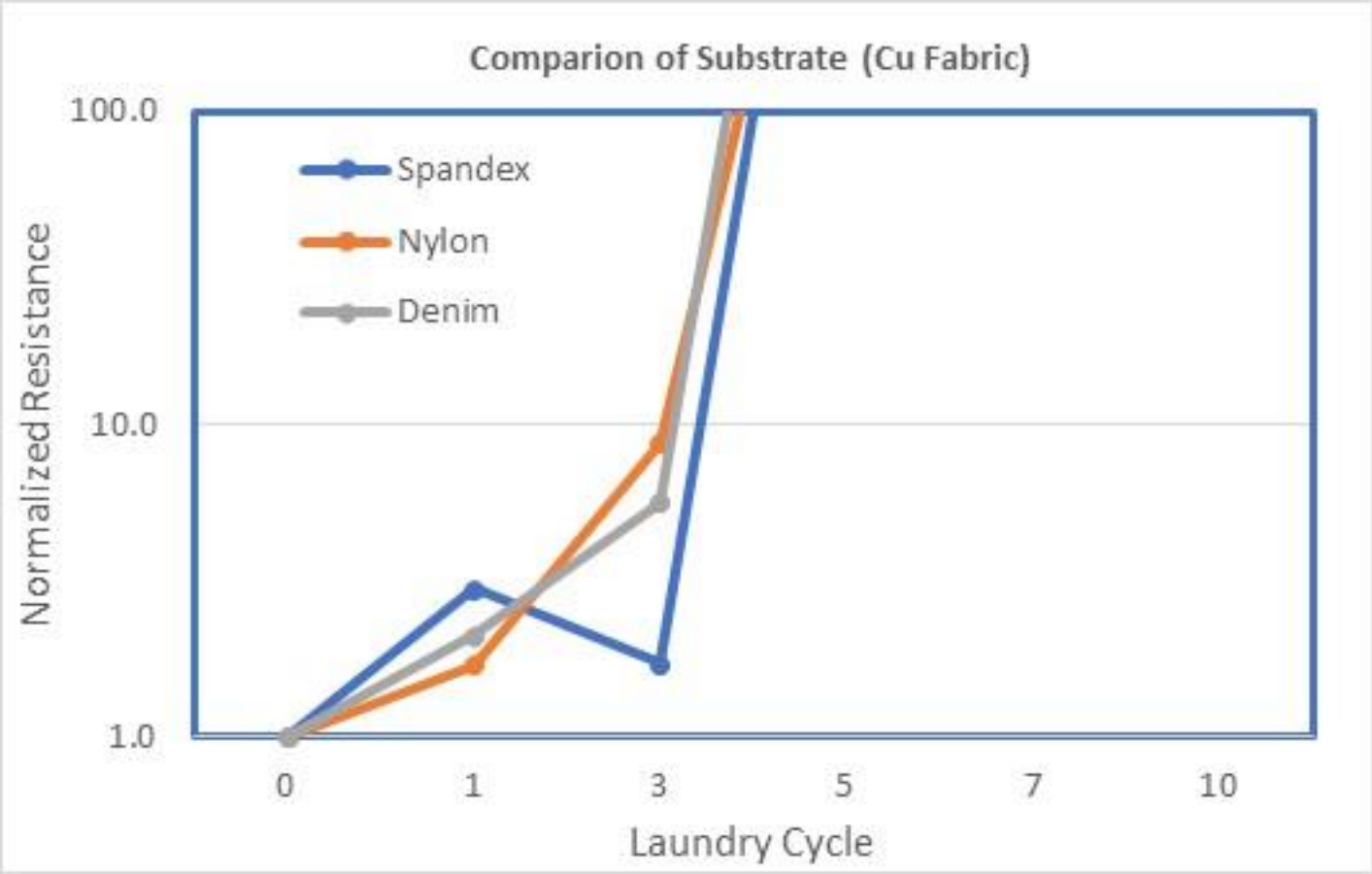
Comparison between Supporting Fabrics



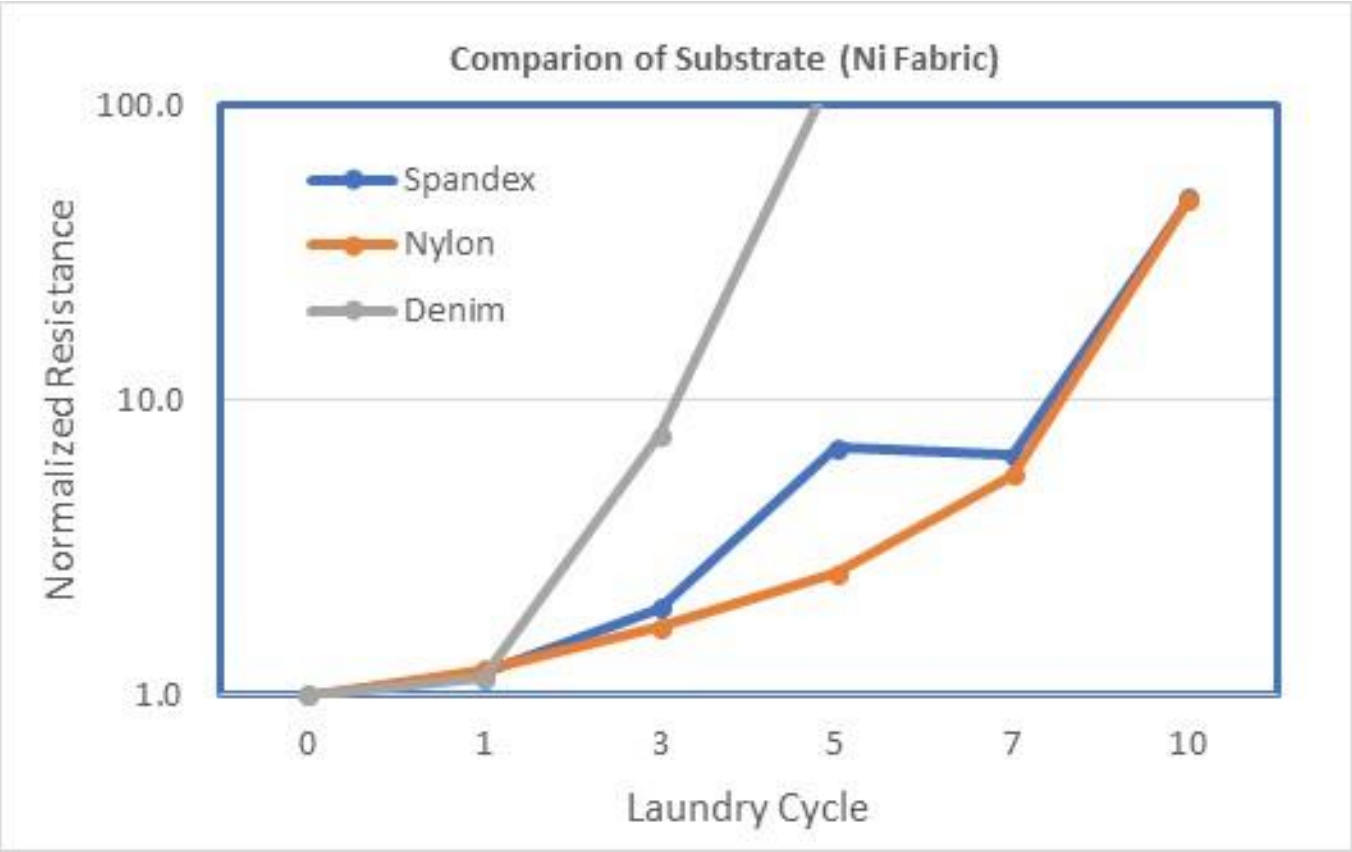
Comparison between Supporting Fabrics



Comparison between Supporting Fabrics



Comparison between Supporting Fabrics



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

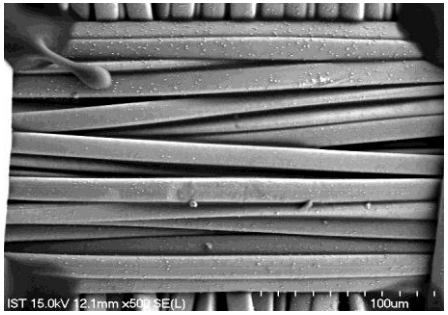
- Scanning Electron Microscope (SEM)

HITACHI Reglus 8240

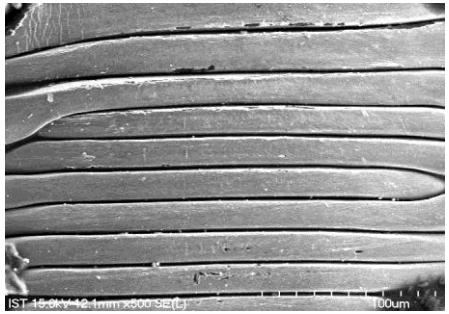
- Electro Gun: Cold FE
- Resolution: 0.7 nm (Accelerating Voltage 15 kV) , 0.9 nm(Accelerating Voltage 1kV)
- Magnification: 20~1000k
- Accelerating Voltage: 0.01~30kV

SEM Inspection (Before/After Laundry)

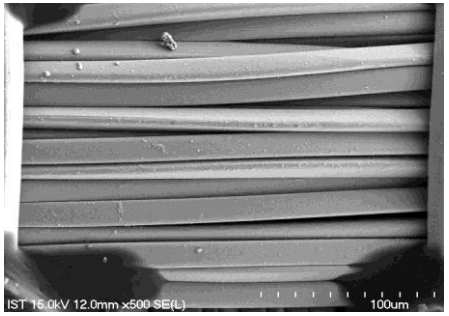
Before Laundry Test



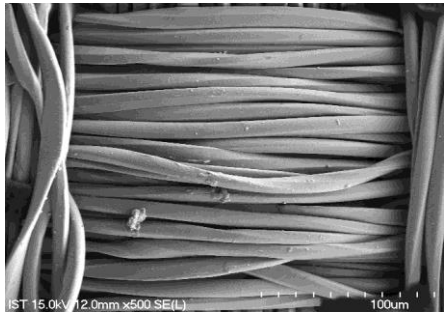
Cu



Ag

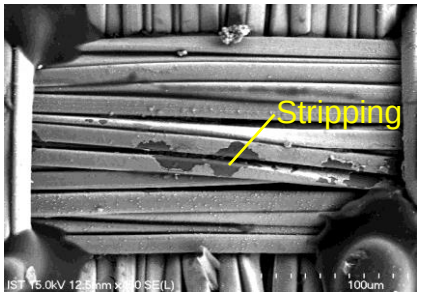


Ni

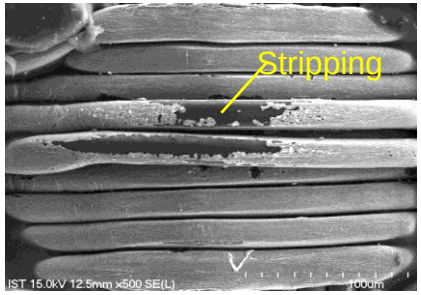


Ni-Co

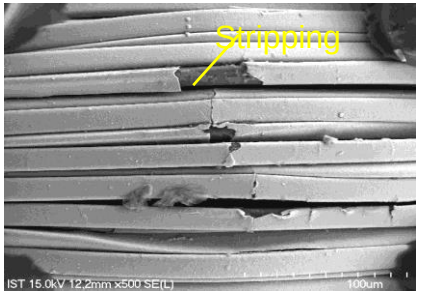
After 10th Laundry Cycle



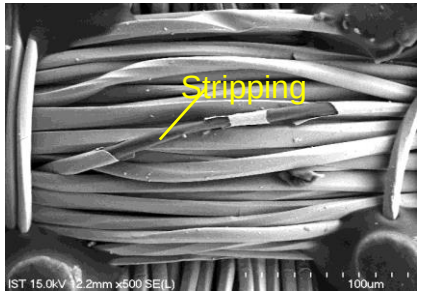
Cu



Ag



Ni

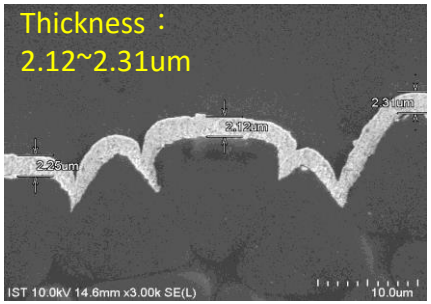


Ni-Co

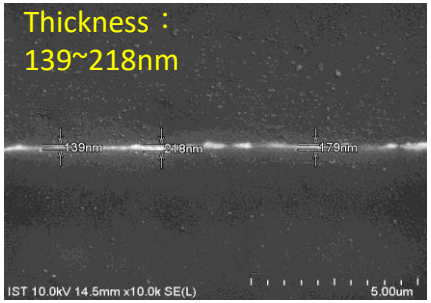
Magnification：x 500 times
Supporting material: Spandex

SEM Evaluation: metal coating thickness

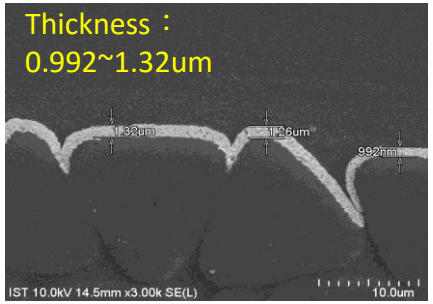
Before Laundry Test



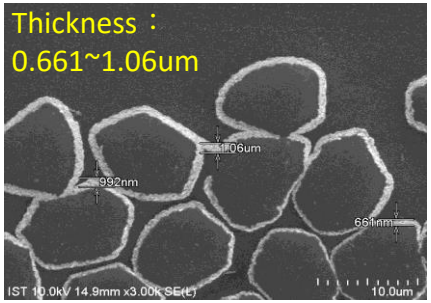
Cu



Ag

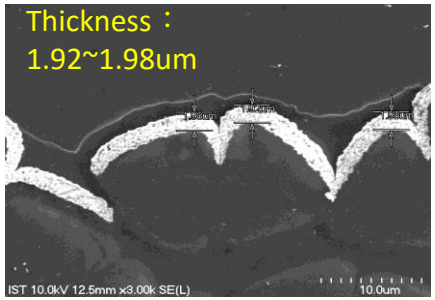


Ni

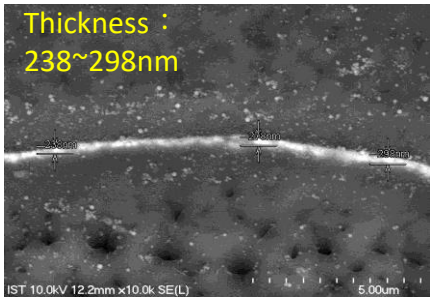


Ni-Co

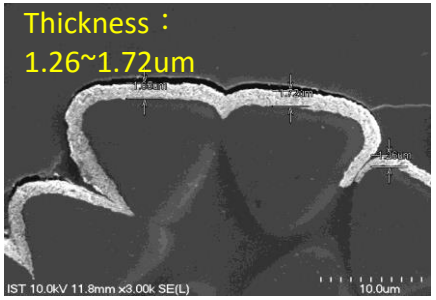
After 10th Laundry Cycle



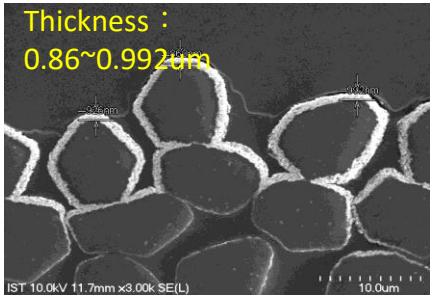
Cu



Ag



Ni



Ni-Co

- 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**

Metal Coating	Thickness (um)	Rf/R0 aft 10th Laundry
Ag	0.2	1.8
Cu	2	13300
Ni	1.5	1784
Ni-Co	1	96

- **Metal material**

Metal	Modulus (Gpa)	Vickers Hardness (Mpa)	tensile strength(MPa)	Relative ductivity (Gold=1)
Ag	83	251	125	0.73
Cu	110	343	200	0.62
Ni	200	638	450	0.5
Co	209	1043	675	0.5

- **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 acknowledgment the contributions from:

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- IST's FA team for their SEM observation
- Prof. Chin Lee and Dr. Sheikhishooshtari of UC Irvine for XRD analysis
- 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

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