Washability of E-Textile Materials

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ABSTRACT
E-textiles, also known as electronic textiles, smart textiles, smart clothing, smart garments, or smart fabrics, are fabrics with electronic components and sensors embedded in them. Key components of e-textiles are the conductive materials to connect different sensors, modules and power supplies to form a body area network (BAN). In their lifetime, e-textiles including the conductive materials may experience many washing and drying laundry cycles, one of the biggest challenges facing the application of e-textiles.

Limited data are available on the performance of conductive materials going through the washing and drying cycles. This paper presents studies on the washability of three types of commonly used conductive materials in making e-textiles: conductive yarn, conductive fabric, and conductive ink. Different options to protect the conductive materials are explored, such as water-resistant coating, thermoplastic urethane (TPU) film lamination, and dielectric ink printing. Electrical resistance as a function of laundry cycles is used to characterize the performance of the conductive materials. After the intended laundry cycles, samples were inspected under optical microscope and SEM to provide further insight on the performance of these materials.

Keywords: Washability, Launderability, Water Resistant Coating, E-textile, Conductive Yarn, Conductive Fabric, Conductive Ink.

1. INTRODUCTION

E-textiles are fabrics with electronic components and sensors embedded in them to form a body area network (BAN), with conductive materials attached to the fabrics to connect different sensors, modules and power sources. With their intended use for people to wear, e-textiles will inevitably experience many washing and drying cycles; however, with embedded electronics, washability, often also called launderability, of e-textiles becomes a serious question for many wearable designers, researchers and consumers. Can e-textiles survive laundry cycles? How many cycles can they survive? Will washing and drying cause performance degradation of the electronics if not failure? What laundry factors cause the most damage to the e-textiles? How can e-textiles be designed to be washing and drying proof? There are many more questions to be answered before successful application of e-textiles.

Currently very little information is available on the washability of e-textile materials and components. From extensive online literature search, only a few publications on the subject were obtained [1, 2]. Although these references provide experimental data on the performance of conductive materials during laundry cycles, they lack fundamental studies on why the conductive materials show a certain behavior during laundry and therefore they do not provide insight on the degradation mechanisms of the materials and the factors impacting their performance.

Another equally challenging issue is there lacks industry standards on e-textile washability. AATCC (American Association of Textile Chemists and Colorists) and other industry associations have developed quite a few standards on washability [3,4], but these standards are mainly developed for traditional textiles and may not be well suitable for e-textiles as e-textiles bring new requirements. Modifications may be needed for e-textiles. Recently, AATCC committee RA111 developed "Conductance Changes to Electronically-Integrated Textiles after Home Laundering [5];" however, this document is not openly published yet, and industry acceptance has a long way to go.

To address the challenges, the company initiated this project on e-textile washability study. This project is multi phased, the first phase is mainly to obtain first hand understanding of the behavior and performance of conductive materials, coatings and encapsulants of e-textiles during laundry cycles. Based on the findings from the first phase, the project may proceed with more scope and tasks. This paper presents results of this first phase study.

EXPERIMENTAL

Multiple tasks were performed for this washability study:

1. Select conductive materials, water resistant coatings and encapsulants;
2. Design and fabricate the test vehicles;
3. Perform washability testing;
4. Perform electrical resistance measurement before and after laundry cycles;
5. Perform material inspection and failure analysis.

During the process, we had a few iterations of the above steps based on new findings from the experimental work.

Three types of conductive materials were selected for this study: conductive yarn, conductive fabric and conductive ink. For the conductive yarn and conductive fabric, materials from different suppliers and with different metal coatings were selected for comparison. For the conductive ink, only one silver based conductive ink was evaluated for this study.

Three types of protection layer over the conductive materials were evaluated: water resistant coating, TPU lamination and dielectric ink printing. Water resistant coating has been used extensively in the electronics and textile industries. It is a natural thought to apply water resistant coating to provide protection to the e-textile materials and components. For this study, three water resistant coatings were evaluated: one commercial off the shelf product purchased from an online store and two industrial level nano coating materials obtained from our partners. The conductive yarns and fabrics were dipped inside the water resistant coating solutions, heat treated at 115^{o}C for over 30 minutes, before being laminated to substrates. TPU lamination was done using a typical household steam press ironing machine with temperature kept at 150-160^{o}C for 10 seconds. The conductive ink was screen printed on a TPU film and then cured at 120^{o}C for 10 minutes, and the dielectric ink was screen printed over the conductive ink and cured under UV light.

A typical household top loaded washing machine was used for this study, as shown in Figure 1 (A). The washer was tuned to the "normal" setting with single spin and cold tap water. One washing cycle typically lasts 60 minutes. Figure 1(B) shows the dryer used for this study. The machine was set at the "median" setting for the drying temperature. Actual measurement was performed, showing a large temperature swing from 36^{o}C to 75^{o}C. A typical drying cycle lasts 30 minutes. A cup of liquid detergent in the amount of 50ml was dropped in the washer before starting the washing. The liquid detergent is a typical household detergent, shown in Figure 1(C), purchased from a local grocery store. We also purchased a few laundry bags (Figure 1(D)) to hold the samples during laundry.

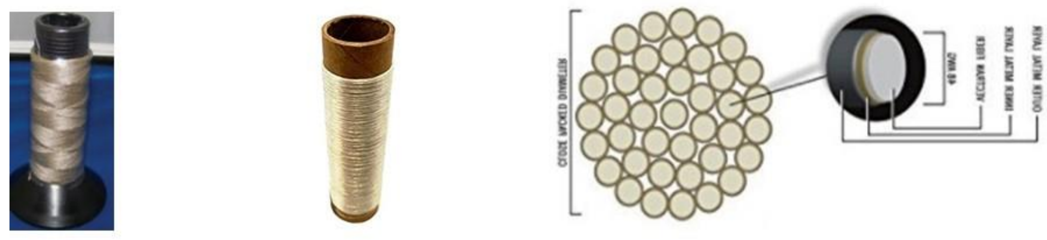
Figure 1 - Washability testing equipment and detergent: (A) washer, (B) dryer, (C) typical household liquid detergent, (D) laundry bags to hold the test samples.

RESULTS AND DISCUSSION

In the following, the washability evaluation results are presented in the order of conductive yarn, conductive fabric and conductive ink.

1.1. Washability evaluation of conductive yarns

Three conductive yarns were evaluated. Each yarn is made from a bundle of finer fibers which are coated with metals and are spun together. Figure 2(A) shows the yarn made from silver coated fibers. Figure 2(B) shows the yarn made from liquid crystal polymer (LCP) fiber coated with multiple layers of metal (inner layer: copper, middle layer: nickel, outer layer: silver). The third yarn is made from silver coated aramid fiber (not shown). The yarns come in the range of 0.25-0.5mm in diameter with fiber diameter in the range of 10um and metal coating thickness around 1um.

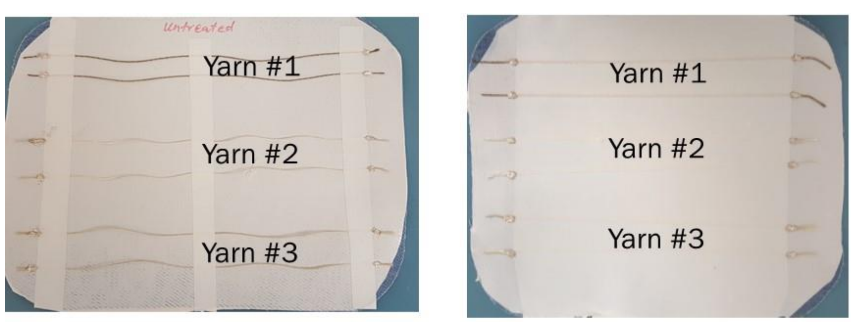


(A) (B) (C)

Figure 2 - Conductive yarns evaluated in this study: (A) yarn#1: silver coated nylon yarn, (B) yarn#2: copper/nickel/silver coated LCP yarn, (C) typical yarns are made from a bundle of metal coated fibers spun together.

Figure 3(A) shows the test coupon made from attaching the conductive yarns to TPU laminated denim patches. The individual yarns were cut to 150 mm length, then permanently attached to the patches using TPU strips laminated at 150ºC using the ironing press. Before the lamination process, some yarns were treated with water resistant coatings. Three coatings were evaluated: one commercial product purchased from an online store, the other two industrial products made from nano materials provided by our partners. After dipping the yarns in the coating solutions for at least 10 minutes, the yarns were heat treated at the temperature of 115ºC for 30 minutes. Figure 3(B) shows the conductive yarns covered by another TPU film laminated at 150ºC as encapsulant. Silver based conductive adhesives were dispensed at the ends of the conductive yarns to serve as test points for electrical resistance measurement. The conductive adhesive was cured at 110ºC for 10 minutes.

The electrical resistance of the conductive yarns was measured before and after each washing/drying cycle. The four wire Kelvin method was used for the measurement to eliminate the measurement wire resistance. Extra care was exercised to ensure the measurement consistency, as the measurement results are highly affected by the tension of the yarns, the pressure on the test probes and measurement locations. Some yarns are known for the fluctuation of resistance during measurement, therefore the measurement data were recorded only after the resistance became relatively stabilized.



(A) (B)

Figure 3 - Conductive yarn evaluation coupons: (A) conductive yarns, either untreated or treated with water resistant coatings, attached to a TPU laminated denim patch through lamination of TPU strips, (B) conductive yarns encapsulated through TPU lamination to a TPU laminated denim patch. Conductive adhesives are applied at the ends of the yarns to serve as test points.

Figure 4 shows the washability testing results of the conductive yarns. A total of 10 laundry cycles were performed. The performance of these yarns is plotted in terms of the resistance after each washing/drying cycle over the initial resistance as a function of laundry cycles. From the figures, it clearly shows that the silver coated nylon yarns (yarn#1) perform the best with relatively stable resistances, and the copper/nickel/silver coated LCP yarns (yarn#2) perform equally well with the exception of one conductive yarn showing a high resistance increase. The silver coated aramid yarns (yarn#3) perform the worst with some yarns showing excessively high resistance just after four laundry cycles. Even with water resistant coatings and TPU encapsulant, the resistance of the conductive yarns do not show consistent improvements, instead some of them show considerable increase as compared with the yarns without treatment.

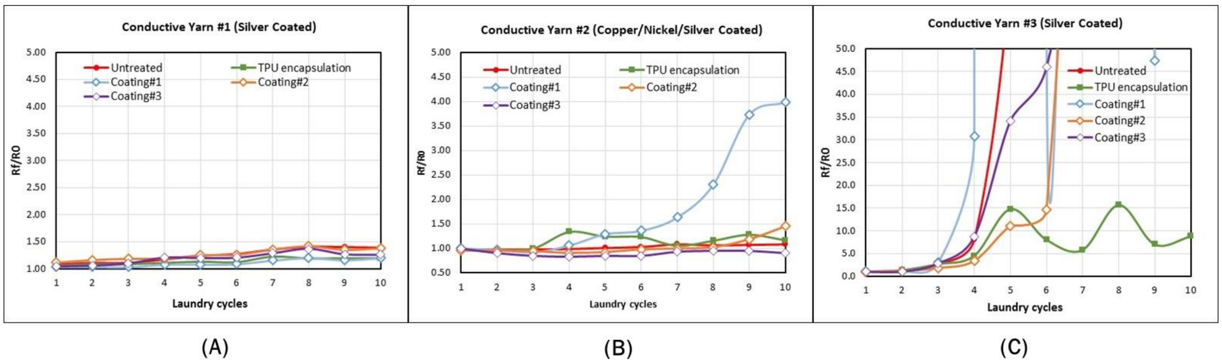


Figure 4 - Washability testing results of conductive yarns during 10 laundry cycles in terms of resistance change (resistance after each cycle over initial resistance) *versus* laundry cycle: (A) yarn#1: silver coated nylon yarn, (B) yarn#2: copper/nickel/silver coated LCP yarn, (C) yarn#3: silver coated aramid yarn.

To understand the performance differences between the three conductive yarns, the yarns after 10 laundry cycles were inspected under optical microscope and scanning electron microscope (SEM). Figure 5 shows the average resistance increase after 10 laundry cycles for the three types of yarns. Yarn#1 and yarn#2 show a relative stable resistance, whereas yarn#3 shows an excessive resistance increase. As seen from the optical images, after 10 laundry cycles the fibers of yarn#1 and yarn#2 maintain the original bundled state; by comparison, the fibers of yarn#3 show considerable loosening and fraying. Some damage to the metal coatings and fibers can be observed for yarn#1 and yarn#2; however, the damage is very limited and do not have a significant effect on their electrical resistance. Fraying of the fibers of yarn#3 makes them more vulnerable to mechanical stresses during washing and drying, leading to significant fiber breakage and metal coating fracture and consequently an excessive resistance increase.

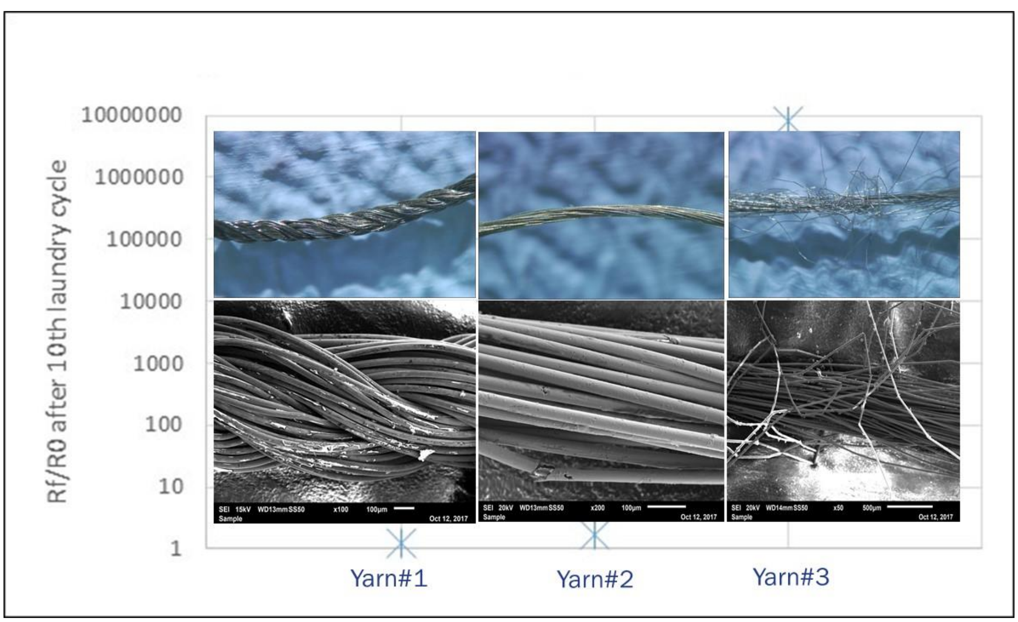


Figure 5 - Comparison of the three conductive yarns in terms of resistance increase and macrostructure after 10 cycles of laundry.

1.2. Washability evaluation of conductive fabrics

Four types of conductive fabrics were evaluated, as shown in Figure 6. All are fabrics woven from yarns made of fibers with different metal coatings. Figure 6(A) shows the silver conductive fabric with nylon fibers coated with silver. Figure 6(B) shows the conductive fabric made from polyester fibers coated with multiple layers of metal with the outer layer being nickel cobalt alloy (for convenience, this fabric is called "nickel-cobalt conductive fabric" or "Ni-Co conductive fabric" in later sections of this paper). Figure 6(C) shows the polyester based fabrics with copper coating. Figure 6(D) shows the copper/nickel coated fabric (in later sections, for convenience, it is called "nickel fabric" or "nickel conductive fabric").

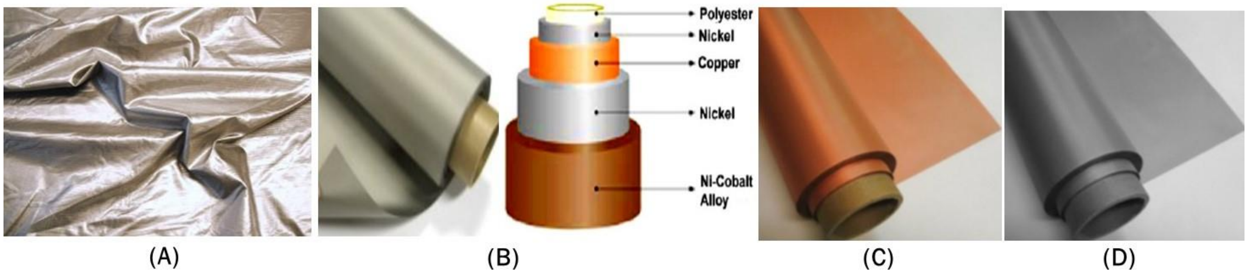


Figure 6 - Conductive fabrics evaluated in this washability study: (A) silver fabric, (B) nickel-cobalt fabric, (C) copper fabric, (D) nickel fabric.

To make test vehicles, the conductive fabrics were cut into narrow strips at a length of around 150 mm and a width of 15mm. The strips were then laminated to a denim patch through a TPU film. Some fabrics were treated with water resistant coatings before the lamination process. Three water resistant coatings were evaluated (the same as the conductive yarn evaluation): one commercial off the shelf coating purchased from an online store and two industrial coatings from our partners. After dipping in the coating solutions for 15 minutes, the conductive fabrics were dried at 115ºC for 30 minutes. Snap buttons were fastened at the two ends of the fabric to make the test points for electrical resistance measurement. Figure 7(A) shows the conductive fabrics laminated to a denim cloth patch.

With the progress of the washability study and new findings emerging from the study, a few new test vehicles were added: conductive fabrics laminated to a spandex patch through a TPU film, conductive fabrics laminated to a denim patch and covered by another TPU film as encapsulant (Figure 7(B)), conductive fabrics laminated to a denim patch and clamped to a rigid wood board (Figure 7(C)).

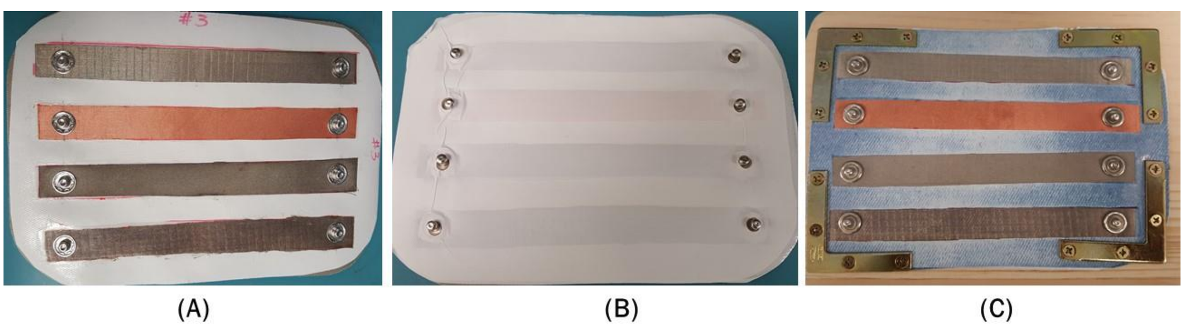


Figure 7 - Conductive fabric evaluation coupons: (A) conductive fabric strips, either untreated or treated with water resistant coatings, laminated to a TPU laminated denim patch, (B) conductive fabric strips laminated between a TPU encapsulant film and a TPU laminated denim patch, (C) conductive fabric strips laminated to a denim patch and clamped to a rigid wood board. Snap buttons are fastened on the fabrics as test points.

In summary, five types of test vehicles were made for this evaluation:

1. Conductive fabric laminated to a denim patch through a TPU film;
2. Conductive fabrics laminated to a denim patch though a TPU film, after being coated with three water resistant coatings respectively;
3. Conductive fabrics laminated to a spandex patch through a TPU film;
4. Conductive fabrics laminated to a denim patch, then covered by another TPU film;
5. Conductive fabrics laminated to a denim patch, then clamped to a rigid wood board.

For all the samples, 10 laundry cycles were performed. Electrical resistance was measured before starting the test and after each cycle, using the 4 wire Kelvin method. Extra care was exercised to ensure the consistency of the measurement results.

Figure 8 shows the test results for the first type of test vehicles: Conductive fabrics laminated to a denim patch through TPU film. The silver conductive fabrics demonstrate the best performance with relatively stable resistance. The nickel-cobalt fabrics and the nickel fabrics show higher resistance increases. By comparison, the copper fabrics show the worst performance, with the electrical resistance increasing excessively within the first few cycles, and the fabrics become virtually open at prolonged cycles. In terms of water resistant coating effect, the nickel-cobalt and copper fabrics treated with water resistant coating #2 appear to show lower resistance as compared to the untreated samples; however, no obvious improvement can be observed for the silver and nickel fabrics with this coating treatment. Comparatively, the other two coatings show either an adverse effect or no obvious improvement.

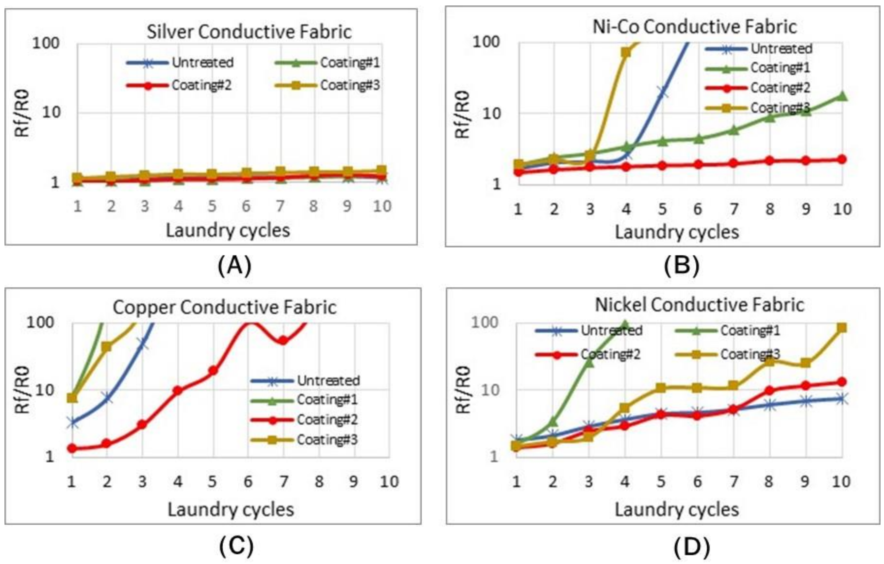
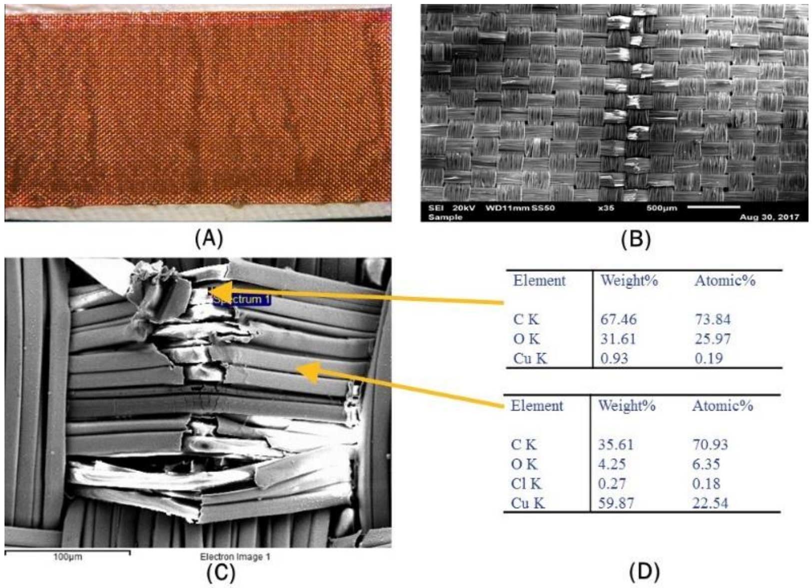


Figure 8 - Washability testing results of conductive fabrics laminated to a denim patch in terms of resistance change (resistance after each cycle over initial resistance) *versus* laundry cycle: (A) silver conductive fabric, (B) nickel-cobalt conductive fabric, (C) copper conductive fabric, (D) nickel conductive fabric.

We needed to find out what caused the resistance increase during the laundry cycles and explain the differences between the performance of these fabrics. Since the copper fabrics showed the most excessive resistance increases, we started with the inspection of the copper fabric. Figure 9 shows the optical and SEM inspection of the copper fabrics. Folding marks are clearly observed on the copper fabrics after 10 cycles of laundry (Figure 9(A)). Resistance was measured across the folding marks, showing either excessively high resistance (in million-ohm range) or completely open. Figure 9(B) and Figure 9(C) show the folding areas in high magnification under SEM, showing fracture and complete loss of coated metals at the folding areas, which are confirmed by EDS measurement (Figure 9(D)).



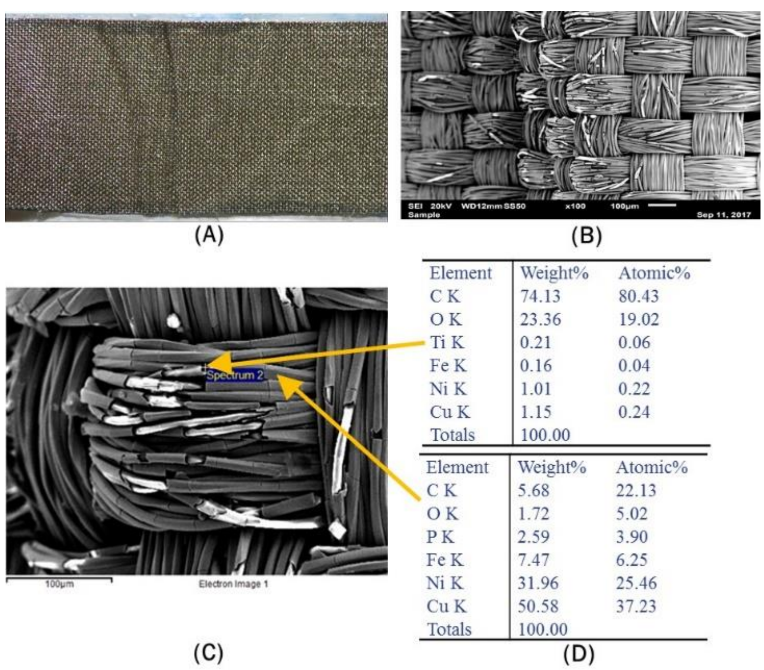
Element	Weight%	Atomic%
C K	67.46	73.84
O K	31.61	25.97
Cu K	0.93	0.19

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

Figure 9 - Copper conductive fabric after 10 laundry cycles: (A) folding marks on the fabric under optical inspection, (B) cracks of coated metal layers under SEM, (C) and (D) macrostructure of the fabric at the fracture areas and EDS analysis.

Folding marks are also observed on the nickel-cobalt conductive fabrics, as shown in Figure 10(A). SEM and EDS confirm the fracture and loss of coated metal layers at the folding areas. By comparison with the copper conductive fabrics, the loss of coated metal layers is less significant for the nickel-cobalt conductive fabrics, correspondingly the electrical resistance showed a modest increase during laundry.

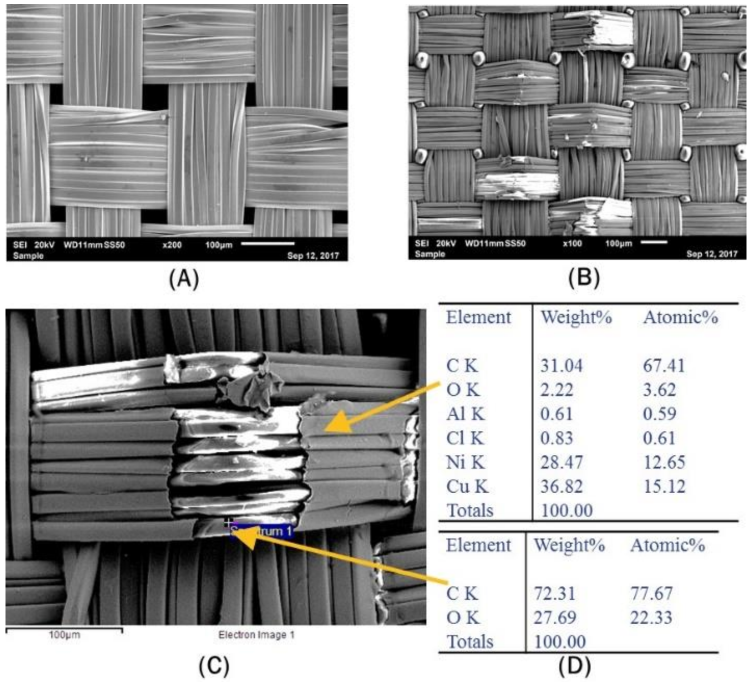
The nickel conductive fabrics perform similarly to the nickel-cobalt conductive fabrics, showing a modest level of coated metal fracture and increase in electrical resistance. Figure 11 shows the optical and SEM inspection results and EDS measurement of the nickel conductive fabrics after 10 laundry 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	

Figure 10 - Nickel-cobalt conductive fabric after 10 laundry cycles: (A) folding marks on the fabric under optical inspection, (B) loss of coated metal layers under SEM, (C) and (D) macrostructure of the fabric at the fracture areas and EDS analysis.

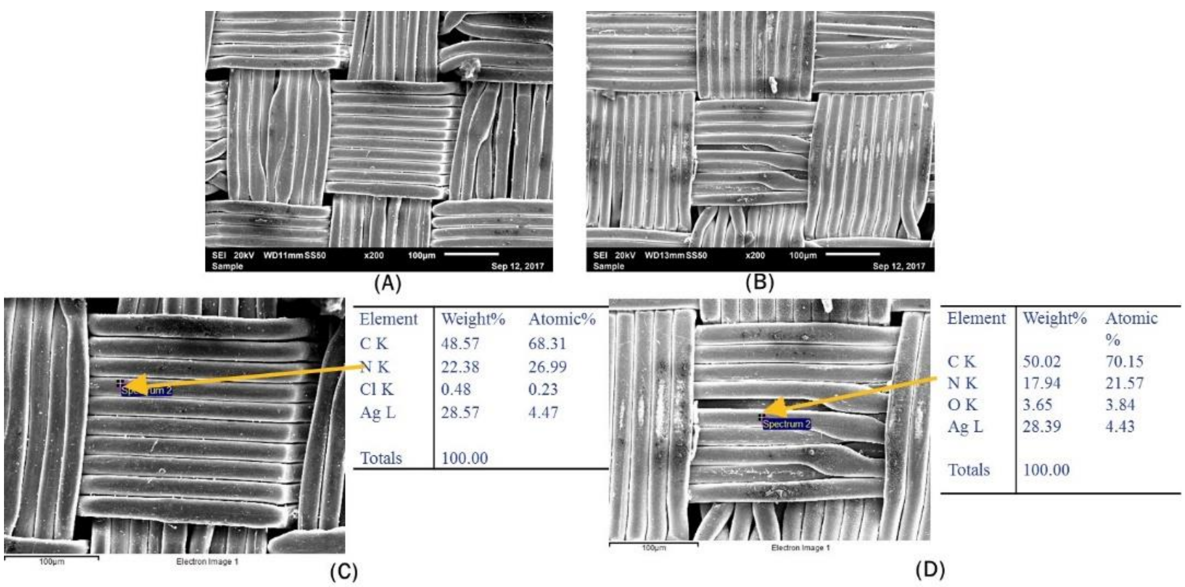


Element	Weight%	Atomic%
C K	31.04	67.41
O K	2.22	3.62
Al K	0.61	0.59
Cl K	0.83	0.61
Ni K	28.47	12.65
Cu K	36.82	15.12
Totals	100.00	

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

Figure 11 - Nickel conductive fabrics before and after 10 laundry cycles: (A) fabric before laundry, (B) loss of coated metal layers under SEM, (C) and (D) macrostructure of the fabric at the fracture areas and EDS analysis.

By comparison, the silver conductive fabrics perform much better than the rest of the conductive fabrics. SEM inspection reveals little damage on the silver conductive fabrics, as shown in Figure 12, which is consistent with the electrical resistance measurement.



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	

Figure 12 - Silver conductive fabrics before and after 10 laundry cycles: (A) fabric before laundry, (B) fabric after 10 laundry cycles, (C) macrostructure of the fabric before laundry and EDS analysis, (D) macrostructure of the fabric after 10 laundry cycles and EDS analysis.

From the above washability test and inspection results on the conductive fabrics laminated to denim cloth patches, a hypothesis was gradually formed: the increase in electrical resistance of the conductive fabrics is mainly a result from the fracture and loss of the metal coatings on the yarn fibers, which is caused by the dynamic mechanical stresses during washing and drying. The dynamic mechanical stresses come in different styles during laundry, such as agitation, tumbling, torsion, crumpling, folding, bending, et al; as a result, the denim patches will fold or bend back and forth repeatedly, forcing the conductive fabrics to fold or bend correspondingly, which will inevitably cause the fracture of metal coatings and lead to an increase of resistance. Based on this hypothesis, it is natural to ask the question: how will the conductive fabrics perform if the mechanical stresses are minimized?

Based on this train of thought, we redesigned our experiments and added three test vehicles using the four types of conductive fabrics:

1. conductive fabrics laminated to spandex cloth (same as shown in Figure 7(A));
2. conductive fabrics laminated to denim with TPU film encapsulant (Figure 7(B));
3. conductive fabrics laminated to denim and clamped to a rigid board (Figure 7(C)).

Spandex is a stretchable fabric, much softer than denim. It is expected that the conductive fabrics laminated to spandex will experience less mechanical stresses during washing and drying. By comparison, the conductive fabrics laminated to denim will experience forced bending and folding. By covering the conductive fabrics with a TPU film, the conductive fabrics are sealed off to the attack by chemicals in the water; furthermore, the TPU film may serve as the reinforcement to the underneath conductive fabrics to minimize the mechanical stress and consequently may reduce the damage to the metal coatings. By clamping the conductive fabrics to a rigid board, the conductive fabrics may not experience the same bending or folding as in other test vehicle configurations, especially lamination to the semi-flexible denim patch. It was expected that these added test vehicles will provide better performance as compared with the original one: conductive fabrics laminated to denim.

Figure 13 shows the performances of the added three test vehicles during the ten cycles of laundry. Clearly, the conductive fabrics clamped to a rigid board demonstrate the best performance with resistances kept at stable values throughout the laundry cycles. The conductive fabrics laminated to spandex show a modest increase in resistance, whereas the conductive fabrics laminated to denim with TPU film encapsulation show the highest increase in resistance in general. In terms of comparison between the four conductive fabrics, the silver conductive fabrics exhibit the most stable resistance, the copper fabrics show the highest increase, and the nickel-cobalt and nickel conductive fabrics come in between.

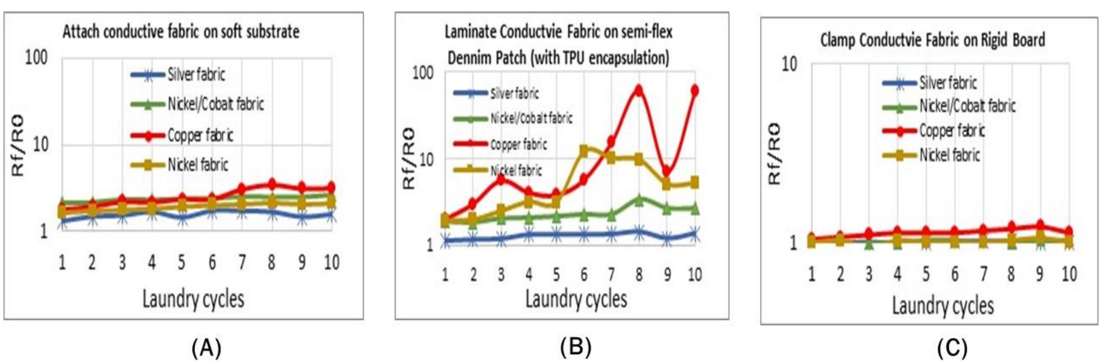


Figure 13 - Washability testing results of conductive fabrics laminated to different substrates during laundry in terms of resistance change (resistance after each cycle over initial resistance) *versus* laundry cycle: (A) conductive fabrics laminated to soft substrate: spandex, (B) conductive fabrics laminated between TPU film and denim substrate, (C) conductive fabrics laminated to denim substrate and clamped to a rigid board.

If we combine the results of the conductive fabrics in four configurations, the trend is clear, as shown in Figure 14. For all the configurations, the conductive fabrics clamped to the rigid board demonstrate very stable resistance throughout the washing and drying cycles. Except for the silver conductive fabrics, the nickel-cobalt, copper and nickel conductive fabrics laminated to the flexible spandex patch show better performance than the fabrics laminated to the semi-flexible denim patch. For the conductive fabrics laminated to denim and covered by TPU film, the resistances do not maintain stable values as we expected, instead they show modest increases, although they are sealed off from the water.

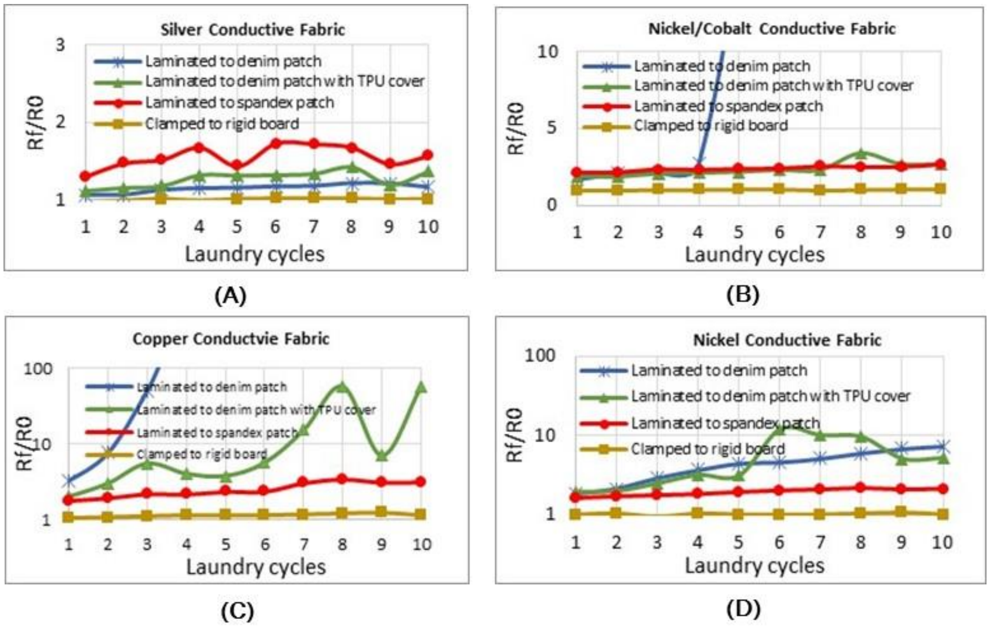


Figure 14 - Washability testing results of conductive fabrics laminated to different substrates during laundry, in terms of resistance change (resistance after each cycle over initial resistance) *versus* laundry cycle: (A) silver conductive fabric, (B) nickel-cobalt conductive fabric, (C) copper conductive fabric, (D) nickel conductive fabric.

Figure 15 shows the final resistance change after the 10th laundry cycle for the four types of conductive fabrics. All the conductive fabrics clamped to rigid boards demonstrate the best performance by maintaining very stable resistance throughout the laundry cycles. With the exception of the silver conductive fabrics, the other conductive fabrics laminated to the semi-flexible denim patch demonstrate the worst performance with highest resistance increases, especially for the copper and nickel-cobalt conductive fabrics. The conductive fabrics laminated to the soft spandex patch come in between with modest resistance increases. The silver conductive fabrics maintain relatively low resistance increases as compared to other types of conductive fabrics.

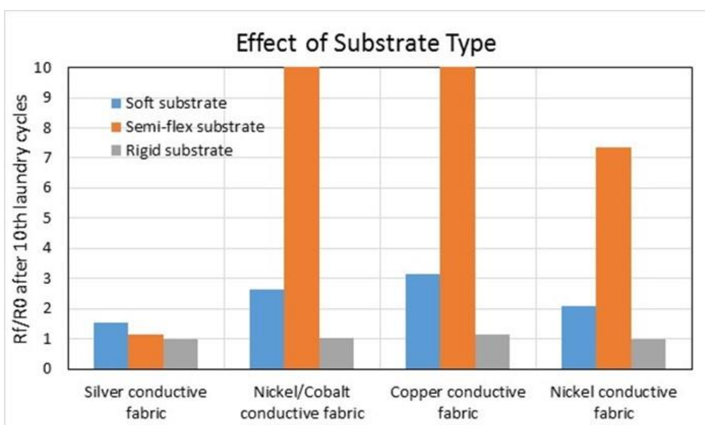


Figure 15 - Comparison of resistance change of the conductive fabrics after 10 laundry cycles.

Figure 16 shows the SEM inspection of the conductive fabrics clamped to the rigid board after 10 cycles of washing and drying. Except for the silver conductive fabrics, no visible damage was observed for the other three types of conductive fabrics. The currently used detergent has not caused an obvious effect on the copper, nickel and nickel-cobalt coated fabrics. Once the mechanical stresses are minimized, these conductive fabrics will maintain their metal coating integrity and therefore maintain stable resistance values. The silver conductive fabrics show certain damage of the metal coatings on the yarn fibers bulged from the fabric surface. It appears that the metal damage was more likely caused by the abrasion of the fabric with the laundry bag than by the corrosion of chemicals in the water, since the metal coating damage only shows up on certain yarn fibers which are bulged from the fabric surface. If it were corrosion, the metal coating damage should have occurred randomly on all the yarn fibers, not just on fibers along a certain orientation. Since the damage is limited and the coating layers are still continuous along the fibers, the silver conductive fabrics have not shown an increase in resistance.

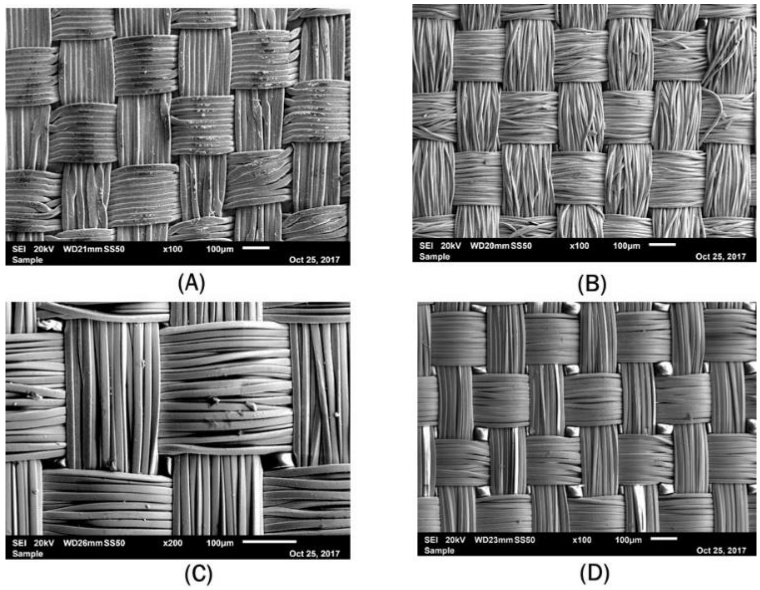


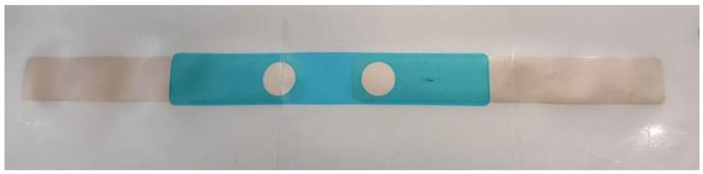
Figure 16 - SEM inspection of the conductive fabrics clamped to rigid board after 10 laundry cycles: (A) silver conductive fabric, (B) nickel-cobalt conductive fabric, (C) copper conductive fabric, (D) nickel conductive fabric.

Below is a summary of the performance of the four types of conductive fabrics during the laundry cycles:

- In general, the conductive fabrics show an increase of resistance with laundry cycles. The extent of the increase depends on the fabric type, metal coating, and the substrates to which the fabrics are attached.
- The conductive fabrics clamped to a rigid board demonstrate the best performance with resistance maintaining at stable values, the conductive fabrics laminated to a semi flexible substrate like denim perform the worst with the highest increase in resistance, whereas the conductive fabrics laminated to a soft substrate like spandex show the performance in between. By clamping the fabrics to the rigid board, the conductive fabrics are prevented from folding or bending due to mechanical stresses during laundry, the metal coatings maintain their integrity without fracture and therefore their resistance remains stable. By laminating the fabrics to the semi flex substrate, the fabrics will be forced to bend and fold, causing fracture of the metal layers and correspondingly a significant increase of resistance. When the conductive fabrics is laminated to a soft substrate, the bending stresses will be mitigated although they may not be completely eliminated, corresponding to the resistance of the fabrics showing a modest increase.
- The silver conductive fabrics perform the best among the 4 types of conductive fabrics evaluated. No obvious evidence of metal coating fracture is observed. The silver coating on resilient nylon fiber cores may be more resistant to mechanical stresses and therefore less prone to fracture and damage. Consequently, silver conductive fabrics show relatively stable resistance during washing and drying cycles.
- In general, with water resistance coatings and TPU laminations, the conductive fabrics continue to show an increase in resistance. Water resistance coatings may be washed away with washing cycles and gradually lose their intended function to seal off the conductive fabrics from attack of chemicals in the water. However, with untreated samples, no strong indication of corrosion or erosion on the metal coatings is observed with current mild household detergent. Therefore, chemical stresses during laundry are regarded as a secondary factor, the most significant factor is the mechanical stresses experienced by the conductive fabrics. The water resistance coatings and TPU lamination do not provide adequate mechanical reinforcement to the conductive fabrics, consequently the electrical resistance of the conductive fabrics continue to increase even with the water-resistant coatings and encapsulations.

1.3. Washability evaluation of conductive ink

Besides conductive yarns and conductive fabrics, a limited evaluation was also done on conductive ink. A prototype ECG (electrocardiogram) sensor is used for this study (Figure 17(A)). To make the ECG sensor, a silver conductive ink was printed on TPU film, then Ag/AgCl ink was printed over the selected areas of the printed silver ink to make the electrodes, with the rest of printed silver ink covered by a layer of dielectric ink with the exception of the connection areas to the control module. For this study, the printed ECG sensor was laminated to a spandex fabric. Electrical resistance was measured from one end of the printed ink strip to the center areas where the connection to the control module is made. For comparison purposes, the printed ECG sensor was also clamped to a rigid board (shown in Figure 17(B)). Two resistances were measured. One resistance was measured from the edges of the printed dielectric ink to check the effect of the dielectric ink protection during the laundry cycles. The other resistance was measured across the exposed electrode (Ag/AgCl) area (not covered by the dielectric ink).



(A)

(B)

Figure 17 - Conductive ink coupons evaluated in this study: (A) conductive ink printed on TPU film and laminated to spandex substrate, (B) conductive ink printed on TPU film and clamped on a rigid board. Some areas of the conductive ink are covered by dielectric ink (green color).

Figure 18 shows the comparison between the conductive ink laminated to a soft substrate (spandex) and clamped to a rigid board. A clear difference can be observed. The conductive ink laminated to spandex fabric shows a sharp increase in resistance during laundry, whereas the conductive ink clamped to the rigid board, either covered or not covered by the dielectric ink, does not see any change in resistance. As a matter of fact, the conductive ink clamped to the rigid board even show a slight decrease in resistance. This study further confirms our initial hypothesis drawn on the study of conductive fabrics: it is the mechanical stresses during the laundry that cause major damage to the evaluated materials, leading to the increase in resistance. Chemical stresses do not show an obvious effect on the integrity of the materials at current laundry conditions and cycles.

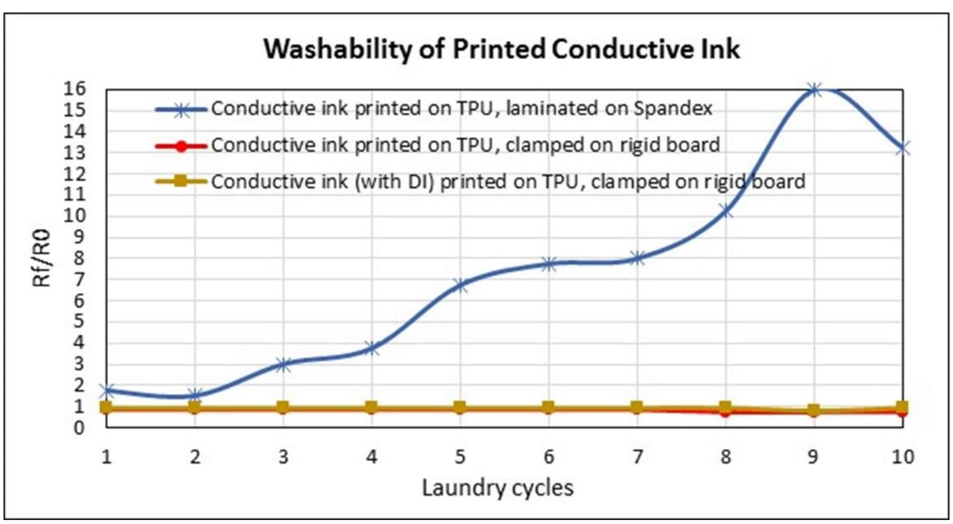


Figure - 18 Comparison of resistance change of the conductive ink attached to different substrates during 10 laundry cycles.

2. SUMMARY AND CONCLUSIONS

Washability testing was 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 was also evaluated.

In general, the conductive fabrics show an increase of resistance with laundry cycles. The extent of the increase depends on the fabric type, metal coating, and the substrates to which the fabrics are attached or laminated.

During laundry the e-textile materials experience a variety of mechanical, thermal and chemical stresses. The dynamic mechanical stresses play a dominant role causing the degradation of the materials while the chemical stresses do not appear to be a factor for the currently used detergent and laundry conditions. During laundry, the dynamic bending and folding of the materials cause fracture of the metal coatings and correspondingly loss of metals, leading to an increase in electrical resistance. The substrates to which the conductive materials are attached significantly impact the performance of the conductive materials during laundry cycles. 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.

Water resistance coatings and TPU encapsulation do not show a consistent and clear-cut improvement, since they may not provide adequate mechanical reinforcement to the conductive materials.

Further work is underway to fully understand the impact of different test and design factors on the washability of e-textile materials. Hopefully our work will serve as a catalyst to motivate more studies in the wearable and e-textile industries.

ACKNOWLEDGMENTS

The authors would like to thank Allen Ray, Christopher Vu, Francoise Sarrazin of AEG Lab of Flex for some of the inspection and testing work.

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Washability of E-Textile Materials

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Outline

- Introduction to E-Textiles
- Challenges with E-Textiles
- Washability Testing: plan, results and analysis
- Summary and Conclusions

Introduction to E-Textiles

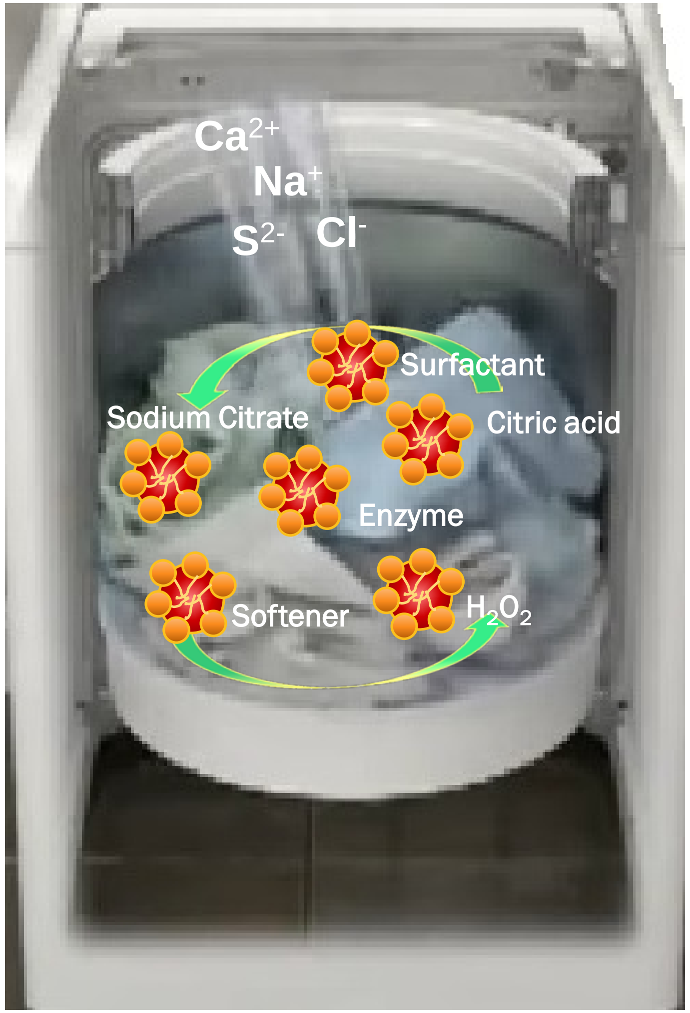
E-textiles, also known as intelligent textiles, smart textiles, smart fabrics, smart garments, or smart clothing, are fabrics with electronics, sensors, and power sources embedded in them which provide electronics functionality and at the same time maintain textile characteristics

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 Washability 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 Washability

- Limited studies on e-textile washability

- Lack of knowledge on e-textile behavior during washing and drying cycles
  - What are the factors affecting the e-textile washability 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 washability 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)

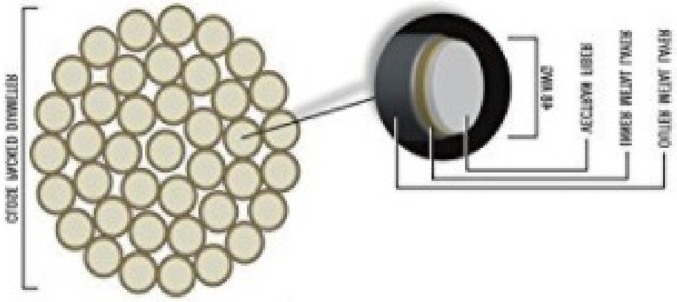
Liquid detergent

Drying Condition (Normal, 30 minutes per cycle)

Laundry bag

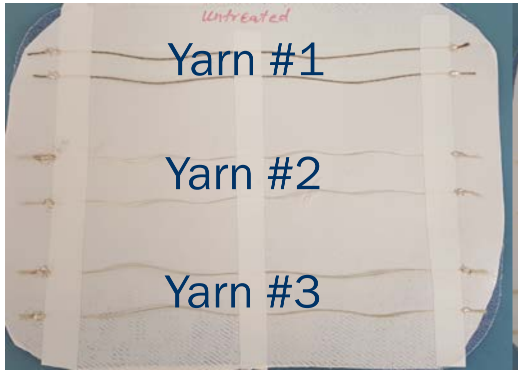
Washability of Conductive Yarns

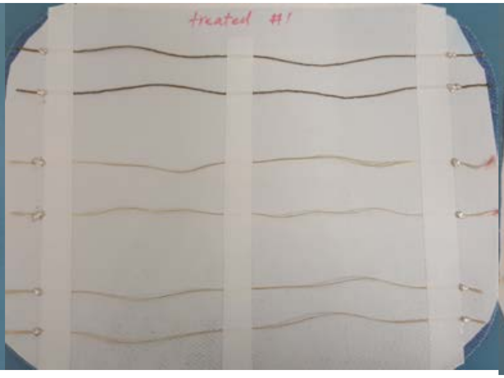
- **Evaluated three types of conductive yarns**
  - #1: silver coated nylon yarn
  - #2: copper/nickel/silver coated LCP yarn
  - #3: silver coated aramid yarn

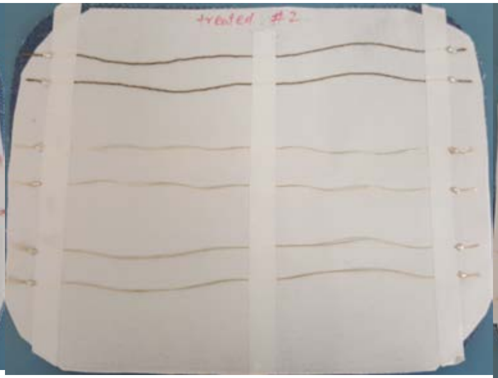


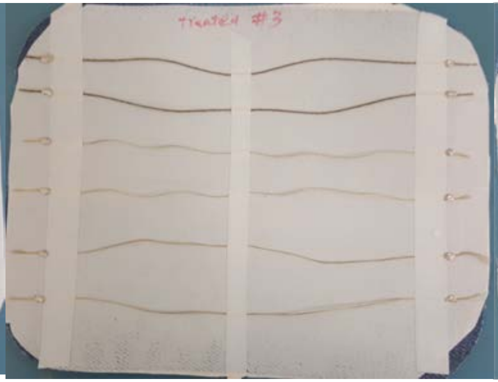
- **Sample preparation**
  - Three types of water resistant coatings (yarns dipped in coating solutions and heat treated at 115^{o}C)
  - The yarns permanently secured to denim patches through lamination of TPU strips or TPU lamination as encapsulant (laminated at 160^{o}C)
  - Silver conductive adhesives dispensed on the ends of yarns to make test points

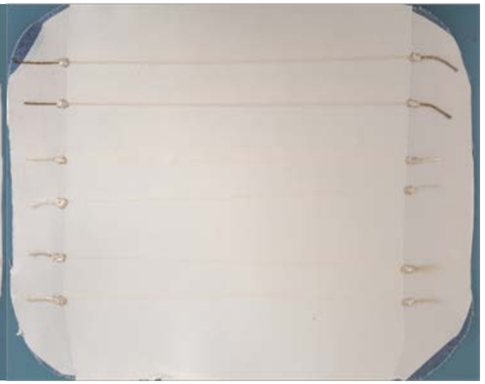
Untreated samples | **WR Coating #1** | **WR Coating #2** | **WR Coating #3** | **TPU Laminated**





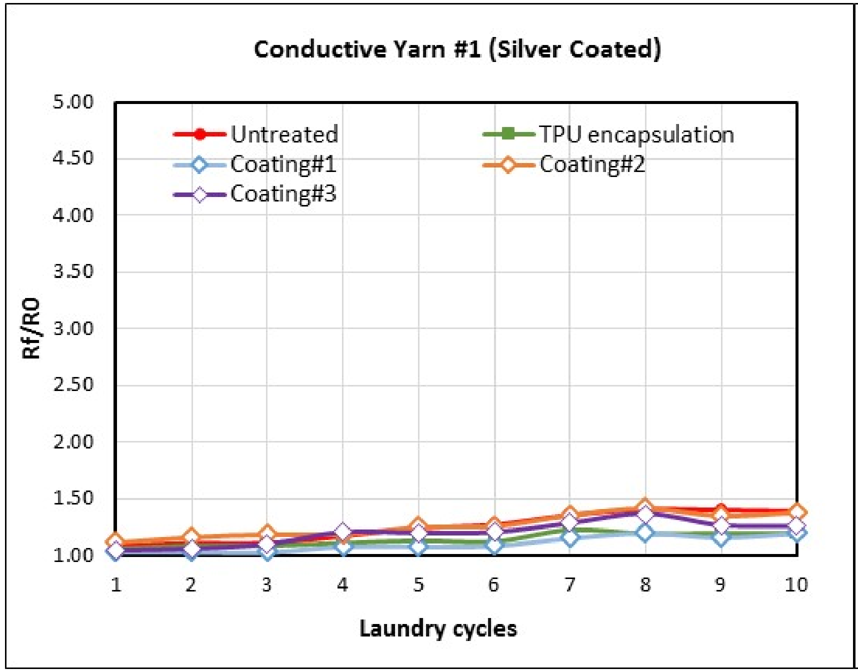


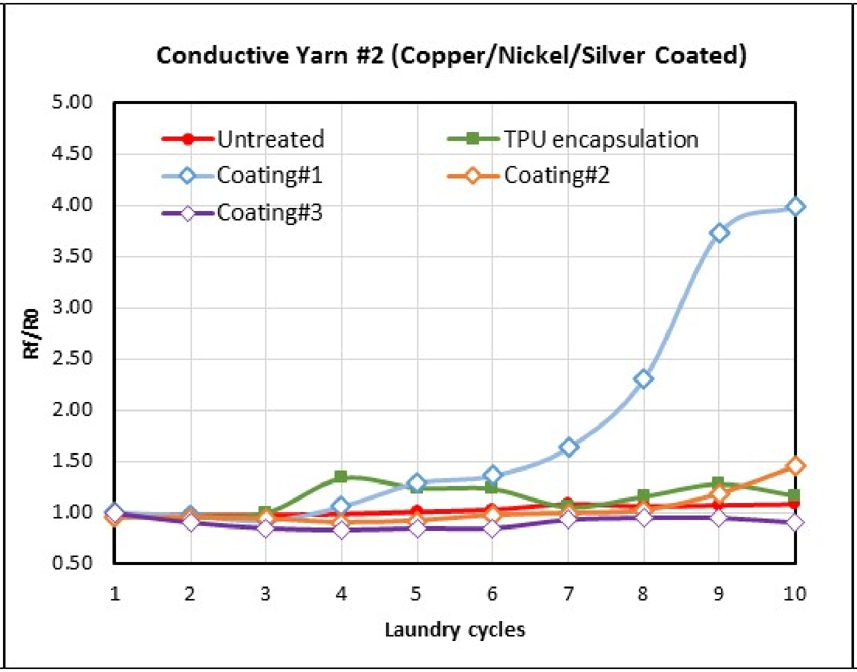


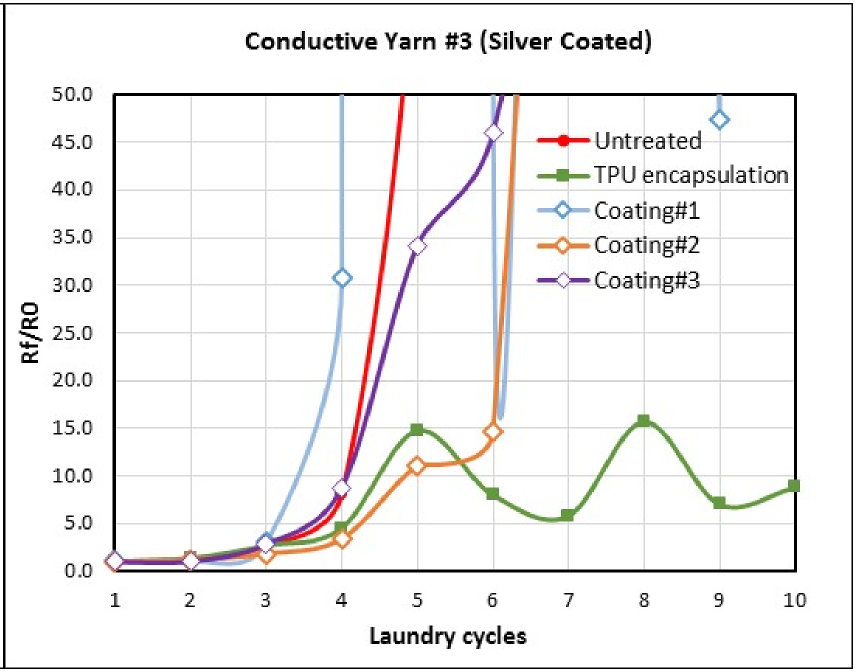


Washability of Conductive Yarns

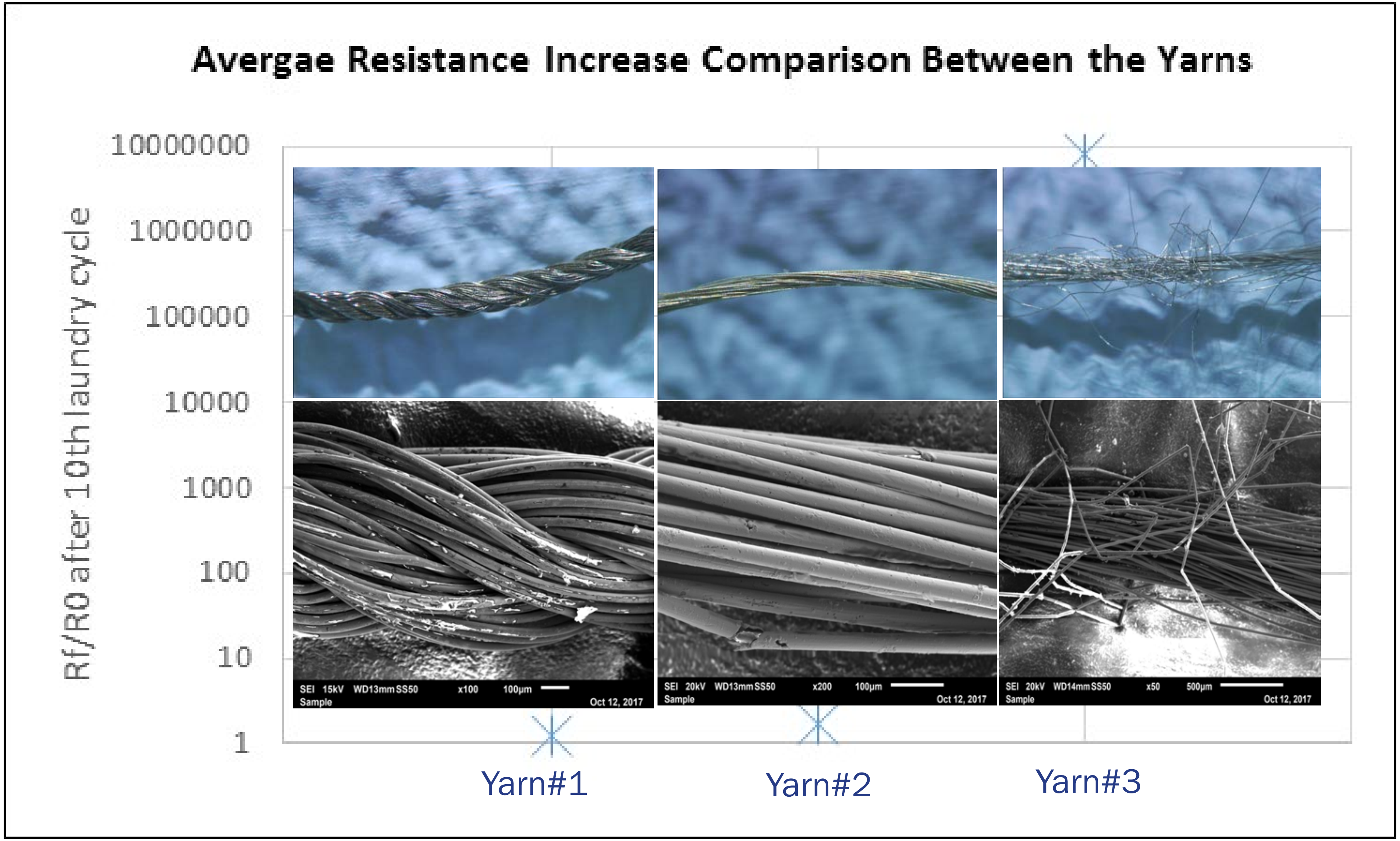
- In general resistance of the yarns increases with washing/drying cycles
  - Yarn#1 performs the best, yarn#2 performs similar to Yarn#1 with exception of one yarn, yarn#3 shows an excessive increase in resistance
- Resistance continues to show increase even with water resistance coatings and TPU lamination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







Washability of Conductive Yarns (Av. Resistance Increase)

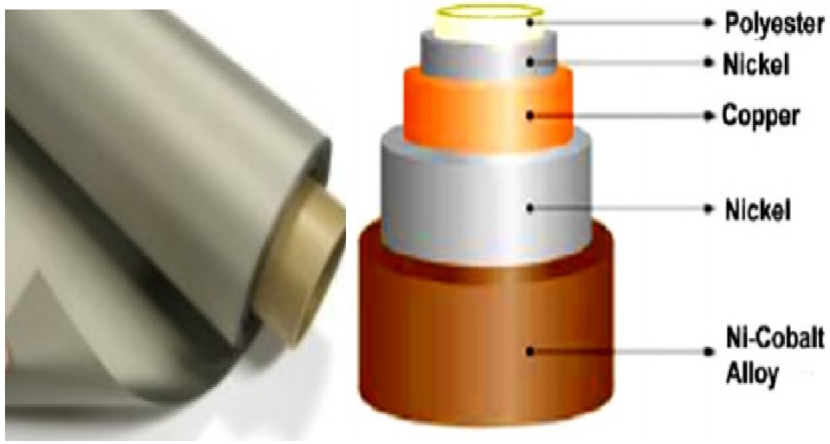


Washability of Conductive Fabrics

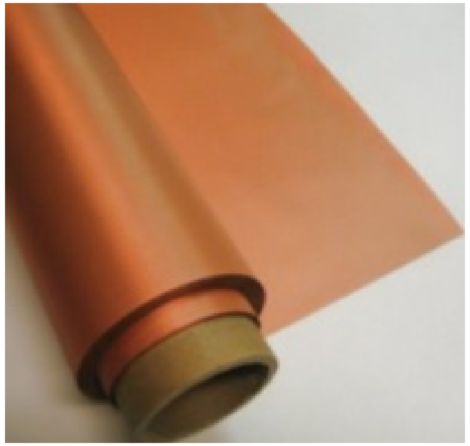
Evaluated four types of conductive fabrics:

- 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)

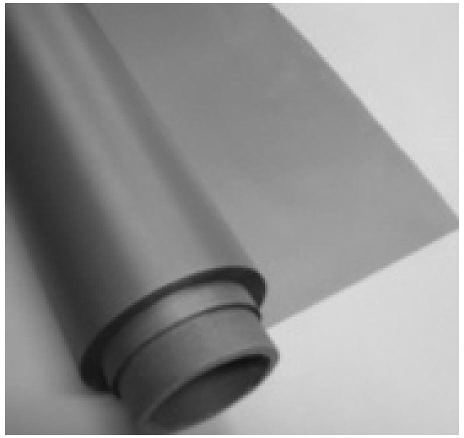
Silver fabric



NiCo fabric



Copper fabric



Nickel fabric

Washability 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

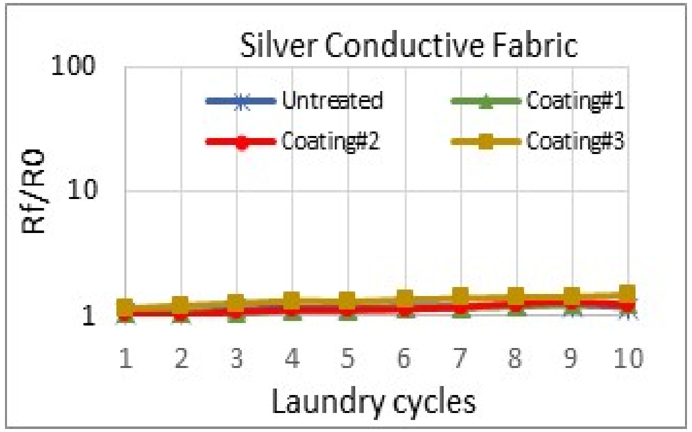
Conductive fabric laminated to denim patch with TPU film laminated as encapsulant

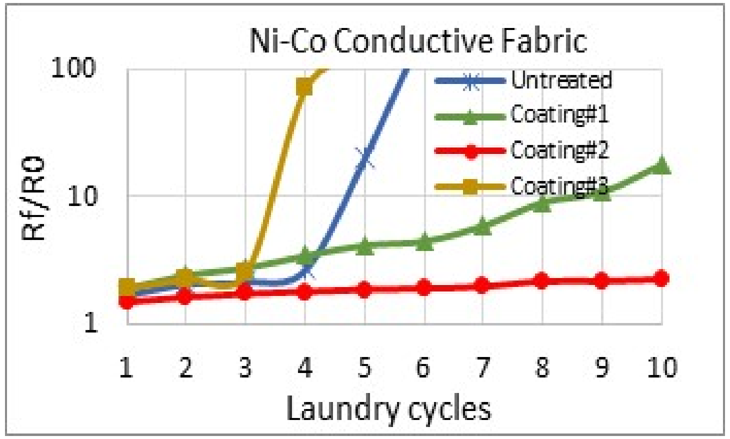
Conductive fabric laminated to denim patch then clamped on rigid board

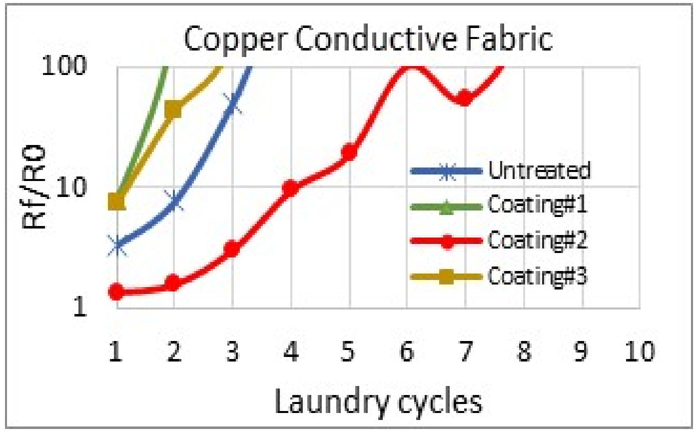
Analysis of Washability Study

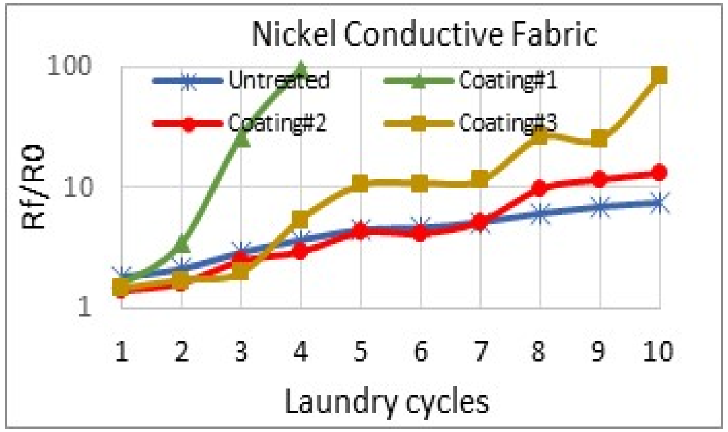
- 10 cycles of washing and drying performed
- Resistance of the conductive fabrics shows increase with laundry cycles. The level of increase depends on the type of fabric:
- Performance ranking: Silver fabric>nickel fabric~cobalt fabric>copper fabric
- With water resistance coatings, resistance of the 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



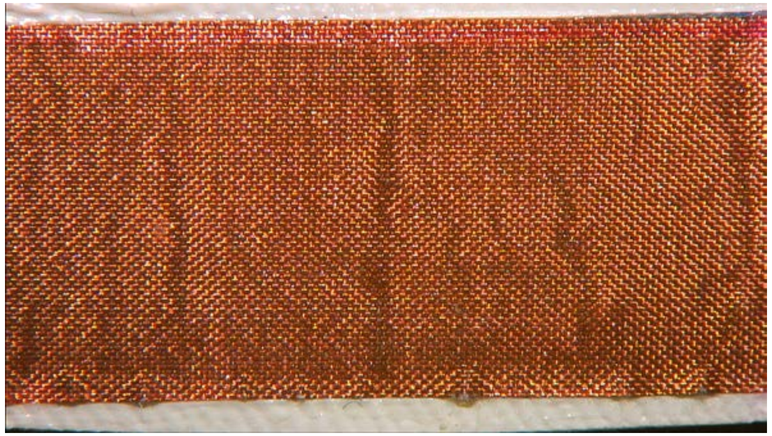


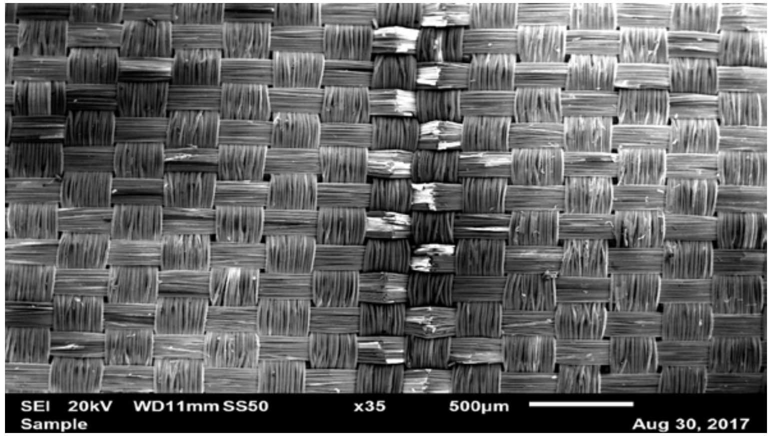


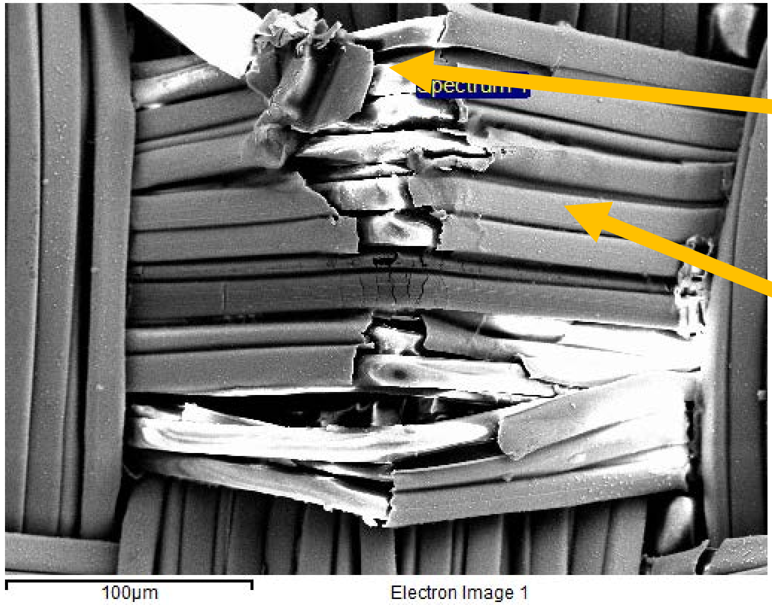


SEM Inspection after 10 Cycles Washability Study

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





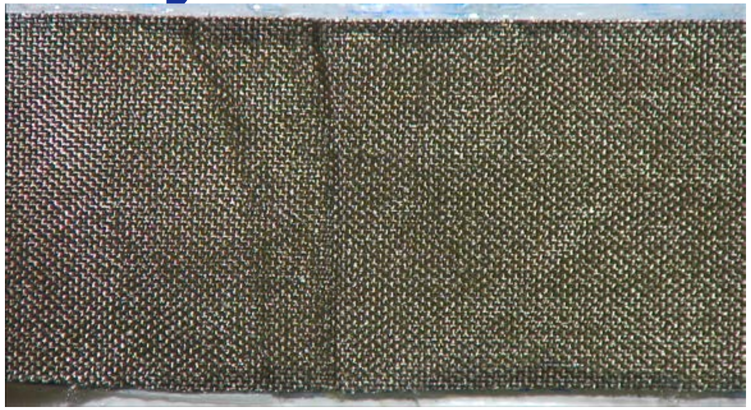


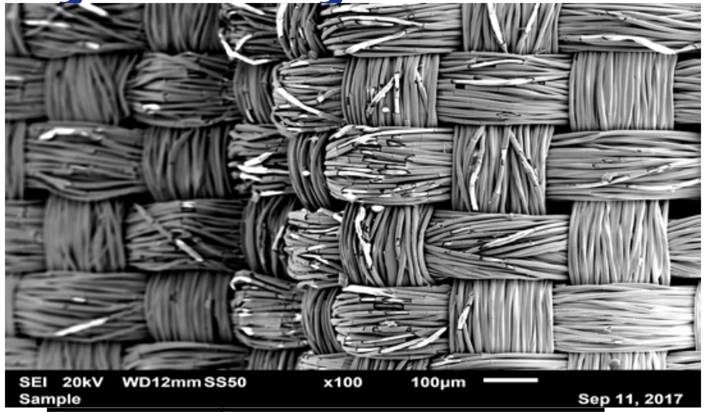
Element	Weight%	Atomic%
C K	67.46	73.84
O K	31.61	25.97
Cu K	0.93	0.19

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

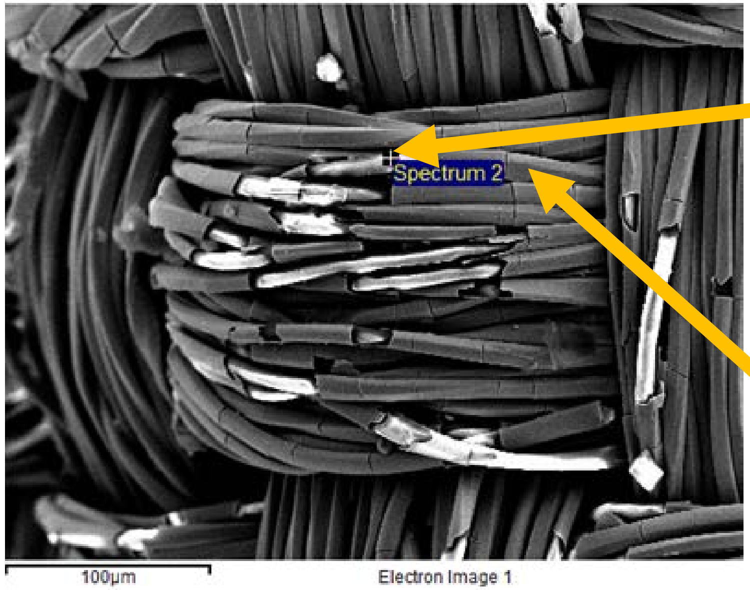
SEM Inspection after 10 Cycles Washability Study

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	

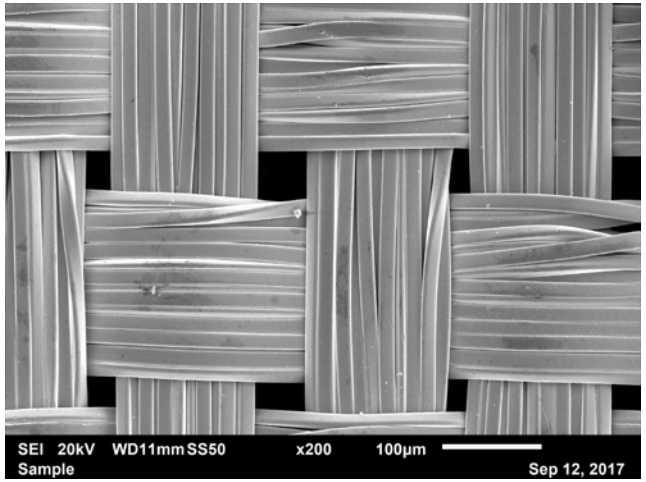


Element	Weight%	Atomic%
C K	5.68	22.13
O K	1.72	5.02
P K	2.59	3.90
Fe K	7.47	6.25
Ni K	31.96	25.46
Cu K	50.58	37.23
Totals	100.00	

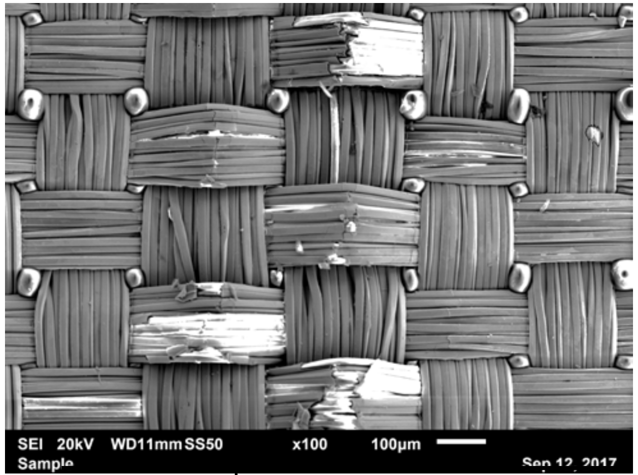
SEM Inspection after 10 Cycles Washability Study

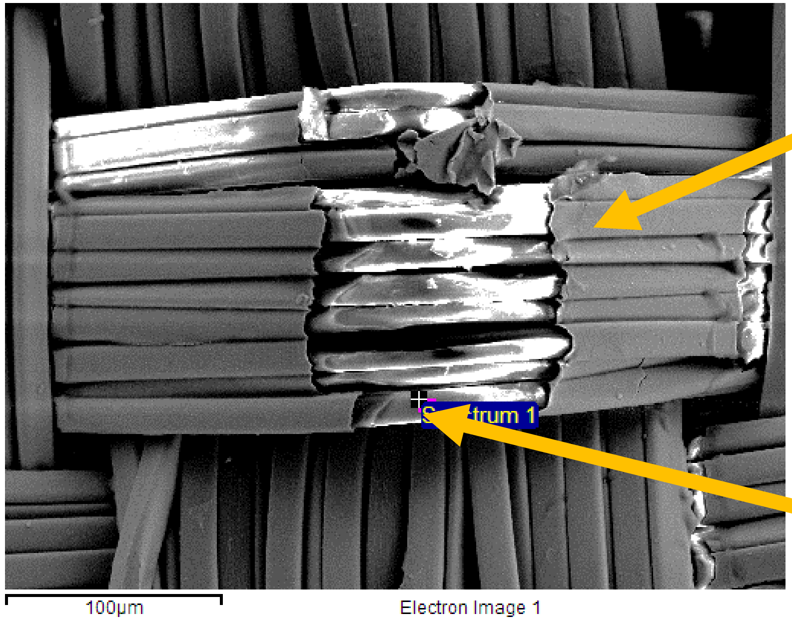
Nickel conductive fabric laminated to semi-flex substrate (Denim) after 10 laundry cycles

Nickel conductive fabric



After wash (laminated to denim)





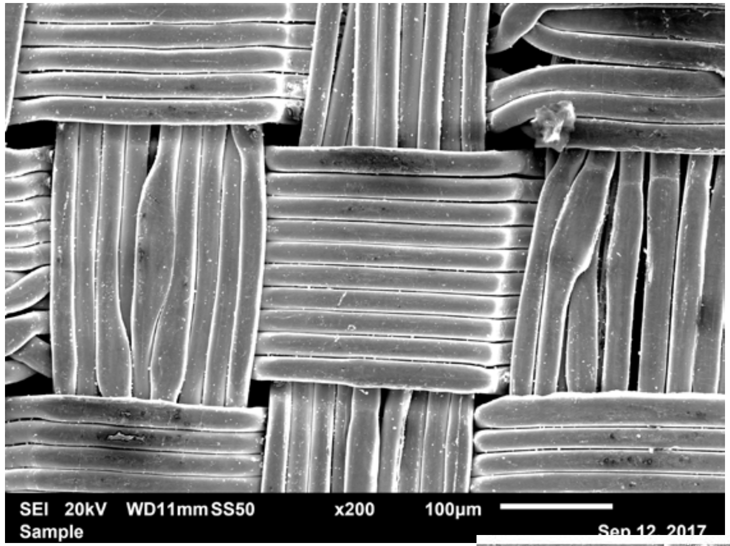
Element	Weight%	Atomic%
C K	31.04	67.41
O K	2.22	3.62
Al K	0.61	0.59
Cl K	0.83	0.61
Ni K	28.47	12.65
Cu K	36.82	15.12
Totals	100.00	

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

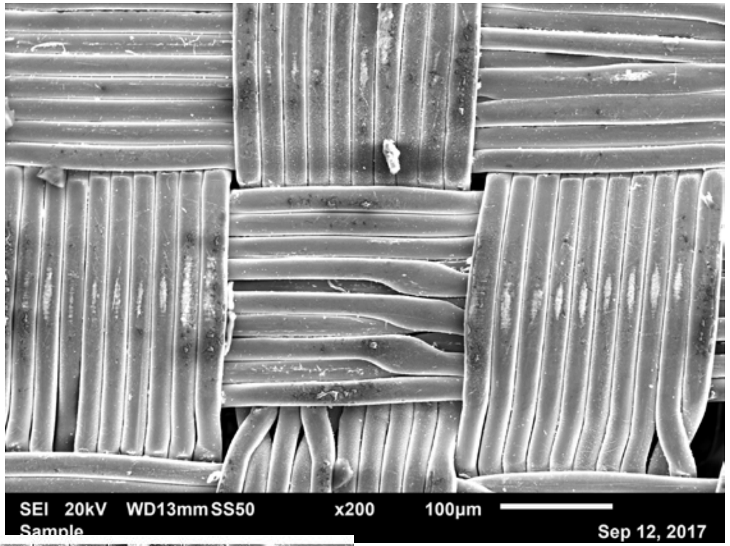
SEM Inspection after 10 Cycles Washability Study

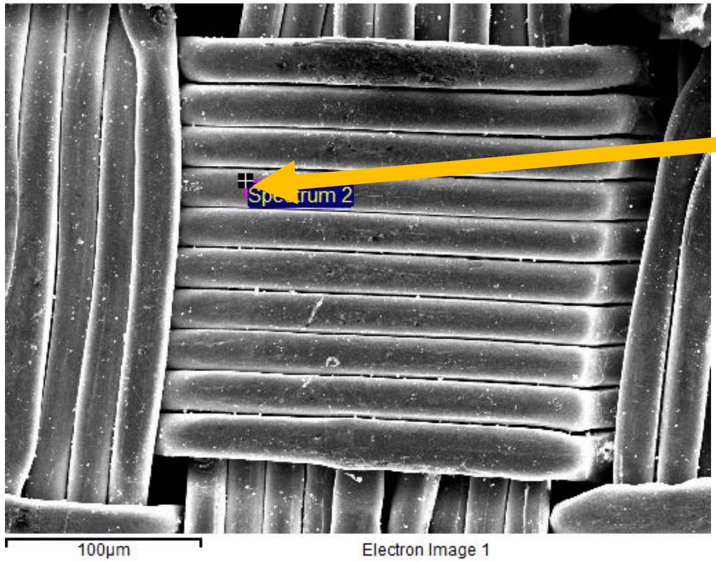
Silver conductive fabric laminated to semi-flex substrate (Denim) after 10 laundry cycles

Before wash

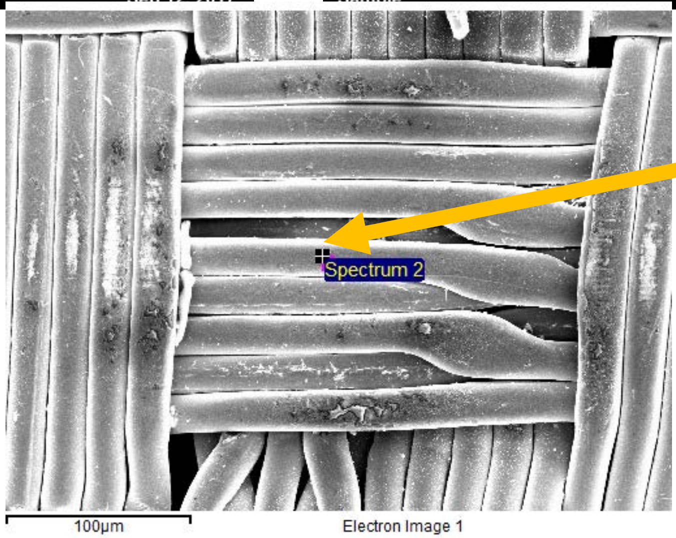


After wash





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	

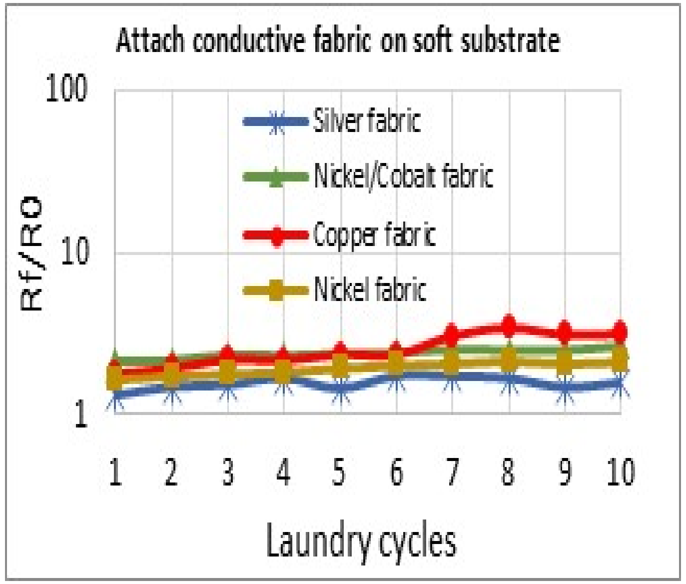
Analysis of Washability Study

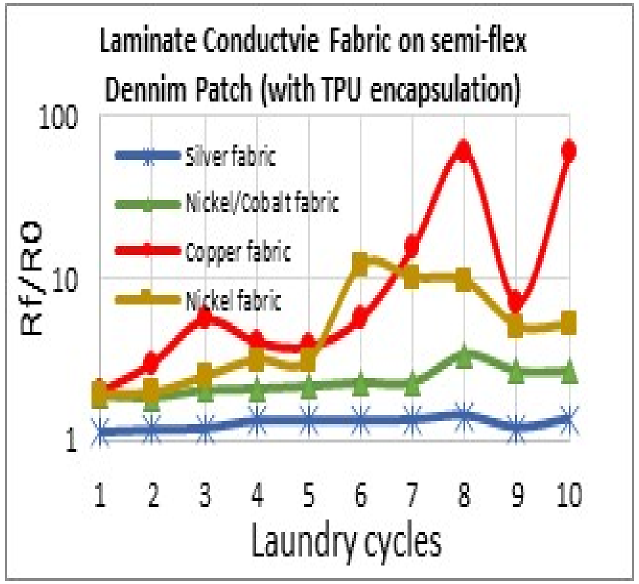
- Based on the test results and SEM inspection, a hypothesis was gradually formed: the increase in electrical resistance of the conductive fabric is mainly caused by fracture and loss of metal coatings on the yarn fibers, which is caused by the dynamic mechanical stresses during washing and drying

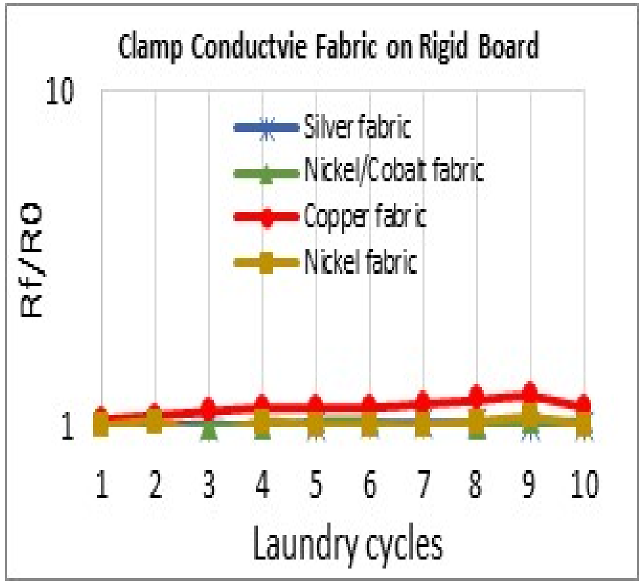
- If the mechanical stresses are minimized, what will happen to the conductive fabrics?

Conductive Fabrics Laminated to Different Substrates

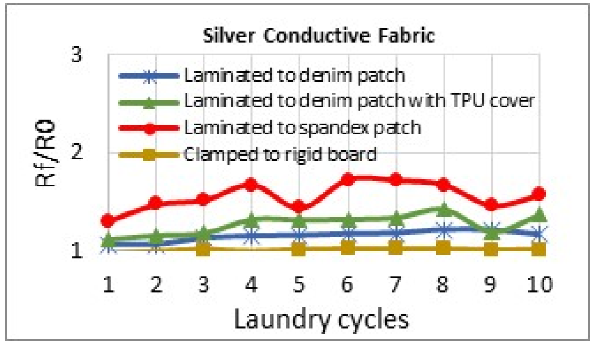
(Spandex, Denim with TPU encapsulation, Rigid board)

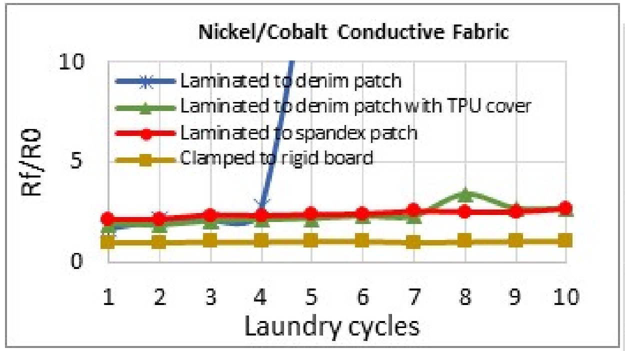


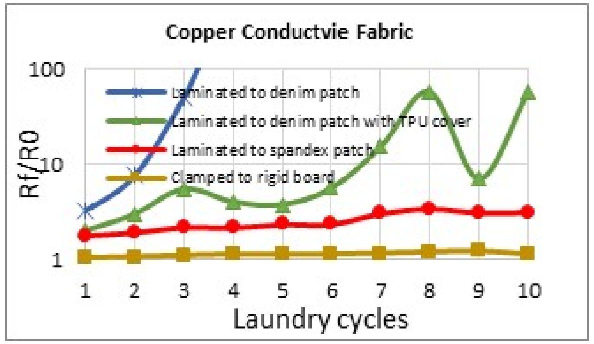


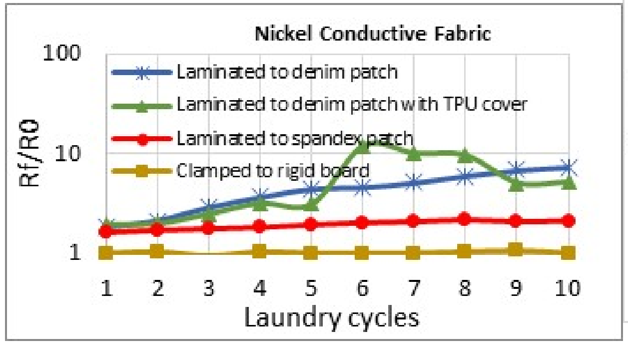


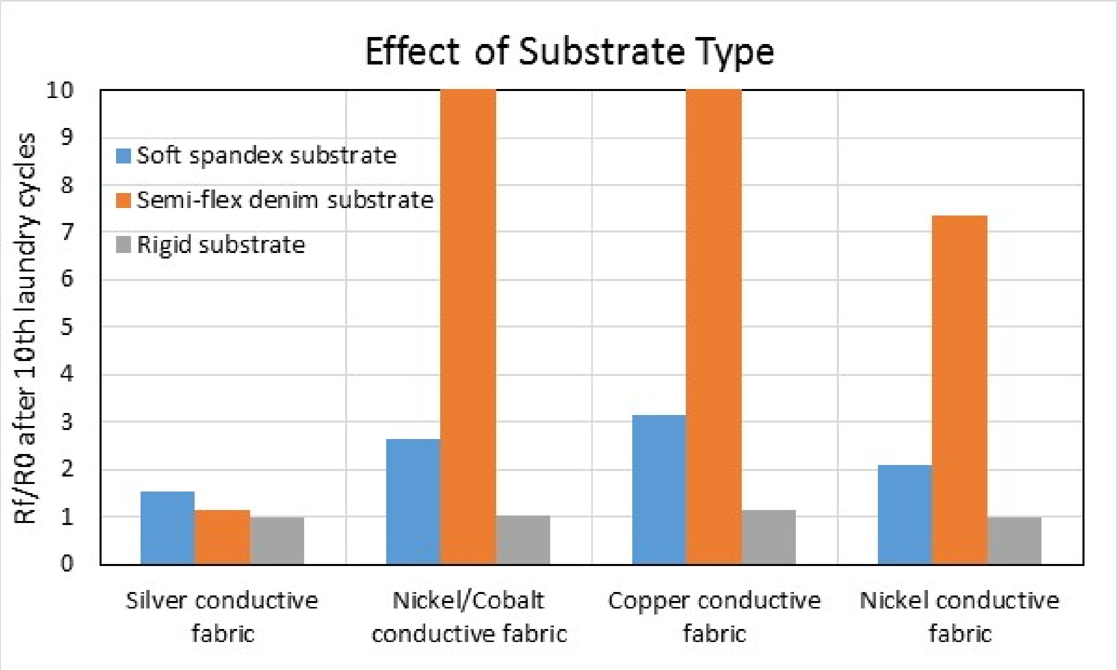
Analysis of Washability Study







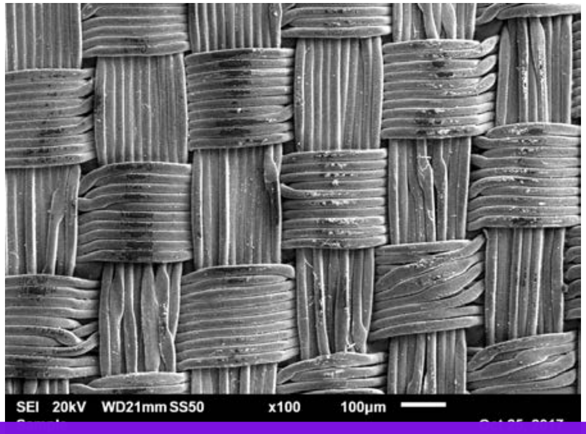


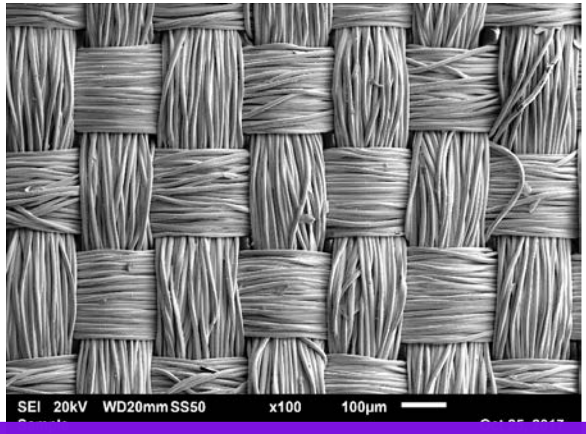


- Performance ranking in general:
  - Fabric clamped to rigid board > Fabric laminated to soft substrate > Fabric laminated to semi-flex substrate
- The results confirm our initial hypothesis that mechanical stresses during laundry cause fracture and loss of metal coatings on the yarn fibers, leading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

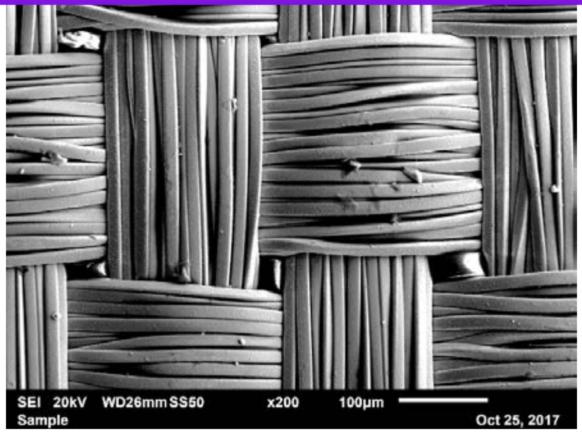
Silver conductive fabric clamped to rigid board after 10 laundry cycles

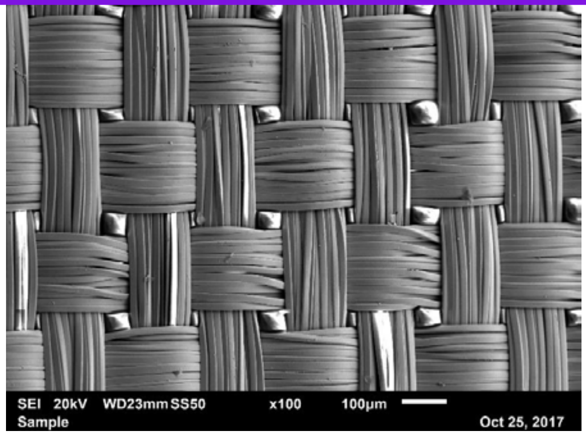




Nickel-cobalt conductive fabric clamped to rigid board after 10 laundry cycles

Copper conductive fabric clamped to rigid board after 10 laundry cycles





Nickel conductive fabric clamped to rigid board after 10 laundry cycles

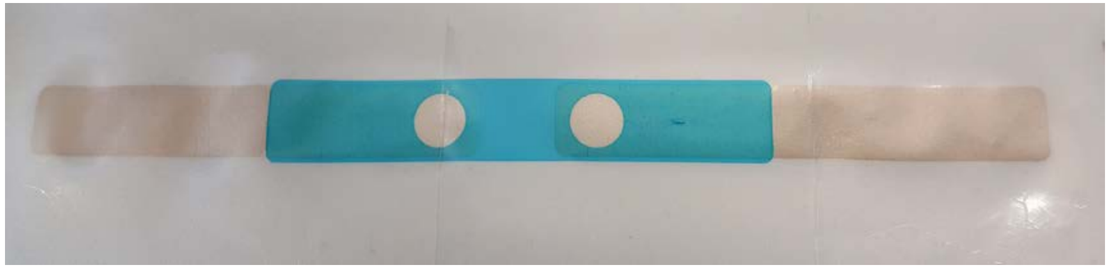
- No evidence of metal coating fracture and corrosion observed for the Ni-Co, copper and nickel conductive fabrics clamped to the rigid boards
- Some damage observed on the silver conductive fabrics clamped to the rigid board, however, it has not caused an obvious increase in resistance.

Washability of Conductive Ink

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

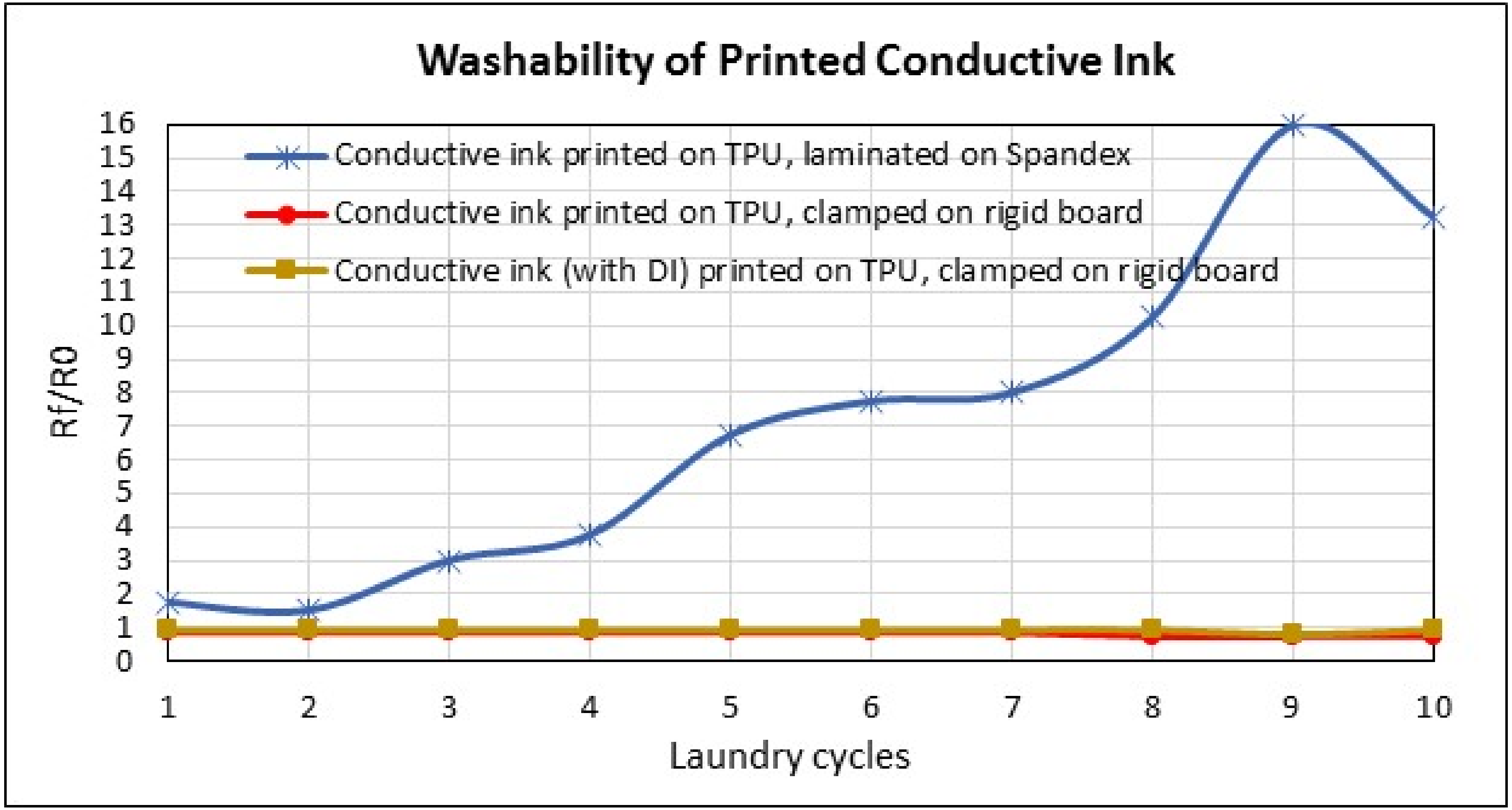
- **Test vehicles**
  - Conductive ink printed on TPU then laminated on spandex
  - Conductive ink printed on TPU, laminated to denim patch and then clamped on a rigid board

Conductive ink printed on TPU/laminated on spandex



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

Washability of Conductive Ink



Summary and Conclusions

- Washability 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 damage 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 evidence of metal corrosion/erosion 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.

Future Work

- Continue washability studies and understand effects of a variety of test parameters
  - Test conditions: Temperature (water/air), detergent, bleach, softener, ph level……
  - Effect of detergent: AATCC certified detergent versus household detergent
  - 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
  - Design guidelines on how to make e-textiles robust and washability proof

Acknowledgement

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