The Effects of Washing Environment on the Resistance of Silver Plated Nylon and Stainless Steel Conductive Threads

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6/11/2015

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Date Submitted: June 11, 2015

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ABSTRACT

Electronic textiles are the integration of small electronics into a textile foundation. This means that the material can function as an electronic conductor or device while retaining all the properties expected of tradition textiles including flexibility, washability, and strength. With the increasing integration of these materials into clothing it becomes important to consider the life span of material. Three varieties of conductive thread were chosen, one silver plated nylon and two stainless steel, sized thick and thin. 12" samples were cut and hand sewn in to pieces of muslin cloth. Samples were divided into groups of hot or cold water, and soap or no soap. Washing tests were performed to record the change in resistance over ten cycles with measurements taken after each cycle. An increase in resistance was observed in the silver plated nylon samples due to delamination caused by the abrasive forces of turbulent water; this effect increased when laundry detergent was added to the system. The stainless steel samples are made completely of 316L and their resistance was not affected by any of the factors. SEM Images were taken to confirm these changes. However, the final decision on which thread should be used needs to be made based on the user's skill level.

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1. Introduction

E-textiles, Smart Fabrics, Wearable Electronics, Intelligent Clothing, and many other names are used to describe the new area of electronic textiles. Electronic textiles are the integration of small electronics into a textile foundation.[1] This means that the material can function as an electronic conductor or device while retaining all the properties expected of tradition textiles including flexibility, wash-ability, and strength.

1.1: Applications

1.1.1: Fashion

The precursors to modern electronic textiles date back over 100 years. In theater, costumes covered in lights with hidden batteries were used to enhance the audience experience. In 1884, this kind of theatrical special effect was brought into the home by the Electric Girl Lighting Company from whom you could hire a girl to be your personal lamp that could move with you around your home and entertain your party guests.[2]

The integration of lighting into the world of fashion continued to grow and improve throughout the 20th century. Disney launched its Main Street Electrical Parade in 1972, which integrated lighting into every part of the floats and costumes.[3] The parade's wild popularity allowed for it to run for years rather than just a few seasons and to this day is a piece of iconic Disney history. In the 1980's Harry Wainwright, a former science teacher, pushed the limit of what could be done with optics and lighting in fashion. He holds patents for integrating optical fibers into fabrics and using them to create motion (Figure 1). His list of clients is long and includes everyone from The Boy Scouts of America to Brittney Spears.[4]

Figure 1: Wainwright's integrated display replicating the motion of fireworks.

1.1.2 Georgia Tech: Smart Shirt

As computer components got smaller throughout the 1990's, researches at Georgia Tech began looking into the idea of integrating electronics into fabrics. Called the Smart Shirt (Figure

2), the wearable motherboard was design for combat casualty care with the abilities to sense bullet wounds and monitor vitals sign in an unobtrusive way and report out real time data. The team hopes to one day expanding its use into the general health care system. The Smart Shirt's design allows for a variety of sensors to be attached with this flexibility the system was readily adaptable.[5]

Figure 2: Georgia Tech's Wearable Motherboard

1.1.3: Cornel: Pregnancy Monitoring

The concept of the smart shirt created by Georgia tech was great, however it lacked the appeal of being fashionable. This may be fine if you are a soldier or sick in a hospital, but not all illnesses and health situations need only to be monitored while in a hospital.

One Cornell student understood this and incorporated these basic technologies into her project. She was given the challenge to create clothing that would make pregnant women feel both healthy and beautiful. Her designs went far beyond this, she integrated silver thread in to the fabric to be used as a network for a monitoring system that would track the heart rate, blood pressure, body temperature, and respiration levels of the mother and child just through skin contact. This fashionable monitoring system (Figure 3) was designed to adapt to a women's changing body shape throughout her pregnancy and could even be worn at other times in her life when monitoring might be needed.

Figure 3: sketches of the full line of maternity clothing and the associated monitoring app[6].

1.2 Stakeholders

1.2.1: At Home Crafters

The market for homemade products is growing quickly with the help of websites like Esty[7] and places like MakerSpace[8] (Figure 4). The incorporation of conductive threads, fabrics, and lights can turn you average craft in to a work of art. Hand knitted texting gloves and light up flower crowns are just a few on the products being made and sold online.

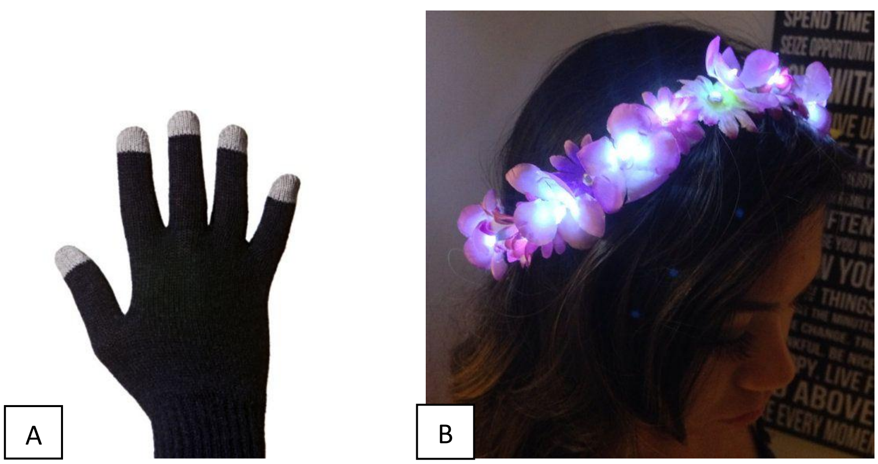


Figure 4: A) Texting gloves[9] and B) LED flower crown[10]

1.2.2: Teachers

E-textiles are a simple and easy way to teach the basic of electronic circuits to children of all ages. Other system such as snap circuits and littleBits are about building (Figure 5). Components are put together and taken apart creating a trial by error learning environment.

Using conductive thread adds the additional element of design with this more critical thinking analysis can also be added into the lessons. Using soft materials allow the children to be creative beyond the bounds of grid and in the end have a project that they can be proud of and take home.

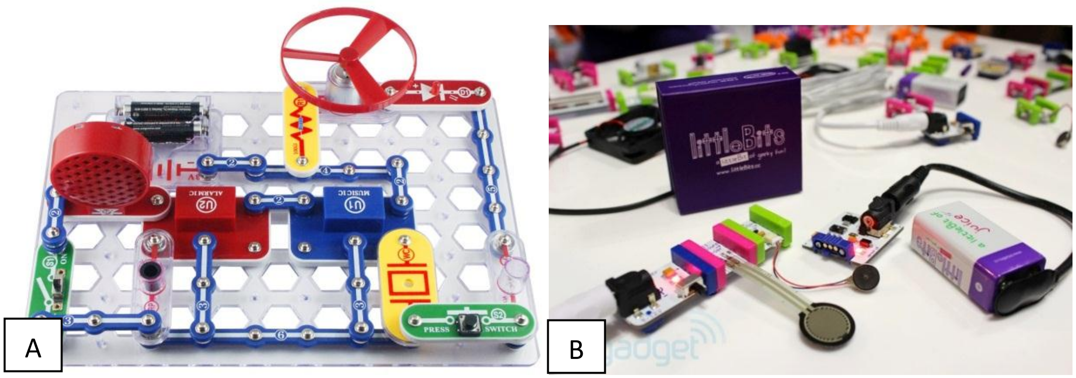


Figure 5: A) Snap Circuits attached to building grid[11] and B littleBits kit using several different components.[12]

1.3 Recycling of Textiles and Electronics

Today's world of fashion is built on the business model of fast fashion. Fast fashion can be defined as the making of inexpensive clothes and providing the ability to buy new things all of the time.[13] Integrating electronics into this fast paced and ever changing fast fashion system presents a new problem, the merging of the electronic waste stream and textile waste stream.

1.3.1: Textile Recycling

First it is important to understand why recycling textiles are important. Every year the average consumer throws away 70 pounds of perfectly good clothing a year. If you multiply that by the population of the United Sates, the number turns into approximately 20 billion pounds per year. Only a small fraction of that gets recycled per year where most ends up filling the landfills.[14]

The first and easiest way to recycle clothing is through donation. Goodwill[15] and Planet Aid[16] have drop off locations in nearly every city across the country, and nearly all homeless shelters and soup kitchen will take donations as well. By donating clothes instead of throwing them away, clothes are kept out of the waste stream for a longer amount of time.

However, all clothes will eventually reach an end of life state and this is where they can no longer be reused. This is when textile recycling takes place. Some fabrics are cut up and sold as cleaning rags and others go through the process of fiber reclamation. Fiber reclamation is the process by which materials of similar content are cut into strips and run through a series of

machines that remove hardware such as buttons and zippers while pulling apart the individual fibers. These fibers are bundled together and sent out to manufactures that either create new textiles from them or are reused as insulation and stuffing.[17]

1.3.2: E-Waste Recycling

Electronic waste more commonly referred to as E-waste is the term used to describe consumer electronic like computers, phones, and tablets when they have reached an end of life state. E-waste is recycled by separating the components of electronics into their major components; the motherboards are separated from the casing and the wires. Each of these groups is then subjected to a similar process. The materials are first fed into a crusher where the material is chopped into pieces about 5 mm in size. From here the materials are run though a magnetic separator which removes magnetic materials from the waste stream. To further specify the contents in each stream, the material is run through a machine that separates materials by their density. Each stream is now consisting of almost one kind of material and by going through a final chemical process they are ready to be resold to companies.[18]

The effectiveness of e-waste recycling is dependent on the government's ability to encourage both the people and companies to participate. Currently there are two different models - tax or rate. The tax model is what is most common in the United States' it has the government place taxes or fees on the companies or the products themselves. Those fees are collected to run the electronics recycling system.[19] California has been run under this model since the Electronic Waste Recycling Act of 2003(SB20). [20] The rate model is similar to what Europe uses under the Waste Electrical and Electronic Equipment Directive (WEEE). The rate model requires that companies take back their product in certain rates, for example when WEEE was first introduced in 2006, they required that 65% by weight of the material must be recycled and since then they have pushed towards 80%.[21]

1.2.3: E-Textile Problem

If e-textile waste was added to the e-waste stream, it would more than likely end up in a landfill or incinerator because the current e-waste system only allows for traditional hard electronics. Textiles would catch in the gears and parts that are meant to break not cut. Jamming up the machine would slow the already overloaded recycling processes. For these recycling

groups it would be more cost and time efficient to throw soft electronics like these into the trash and avoid the problems all together.

If added to the textile stream, the valuable materials that can be used in electronics would be lost. Workers who sort the clothes would not be able to tell when a piece of clothing has is an e-textile because they have been designed to look and feel like any other piece of fabric or thread and the current machinery is only designed to remove large metal and plastic objects like button, zippers, snaps, and other decorations. The conductive thread and fabrics would be processed the same as any other material leaving the metals to be dispersed among all the other fibers.

As the market for e-textiles grows, a change will need to be made. It will probably start in government and slowly trickle down until a law actually passes and then an even longer time before there is a viable way to implement it. The world is still figuring out how to handle the ever increasing amount of e-waste. This new technology will undergo the same process.

1.4 Project Goals

The goal of this experiment is to determine the effects of washing environment on the resistance of conductive thread. Controlling the water temperature and option of using soap are the variables in the washing environment that would be the easiest to change or control for the average user. Most clothing comes with suggested washing instructions to protect the product and increase the longevity of the useful life. However, most people ignore these instructions and include clothing in whatever washing system they typical use. By observing the effects of various washing environments, the true lifespan of electronic textile materials can be considered by all kinds of users.

2. Background

2.1: Thread Construction

2.1.1: Traditional Thread

Traditional threads are a made by a process of drawing and spinning natural or synthetic fiber like cotton or polyester. Each piece of thread is made from multiple filaments that are wound together to create thread of various weights, sizes and strengths. These traditional threads can be dyed any color of the rainbow and then coated so that they run smoothly through any sewing machine.[22]

2.1.2: Conductive Thread Stainless Steel

To make conductive thread one or more of these filaments are replaced with a conductive material. In metal-wrapped thread the outer filaments are replaced with conductive ones while the core is still a traditional material. Metal filled threads are the reverse of metal wrapped in that only the core is replaced with conductive material. Different from the other two, metal yarn generally refers to thread made of all metal filaments. Figure 6 displays how each design may have an effect on capability of material to effectively carry a current.[23] Currently stainless steel threads are most commonly being produced in the metal yarn style, and this is the type included in the study.

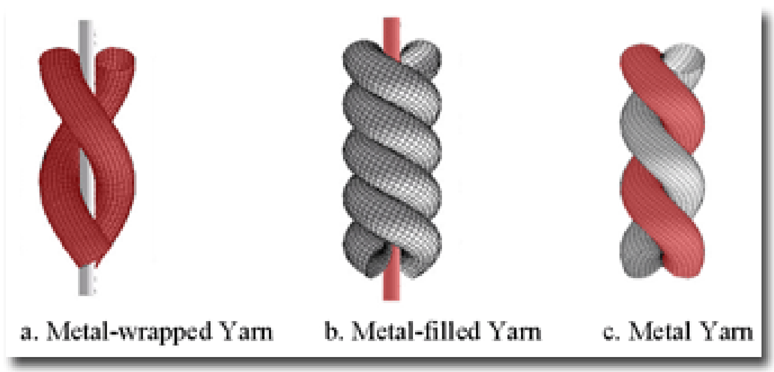


Figure 6: The varying construction of conductive threads with the conductive material represented as red.

2.1.3 Conductive Thread: Silver Plated Nylon

Silver can be plated on to nonmetallic substrates by a process called electroless plating. In this process, the nylon fibers would be run through a series of chemical baths that would prepare the surface. These chemicals may include $SnCl_2$ and $PdCl_2$. This activates the surface so that silver would be readily deposited. Once prepared, the fibers go through a second set of two baths. The first of which contains silver nitrate solution and the second contains a reducing agent. A chemical reaction occurs that allows for the silver ions to be deposited and adhere to the surface of the nylon, metalizing the thread.[24]

2.2 Thread Varieties.

The major resellers for conductive thread are Spark Fun, Adafruit, and Anio Magic. Each sells threads in different thicknesses, price ranges, materials and resistance. Table1 summarizes the available varieties.

Table 1: Thread Varieties: Based on Retail Website, Price, Material, Resistance, and Manufacturer

Website (Variation)	Price Pre-foot	Materials	Resistance Ohms/ft	Manufacturer
Sparkfun(Thin)	$0.18	Stainless Steel	9	Bekaert
Sparkfun (Thick)	$0.22	Stainless Steel	4	Bekaert
Sparkfun (Extra Thick)	$0.48	Stainless Steel	1.4	Bekaert
Sparkfun (Conductive Yarn)	$0.02	80% polyester 20% Stainless steel	Undisclosed	Plug and Wear
Sparkfun	$0.04	Stainless Steel	28	Undisclosed
adafruit (thin)	$0.08	Stainless Steel	16	Undisclosed
adafruit (medium)	$0.12	Stainless Steel	10	Undisclosed
adafruit(yarn/thick)	$0.13	Stainless Steel	Undisclosed	Undisclosed
Anio Magic	$0.10	Silver Plated Nylon	20	Shieldex

2.3 Washing Environments

2.3.1: Soap

The mechanism by which soap removes dirt and oils is by the creating of micelles around the dirt particles (Figure 7[25]). The ingredients are based from sodium or potassium salts but have different proprietary names in every detergent. These same molecules that make micelles are the possible cause for the increase in resistance of some conductive thread.

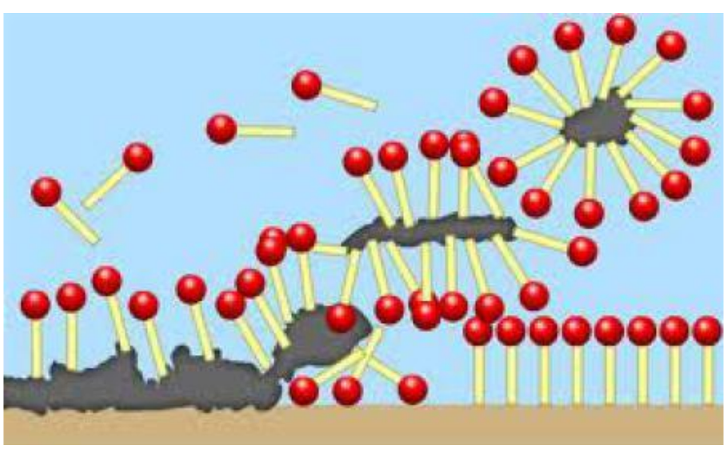


Figure 7: Traditional model of soap creating micelles around dirt particles allowing them to be washed away.

2.3.2: Temperature

The temperature of water when doing laundry has been correlated to both the kinds of fabric being washed, the coloring of the fabrics, and the amount of dirt accumulated on the surface. Hot water is used for heavily soiled items of clothing that need to be cleaned and sanitized. However the heat can cause shrinking and warping in the fabrics as well as reactivate dyes which may cause fading and bleeding of colors. Warm water is considered acceptable for most fabric, the heat kills germ with minimal shrinking and fading. Cold water is best used on delicates and fabrics with strong dyes that are known to fade and bleed more quickly. Cold water has the added bonus of using less energy but does not work as well when removing dirt and germs. Conductive threads typically come with no specific instructions about how they should be cleaned, or a blanks statement, do not wash.

3. Experimental Procedure

A series of experiments was designed to measure the change in resistance of conductive thread made of a stainless steel and silver plated due to washing. The number of washing, effects of laundry detergent and water temperature was considered.

3.1 Materials & Equipment

The selection of thread was narrowed down to the options seen in Table 2 for the variety in thickness, material, and initial resistance.

Table 2: Selected Conductive Thread Included in the Study

Source	Price per Spool	Length of Spool ft	Price per ft	Ply	Material	Resistance Ohms/ft	Manufacturer
Sparkfun(Thin)	$8.95	50	$0.179	2	Stainless Steel	9	Bekaert[26]
Sparkfun (Thick)	$10.95	50	$0.219	4	Stainless Steel	4	Bekaert[27]
Anio Magic	$2.95	30	$0.10	2	Silver Plated Nylon	20	Shieldex[28]

Washings were done using the Wonder Wash, a small load size personal washer with a 7 liter water capacity. The agitation is designed to mimic that of a full size machine using small blades to continually agitate the water. A portion of the samples was washed using Tide original detergent. The resistance measurements were taken with the Fluke117 True RMS Multi-meter using the standard pointed probes. An abrasion test was executed using a standard razor blade to

disrupt the material on the surface. And the critical resistance test used red and blue LED's and a battery holder. Images were taken using a scanning electron microscope (SEM) and digital camera.

3.2 Tests

3.2.1: Washability Test

Samples were prepared by hand sewing 1 foot (12 inches) of conductive thread into a strip of muslin fabric in which the edges have been machine stitched to prevent fraying. Each sample went through anywhere from 1 to 10 wash cycles and each cycle was 15 minutes. One representative sample was chosen for each numbered cycle (i.e., 5 samples per wash). A consistent washing environment was created by ensuring that each cycle has the same number of samples. Temperature and detergent were chosen as variables for the washing environment. Temperature can be easily chosen on most standard machine and is traditionally included as part of the washing directions label. The choice of to use detergent or not is one that a person can control. The chosen washing environments are displayed in Figure 8. The agitation level was kept consistent using the standard setting on the Wonder Wash. Samples were then dried in front of a small wall heater. In Figure 9, images of the equipment used, have been arranged to show the cycle that the sample went through.

Figure 8: The array of washing environment to be completed to determine which variable had an effect on the resistance of the threads.

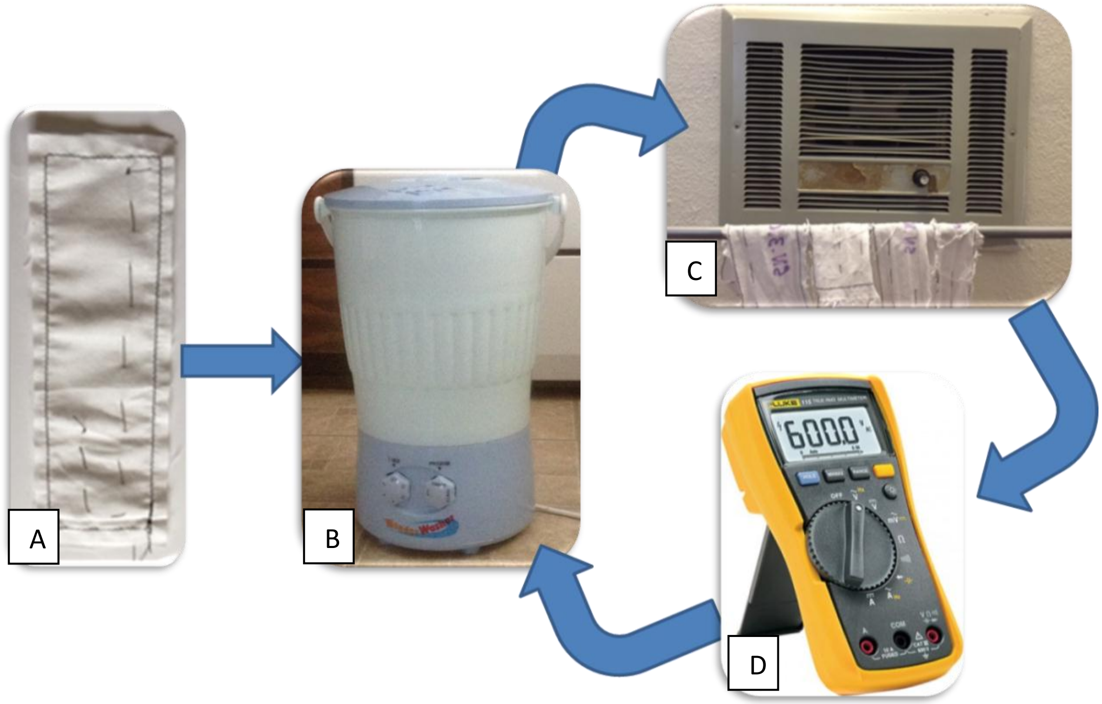


Figure 9 : A: Hand sewn sample. B: Wonder Wash Personal washer. C: Wall heat with sample draying in front of it. D. Fluke Multi-meter.

3.2.2 Resistance Measurements

The resistance of each sample was measured 3 times from the two knots tied in the ends of the thread. From these measurements an average and standard deviation was calculated using Excel.

3.2.3 Abrasion Testing

A standard razor blade was used to scratch the surface of the each variety of thread to simulate extreme damage due to wear. This test was devised to confirm that abrasive force would also cause deterioration. The resulting change in resistance was recorded.

3.2.4 Imaging

Images were taken after washing and abrasion testing with a digital camera to observe changes in the thread such as fraying and unwinding. High magnification images were taken with a scanning electron microscope (SEM) in order to observe any corrosion or delamination occurring on the surfaces.

3.2.5 Critical Resistance Test

Samples from the washing and abrasion test were attached to a LED battery in order to see at which resistance the threads are no longer able to conduct enough energy to power the LED. Both red and blue LEDs were used to encompass the variety of power needed based on different color LEDs. The power needed was also dependent on the size, so LEDs of the same size were chosen.

4. Results

4.1 Abrasion test

The silver plated nylon showed an increase in resistance along with a visible fading in the silver color. The two major strands separated starting at the end and continued to unravel after further passes with the razor blade. The stainless steel showed no change in resistance; however the forces of the blade caused both varieties to curl (Figure 10).

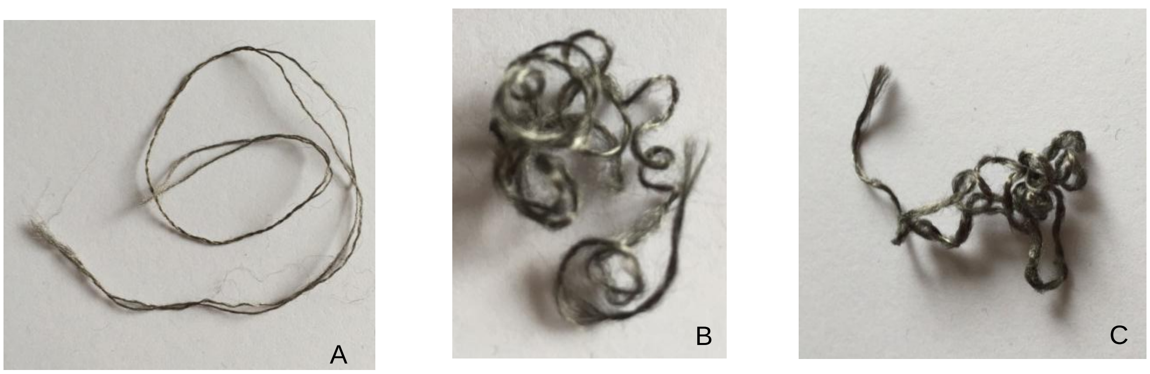


Figure 10: Silver plated nylon (A) with separated plies. Stainless steel Thin (B) and Thick(C) curled but showed no change in resistance.

4.2 Washing Environment Test

4.2.1 Resistance

The first test preformed was the cold and no soap condition where water temperature and agitation were the main destructive force acting on the threads (Figure 11). The second test used the combination of both hot water and detergent (Figure 12). These two tests revealed that there was no significant effect on the stainless steel, which was then, confirmed using a multivariable ANOVA. The alpha value was set at .0l and all of the p values calculated for the stainless steel threads were larger implying that there was no significant change for the resistance after 10 wash

cycles. The silver plated nylon threads were affected by all the factors, having increased resistance in the cold water and no soap condition from 27Ω t0 47Ω after 10 cycles. In the hot water with soap condition a more rapid rate of increase was seen, resistance increasing from 27Ω to over 80Ω. The calculated p values were less than .0001 further showing the strong effects of both water temperature and soap. The silver plated thread had an increased resistance.

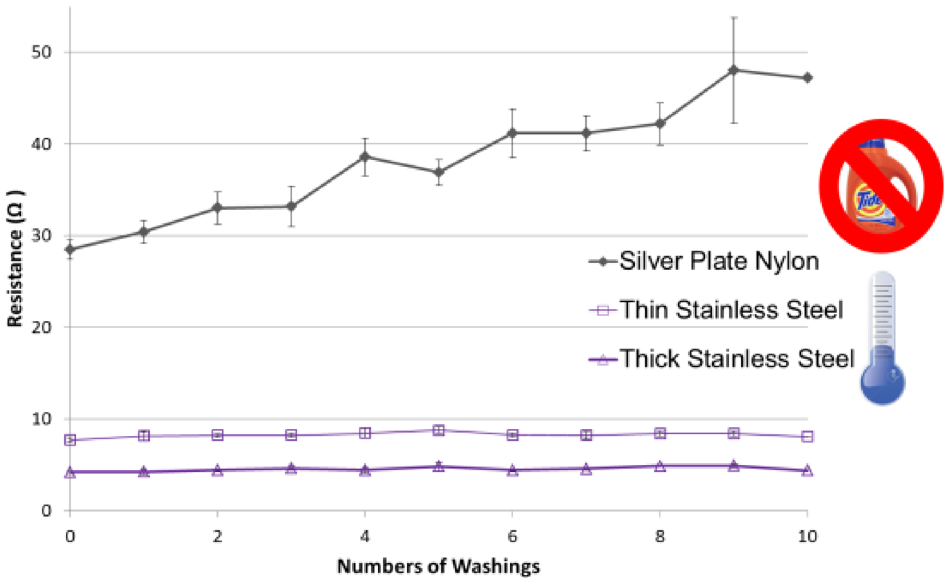


Figure 11: The cold water with no soap test causes an increase in the resistance of silver plated nylon but no effect on the stainless steel.

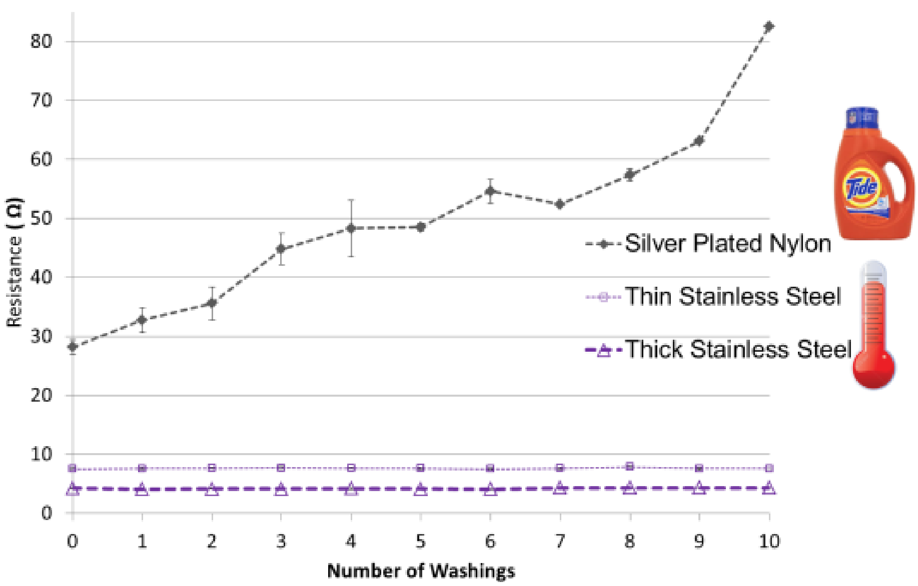


Figure 12: The hot water with soap test reveals that with the addition of soap, the resistances of the silver plated threads were increased more than environments with no soap.

Further tests were only preformed on the silver plated nylon threads and the stainless steel samples were replaced with blank fabric strips to maintain a consistent washing environment. These results showed that that the hot water with no soap environment yielded nearly identical results to the cold water with no soap. But the cold water with soap had a significant increase compared to the hot water with soap condition with the resistance increasing up to 109Ω (Figure 13). Soap seems to play a larger role in increasing resistance. However an ANOVA test was run revealing complicated interaction. The analysis showed that all combinations produced p values less than .0001, because all the factors were considered to have a strong effect.

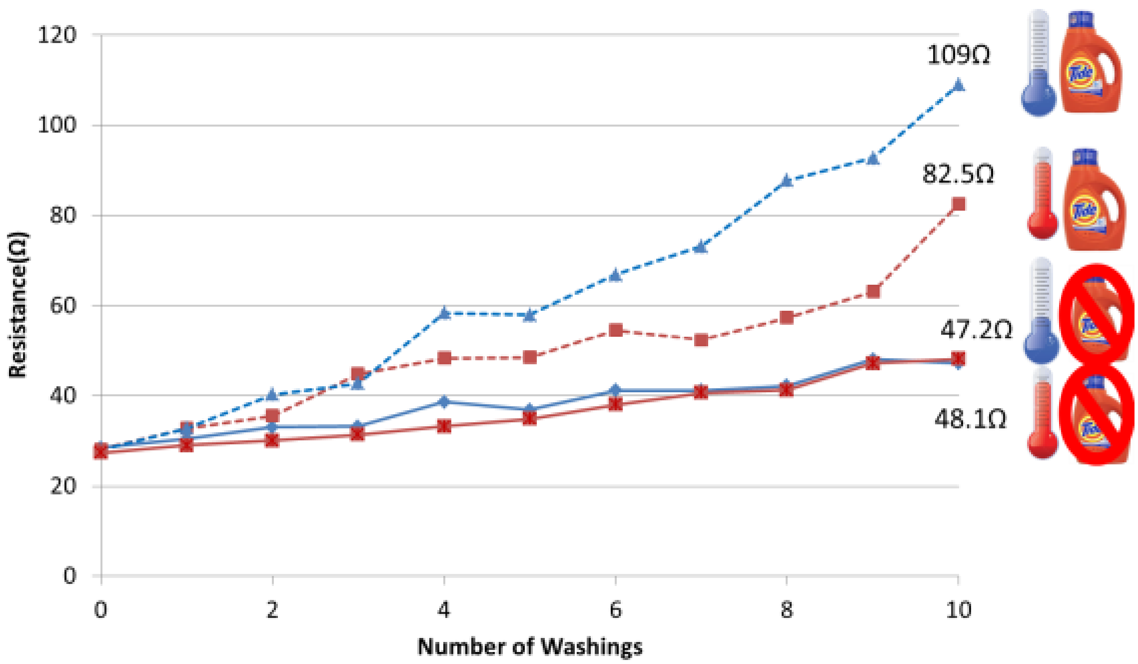


Figure 13: Increase resistance is cause by both soap and water temperature and the interaction caused varying affects

4.2.2: SEM Images

SEM images were taken to visually investigate the condition of the thread after washings. Both backscatter electron (BSE) and secondary electron imaging were used. The images taken with backscatter electron shows missing areas of silver plating as black and the silver plating as gray(Figure 14a). Using the SEM with the backscatter detector gives an image with better depth of field which reveals to us other surface features such as cracks and thinning areas in the plating. The images taken using secondary electrons are best used on conductive samples and because the silver plated threads have a non-conductive nylon core, areas of exposed nylon were

charged by the electron beam (Figure 14b). These charged areas glow making them easily visible even at low magnifications due to the increase in contrast.

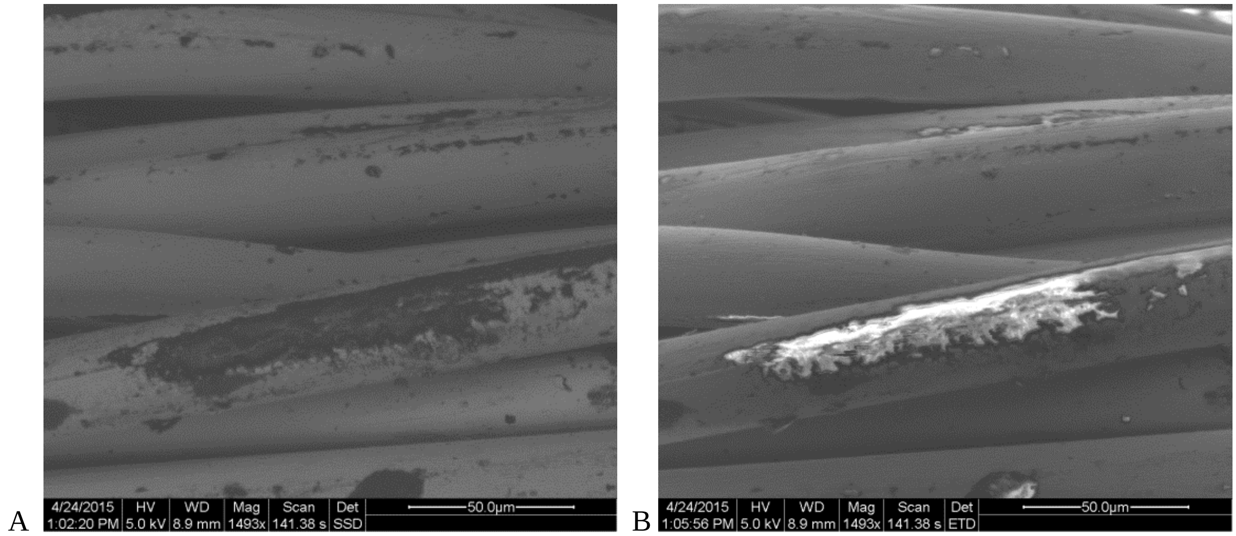


Figure 14: Image A is taken with back scatter electrons the dark areas represent places where the plating has been removed. Image B shows the same image taken with secondary electrons and the exposed nylon core glows due to charging.

Some of silver plating was completely removed in spots while other pieces were left lose and hanging off of the nylon core (Figure 15). All of these situations decrease the conductive path and increase resistance.

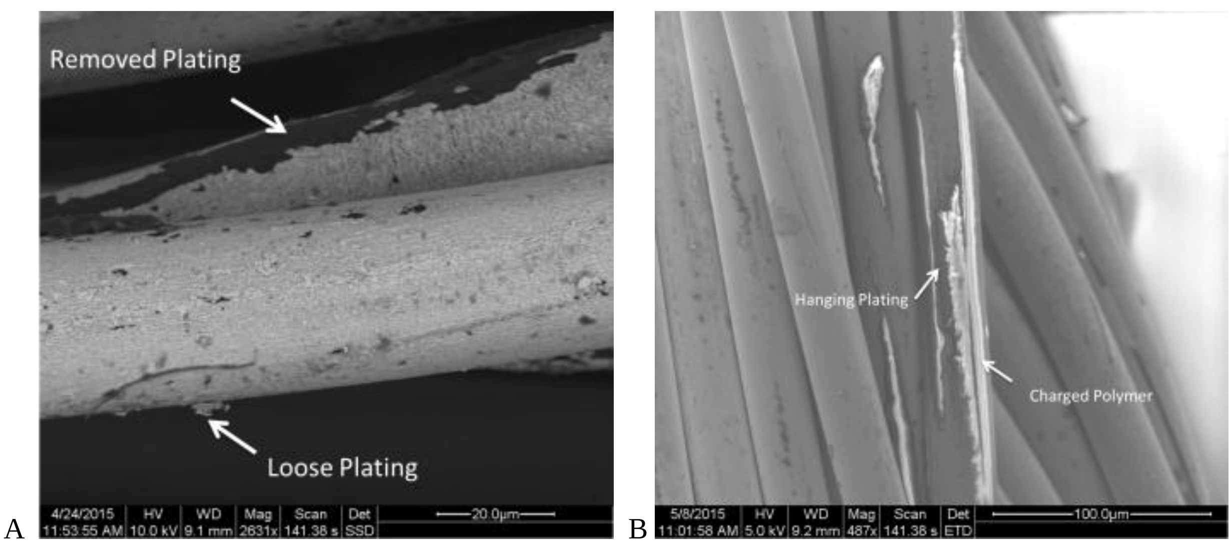


Figure 15: Image A in BSE show removed silver plating and Image B demonstrates the hanging plating**.**

Stainless Steel threads are made entirely out of conductive material in a similar fashion to traditional wire drawing. Figure 16 shows the different number of fibers in the thick and thin threads and the striations left from wire drawing on each individual fiber.

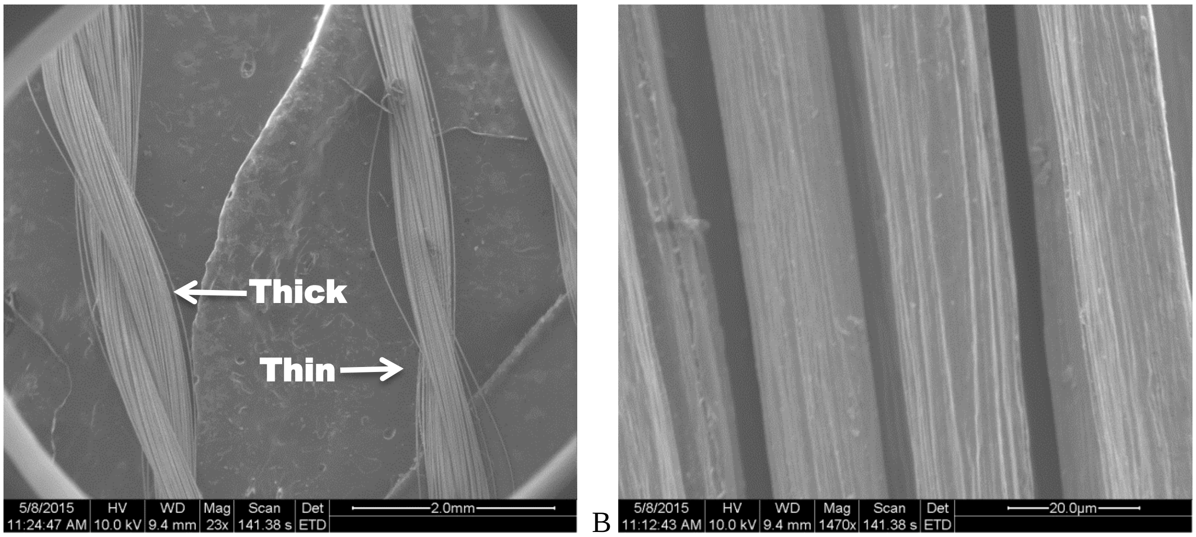
A  B

Figure 16: A: Thick and thin stainless steel threads differ only by the amount of fibers that make up the thread. B: Individual fibers show striations left from wire drawing but no damage from washing environments.

4.3 Critical Resistance Test Results

The resistance at which the thread could no longer carry enough current to power the blue LED was never reached with the number of washing. There was a visible decrease in the brightness of the LED as the resistance increased. Continued washings and degradation of the silver plated threads would theoretically reach a critical level of resistance and no longer be able to power the LED.

5. Discussion

5.1 Stainless steel Threads

The stainless steel used to make these conductive threads is 316L. This variety is known for its corrosion resistance in water and is traditionally used in products like surgical instruments.[29] Due to these properties, traditional washing environments have no effect on resistance of stainless steel threads. The resistances of stainless steel threads are entirely based on the number of fibers in each thread - the more fibers, the lower the resistance. These threads would be

durable in most normal environments that they could be placed. However because the resistance is based on the number of fibers, these threads are very thick and have the size and texture of a small wire. Traditional threads weigh about 70 grams per 1000 meter, and these stainless steel conductive threads weigh between 250-505 grams per 1000 meter. This weight and size difference prevents them from being easily integrated by hand except by someone with lots of hand sewing experience. They are also too thick and stiff to be used in a machine where a thread needs to bend around tight curve and be feed through small needles.

5.2 Silver Plated Nylon

5.2.1: Resistance

The removal of silver plating caused an increase in the resistance. The silver plating is a thin coating on a nylon core, a traditional textile material, creating a very small amount of conductive path in comparison to the stainless steel. The electroless process by which the plating is applied is not perfect, and produces defects where no plating had been applied. Due to the minimal amount of silver plating and pre-existing defects, the resistance of the thread is about 26Ω, this compared to the thick stainless steel which is 4Ω (Figure 11,12). The conductive path in the silver plated threads are severely affected because the water and soap have many point, at which to initiate the process by which areas of silver plating were completely or partially removed.

5.2.2: Water Effects

The removal of silver plating was initiated at cracks and defects (Figure 14) and there are two possible ways that water may interact with the silver plated nylon thread. The first has to do with the fact that nylon is notorious for swelling when it absorbs water. In the wash, the nylon core absorbs water through preexisting defects and expands in size. This may causes an increased amount of cracks and defects in the silver plating that are prevalent in the as-received materials and only get worse with increased washings. Another possible effect of water has to do with the temperature. It may be possible that both the nylon and the silver are more flexible in the hot water which allows for the plating to stay adhered to the surface more easily. In cold water, a reduction in flexibly could increase the amount of delamination that the detergents can cause.

5.2.3: Detergent Effects

The molecules in detergent are designed to remove organic materials and interact with traditional textile materials. Because the silver plating is not an organic and the nylon core is a traditional textile materials, a possible new model of how the detergent interacts with the silver plated nylon thread is proposed (Figure 17).

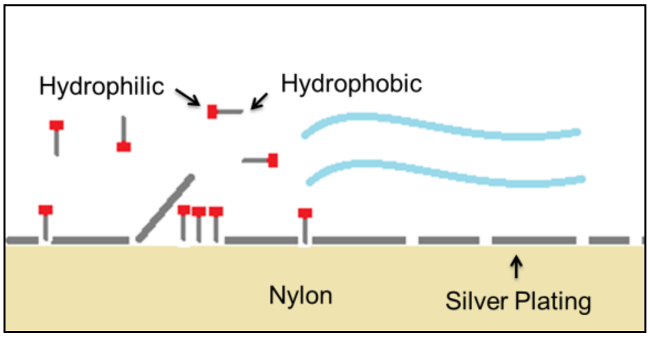


Figure 17: Theoretical model of detergent molecules removing silver plating.

The detergent molecules may remove plating by attaching their hydrophobic ends to areas of exposed nylon. When the edge of a piece of silver plating is loose, the molecules will wedge themselves between the silver plating and the nylon, causing even more of the plating to detach until the whole piece is remove and washed away by the water. With the decrease in silver plating, there would be a decrease in conductive path and an increase in resistance.

6. Conclusion

- Silver plated nylon and stainless steel conductive threads were washed, to see the effects of water temperature and detergent on the resistance.
- The resistance of stainless steel threads was not affected by either water temperature or soap. They are more durable; however, they feel more like wire and would be harder to integrate with other traditional materials.
- Silver plated nylon threads had an increase resistance as the silver plating was removed with increased washings. The threads would be easily integrated with tradition textiles, but lose their ability to conduct electricity over the course of washings.

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