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Article

Electromechanical Characterization of Commercial Conductive Yarns for E-Textiles

Yu Chen [1], Jacob Hart [1], Minyoung Suh [2], Kavita Mathur [2] and Rong Yin [1,*]

[1] Textile Engineering, Chemistry and Science, Wilson College of Textiles, North Carolina State University, Raleigh, NC 27695, USA
[2] Textile and Apparel, Technology and Management, Wilson College of Textiles, North Carolina State University, Raleigh, NC 27695, USA
* Correspondence: ryin@ncsu.edu

Abstract: With the development of smart and multi-functional textiles, conductive yarns are widely used in textiles. Conductive yarns can be incorporated into fabrics with traditional textile techniques, such as weaving, knitting and sewing. The electromechanical properties of conductive yarns are very different from conventional yarns, and they also affect the processability during end-product manufacturing processes. However, systematic evaluation of the electromechanical properties of commercial conductive yarns is still elusive. Different conductive materials and production methods for making conductive yarns lead to diverse electromechanical properties. In this work, three types of conductive yarn with different conductive materials and yarn structures were selected for electromechanical characterization. A total of 15 different yarns were analyzed. In addition, the change of resistance with strain was tested to simulate and predict the possible changes in electrical properties of the yarn during weaving, knitting, sewing and other end uses. It was found that Metal-based yarns have good electrical properties but poor mechanical properties. The mechanical properties of Metal-coated yarns are similar to conventional yarns, but their electrical properties are relatively poor. The data shown in this research is instructive for the subsequent processing (weaving, knitting, sewing, etc.) of yarns.

Keywords: conductive yarns; electromechanical property; conductivity; tensile property; bending property

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1. Introduction

Smart textiles, also known as electronic textiles, E-textiles or intelligent textiles, have innovated people's traditional impression of textiles [1–3]. Smart textiles endow textile fabrics with new functions, enabling them to respond to environmental changes, monitor human bio-signals and accommodate human-machine interactions [4–7]. Conductive textiles are generally considered to be the most fundamental part of smart textiles [2,8]. Different from traditional electronics, conductive textiles are required to maintain their electrical properties while keeping the wear comfort, flexibility and durability [9,10]. Conductive yarn plays an important role in conductive textiles. It can replace wires as connectors for electronics. It can also be sewed/embroidered as heat units, sensors or circuits [11]. Some research reveals that conductive yarns can be designed as self-powered systems or wireless systems [12]. Conductive yarns can be incorporated into textiles with traditional textile techniques, such as weaving, knitting and sewing [13,14]. Depending on the techniques and end-use applications, different electromechanical properties are expected for the yarns [15,16].

Weaving is a process that interlaces two orthogonal sets of yarns [5,17]. The weaving yarns should have high strength to high stresses exerted during the weaving process. In addition, evenness and hairiness are also important, which may result in higher friction during weaving which in turn can result in yarn breaks [18]. Usually, the warp yarns are sized to improve tensile properties and reduce friction [16,19]. Knitting converts yarns into fabrics by creating yarn loops and entangling them with each other. Therefore, bending rigidity, flexibility and extensibility are of prime concern [19,20]. Sewing is the process of applying a thread into a fabric substrate by penetrating the substrate with a needle [21,22]. A thread with good sewability is uniform in diameter with a good surface finish [21]. The longitudinal uniformity of the thread contributes to uniform strength and low friction as it passes through the substrate forming stitches [3].

Traditional yarns have been used in weaving, knitting and sewing machines for centuries. Different from traditional yarns, conductive yarns are involved with complex materials, structures and processing methods [23,24]. For example, the choices of conductive material can be metals, conductive polymers, graphene, carbon nanotubes, etc. [25–27]. In addition, the processability of conductive yarns is still not fully understood [28]. Thus, it is necessary to evaluate the properties of commercial conductive yarns. Margaret Orth proposed a new method to define the flexibility and sewability of conductive yarns [29]. The washability of e-textiles, studied by Shahood et al., suggested that the damage caused by washing can be divided into four actions with some interactions: mechanical damage (bending, twisting, friction), water stress, thermal stress and chemical influence [30]. Yong et al. investigated breaking, tenacity, breaking elongation, initial modulus, elasticity, electrical resistance, unevenness and hairiness of composite conductive yarns [31]. However, a few researchers investigated the electromechanical properties of commercially available conductive yarns, which are considered key factors for yarn fabrication.

Among commercially available conductive yarns, there are generally three major types. The first type is manufactured directly from fine metal filaments with a certain level of imparted twist, which keeps several filaments together. The second type is made of traditional textile fibers or filaments, which are spun into yarn and sputter coated, plated, or dip-coated with a conductive material. Different kinds of nylon and polyester are used as base yarn and are usually coated with silver, gold or tin [23,32]. The third type of yarn consists of a core made up of several metal filaments and traditional textile fibers/filaments twisted around the core. These yarns may also have an additional coating to decrease the coefficient of friction or to improve durability. In this research, we selected yarn samples from these three types of yarns, and a total of 15 yarns were tested. The basic mechanical properties, such as linear density, strength, strain, tenacity, etc., were measured and analyzed. The electromechanical performance was also evaluated. We measured the resistance change of each yarn sample as a function of strain and external force. Understanding the effect that strain has on the conductivity of the yarns can inform design decisions and potential use cases. Additionally, since the yarns will experience a degree of strain and tensile loads when woven, knitted and sewn, it is important to be aware of the impact that these factors have on the yarn's electrical properties.

2. Materials and Methods

Three different types of conductive yarns were chosen as research objects (Table 1). The metal filaments yarns used in these tests are made of stainless-steel filaments and were produced by company B. The plated/coated yarns are spun nylon filaments plated with silver from company S. The metal core yarns used in these tests were provided by the company, utilizing a core of 4–8 copper filaments surrounded by two layers of twisted polyester filaments with a PU (polyurethane) coating. In the conductive yarn of the same structure, we also selected different specifications for testing and analysis. Yarn specifications are summarized in Table 1. The coating/plating density of plated/coated yarns is summarized in Table 2. In total, 15 yarns were subject to the evaluation.

Table 1. List of 15 commercially available conductive yarns selected for evaluation.

Conductive Material	Yarn Product	Yarn ID
Metal filaments	275 filaments, 6-ply stainless steel	B6
	275 filaments, 4-ply stainless steel	B4
	275 filaments, 3-ply stainless steel	B3
	275 filaments, 2-ply stainless steel	B2
	275 filaments, 1-ply stainless steel	B1
Ag-plated	100% Polyamide/Silver plated yarn, 117 filaments, 2 dtex	SHC40
	100% Polyamide/Silver plated yarn, 235 filaments, 2 dtex	SHC12
	100% Polyamide/Silver plated, Nitrile rubber coated, 2-Ply	S235-2
	100% Polyamide/Silver plated, Nitrile rubber coated, 4-Ply	S235-4
	100% Polyamide/Silver plated, Nitrile rubber coated, 2-Ply	S117
	100% Polyamide (Nylon 6)/Silver plated	S44
	100% Polyamide (Nylon 6)/Silver plated, Nitrile rubber coated	S78
Cu-core	4 copper wire core/polyester, PU coated	A4
	6 copper wire core/polyester, PU coated	A6
	8 copper wire core/polyester, PU coated	A8

Table 2. Ag coating density of Ag-plated yarns.

Yarn ID	Yarn Count Raw (dtex)	Yarn Count Silverized (dtex)	Silver Weight Percent
SHC 40	234	290	0.24
SHC 12	470	610	0.3
S235-2	476	605	0.26
S235-4	952	1220	0.28
S117	234	295	0.26
S44	44	54	0.19
S78	82	98	0.2

SEM images were taken using a Hitachi TM4000Plus tabletop microscope (Tokyo, Japan). The copper core yarns needed to be sputter coated using a gold-palladium target via a Quorum Technologies Model SC7620 (East Sussex, UK) due to their non-metallic surface, unlike the yarns from the other two suppliers. The images were taken at three different magnifications of representative samples from each of the three yarn types.

Electromechanical testing was carried out by performing a unidirectional strain-to-break tensile test paired with a 2-wire resistance measurement for each yarn. The yarns were tested on an MTS Q-Test tensile tester and were connected to a Keysight/Agilent 34410A 6 $\frac{1}{2}$ Digit High Performance Digital Multimeter, which was then connected to a computer equipped with the Keysight BenchVue software (Version 2021) (Figure 1a–c). Electrical tape was used for the insulation of conductive yarn and metal clamps. Copper wire was used to connect the conductive yarn with a multimeter. Using the default resistance monitoring settings allowed for the collection of continuous electrical resistance data as each yarn was extended to break.

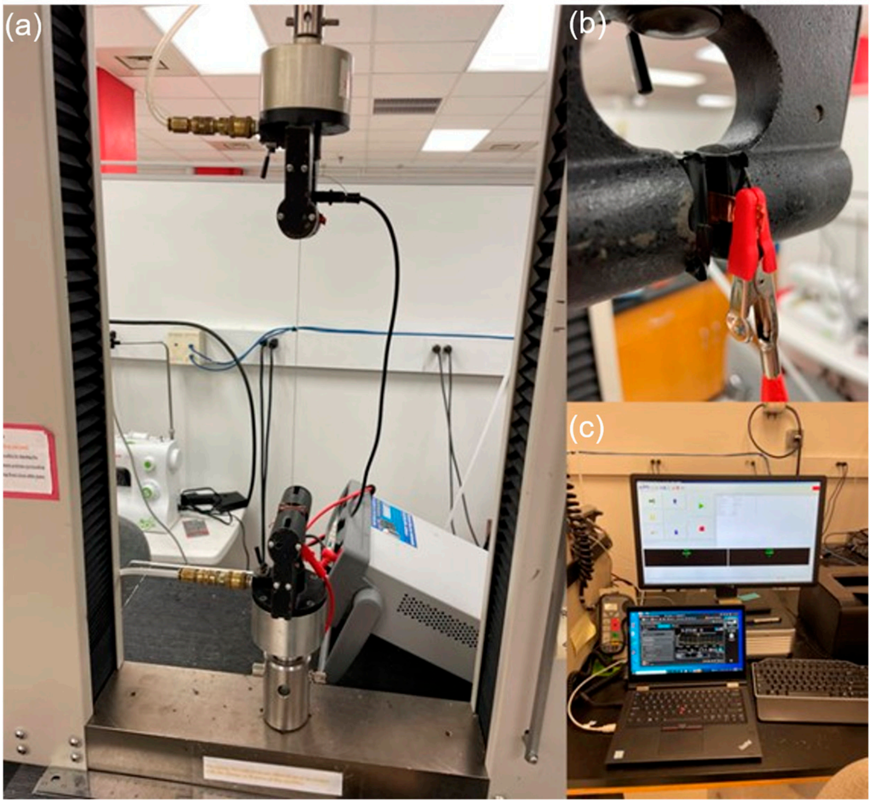

Figure 1. (**a**) Experiment set-up for the electromechanical test of conductive yarns; (**b**) connection of conductive yarn with a multimeter; (**c**) software of data recording.

The tensile tester was operated according to ASTM D2256 and was used to collect the tenacity (gF/denier), strain at break (%) and modulus (gF/denier) of each yarn (Figure 1a). The tests were performed in a controlled environment set to 70 °F and 65% relative humidity, with a 10-inch yarn gauge length. The rate of extension described in the standard was modified from 300 mm/min to 150 mm/min to slow the time to break for the stainless-steel yarns to collect enough resistance data. The tensile tester was equipped with a 250 lbf load cell and pneumatic grips with a 1-inch × 1-inch grip area. Since the multimeter leads were attached directly to the end of the yarn sticking out from the tester grips, the grips were insulated with 3 layers of electrical tape (Figure 1b). Five specimens were tested from each of the 15 yarns. To measure the resistance of the metal core yarns, the outer layer had to be manually removed at both yarn ends by untwisting it. Due to the small diameter of the copper filaments in the core, a small amount of 60% tin/40% lead solder was applied to the exposed copper filaments to be able to connect them to the multimeter leads.

The baseline resistance was measured from an average of 10 s of resistance measurement before the mechanical load was applied to yarns and then divided by the testing length to calculate Ohm/m. This was compared to the manufacturer's claimed range of electrical resistance, which was also presented in Ohm/m.

The diameter of each yarn was measured using a standard handheld thickness gauge and 10 measurements were taken for each of the 15 yarns, and the mean diameter was calculated. The linear density test was operated according to ASTM D1577.

An IDM Instruments Cantilever Stiffness tester was used to test the bendability of the yarns (Figure 2). The yarn was continuously pulled over an angled surface set at 41.5° until it touched the surface, and the extension length was recorded in millimeters. The standard referred to was ASTM D1388, developed for testing fabrics, but it was found that the yarns were able to be tested in this way.

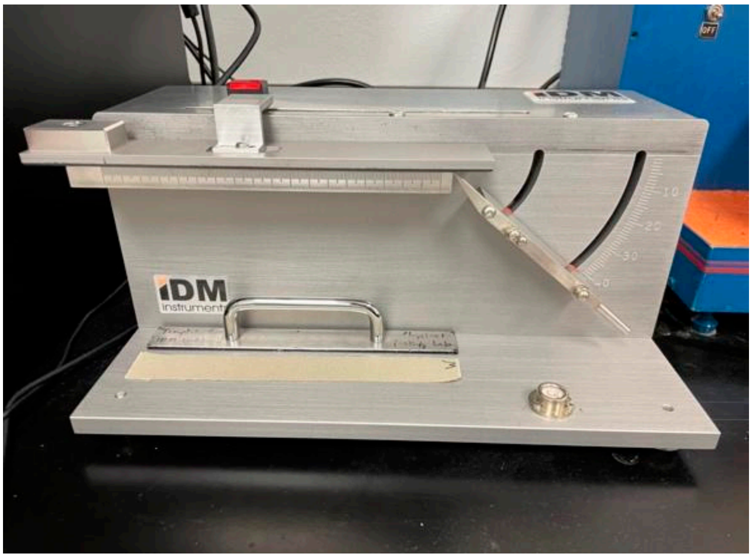

Figure 2. IDM Instruments Cantilever Stiffness tester.

3. Results and Discussion

3.1. Yarn Morphology

The first type of conductive yarn was made by twisting and plying thin stainless-steel wires. From Figure 3, it can be seen that each strand of yarn is composed of a number of extremely fine stainless-steel monofilaments with a very tight structure. Each strand of stainless steel was composed of 275 filaments. The difference between B1, B2, B3, B4 and B6 represented the different ply numbers of stainless-steel filaments.

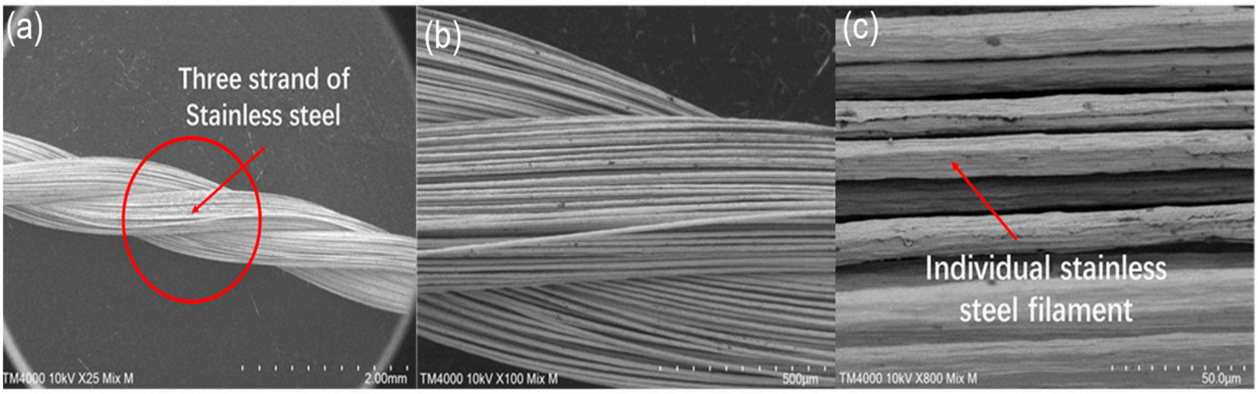

Figure 3. SEM images of a representative stainless steel filament yarn (B3): (**a**) 25× magnification; (**b**) 100× magnification; (**c**) 800× magnification.

The Ag-plated yarns were metal-coated conductive yarns made of 100% Polyamide (Nylon 6,6) with a silver coating (Figure 4). The structure of these yarns is similar to normal nylon yarns but with a higher twist level (~500 tpm). The conductivity of this type of yarn is highly dependent on the amount of silver used and the uniformity of the silver layer. Occasionally, uneven coating layers were observed on the yarn surface under the SEM (Figure 4c), which may contribute to an increase in the yarn resistance. Due to the limitation of the coating methodology and the small weight percentage of silver (~20%), metal-coated conductive yarn had much higher resistance compared to metal-based conductive yarn.

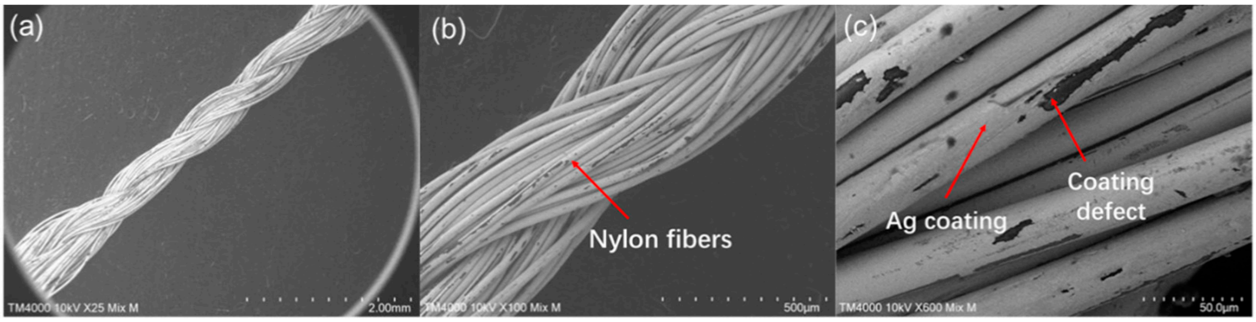

Figure 4. SEM images of a representative nylon silver coated yarn (SHC12): (**a**) 25× magnification; (**b**) 100× magnification; (**c**) 600× magnification.

The third type of yarn consisted of a metal core, usually several metal filaments, and surrounded by a traditional textile fiber/filament (Figure 3). This type of yarn was made on a wrap-spinning machine. The copper wires and stainless-steel filaments were fed into the machine as the core, and nylon or polyester filaments were then wrapped around the core yarn. Finally, it was coated with PU to ensure insulation and reduce the friction coefficient, making it more suitable for handling with mechanical weaving, knitting or sewing. As shown in Figure 5b, the coating layer was important to obtain special mechanical properties. However, it also created uneven surfaces. This kind of yarn had high strength with a certain flexibility, maintaining good electrical conductivity as well.

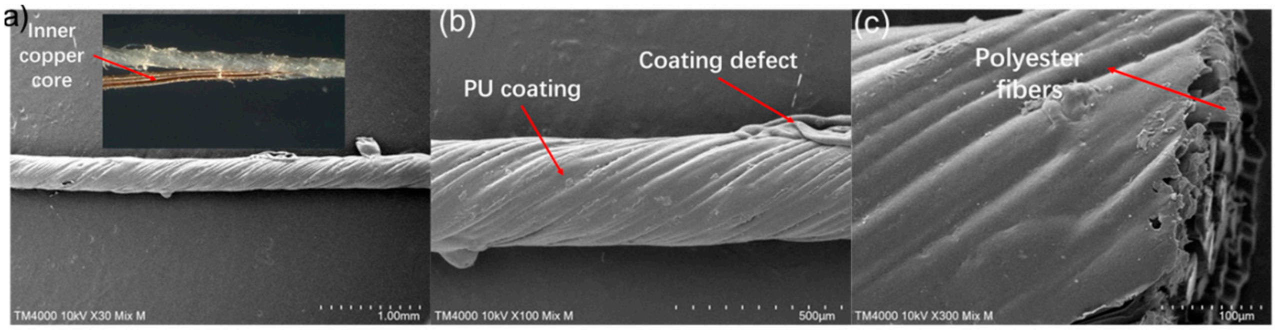

Figure 5. SEM images of a representative copper core polyester wrapped yarn (A6): (**a**) 30× magnification; (**b**) 100× magnification; (**c**) 300× magnification.

3.2. Mechanical Characterization

Table 3 summarizes the selected yarns and their electrical performance. Among the conductive yarns, twisted stainless steel yarns had extremely high linear density and breaking strength. As shown in Table 3, the linear density and diameter increased as additional stainless-steel yarns were plied. Six-ply stainless-steel yarn had a large linear density of up to 13,500D and a diameter of 0.496 mm. However, the tenacity showed an opposite trend, with the 6-ply yarn being recorded as the lowest. This is due to the introduction of the plied structure, which leads to an incline angle of the filament to the yarn axis. This lead to the yarn not being stressed in the same direction as the yarn axis, which decreases the yarn's tenacity and modulus. In addition, this plied structure (twisted angle) gives more space for movement, which slightly increases the elongation from 1.23% to 2.41%. Stainless steel filaments provided excellent conductivity (6.04 ohm/m for 6-ply stainless steel yarn). The increase in the number of conductive filaments reduces the overall resistance. Despite the low tenacity, this type of conductive yarn had a high modulus.

Table 3. Yarn Characterization Summary.

Yarn ID		Denier	Diameter (mm)	Tenacity (gF/Denier)	Strain at Break (%)	Modulus (gF/Denier)	Baseline Resistance (ohm/m)	Bending Length (mm)
B6	value	13500	0.4961	1.30	2.05	96.50	6.04	68.75
	CV	-	1.16%	10.08%	8.19%	9.11%	1.25%	4.95%
B4	value	9090	0.3960	1.78	2.41	129.37	9.08	114.25
	CV	-	1.95%	12.86%	21.99%	5.92%	0.70%	5.51%
B3	value	6840	0.3528	1.69	1.84	141.08	11.78	65.50
	CV	-	2.53%	7.60%	5.77%	2.40%	1.15%	6.77%
B2	value	4545	0.2559	1.81	1.66	154.45	18.37	61.25
	CV	-	3.16%	2.09%	4.05%	4.56%	3.62%	2.05%
B1	value	2115	0.1488	1.90	1.23	194.42	37.50	52.75
	CV	-	2.92%	5.72%	5.17%	2.43%	1.80%	3.24%
SHC40	value	261	0.1760	5.50	22.70	43.99	184.29	56.00
	CV	-	3.76%	1.82%	4.57%	2.00%	3.86%	2.92%
SHC12	value	549	0.2521	5.50	24.84	34.12	59.49	67.00
	CV	-	1.25%	2.18%	2.09%	2.20%	3.46%	5.02%
S235-2	value	544.5	0.2642	5.62	25.70	43.58	64.83	55.75
	CV	-	1.74%	1.64%	2.72%	4.27%	1.05%	7.8%
S235-4	value	1098	0.3947	5.43	27.03	32.47	35.75	56.75
	CV	-	2.46%	2.21%	2.14%	1.63%	6.43%	5.82%
S117	value	265.5	0.1888	5.13	23.39	40.61	167.77	42.50
	CV	-	2.07%	2.34%	6.00%	1.90%	4.26%	3.72%
S44	value	48.6	0.0548	3.90	43.81	3.05	1424.02	37.00
	CV	-	5.95%	3.85%	1.25%	14.43%	3.26%	3.82%
S78	value	88.2	0.0667	3.56	34.69	16.83	816.30	38.50
	CV	-	2.83%	2.81%	2.78%	17.47%	3.39%	3.35%
A4	value	1318.95	0.3395	2.9	17.13	35.11	3.57	140.25
	CV	-	2.92%	5.86%	5.82%	10.68%	12.38%	2.75%
A6	value	1490.94	0.3561	1.55	14.37	50.78	2.53	150.00
	CV	-	3.19%	10.32%	4.99%	10.97%	9.01%	2.72%
A8	value	1845	0.3439	2.05	16.22	51.59	1.86	141.00
	CV	-	1.81%	6.83%	7.54%	10.68%	10.35%	4.52%

For Ag-plated nylon yarns, yarns S235-2, S235-4 and S117 had a nitrile rubber coating in addition to silver plating. Except for S235-4, which was a -ply structure, all plated yarns had a 2-ply structure, as shown in Figure 4. Benefiting from the ultra-fine nylon filaments, extremely small diameters and linear densities are obtained, ranging from 0.055 mm to 0.4 mm and 48.6D to 1098D, respectively. This kind of yarn has high flexibility and stretchability. The elongation at break can be up to 43.81%, and the bending length can be close to 37 mm. Since the base material is nylon, the tenacity of these yarns is not very different from normal nylon yarns. Their resistance was much greater than that of metallic silver (>60 ohm/m) due to the use of conductive coating instead of directly using metal as conductive materials.

There were three specifications with different numbers of internal copper wires (4, 6 and 8). To ensure that the copper core does not break during production, stainless steel wires were added to A6 and A8. The increase of the copper wires increases both the linear density and modulus. The diameter and stretchability of these three yarns were measured the same, indicating that the mechanical properties of this type of yarn are mainly determined by the nylon and PU coatings wrapped in the outer layer. Polyester provides certain stretchability, with elongation around 15%. However, the PU coating results in a stiff structure with a high bending length (~140 mm). The resistance of this type of yarn was less than 4 ohm/m due to the good conductivity provided by copper.

Comparing the three different types of conductive yarns, we found that metal filament yarns had the highest linear density and diameters, which made them the strongest yarn in terms of breaking strength. However, it had limited stretchability or deformability; the elongation was less than 2.5%. The advantages of these yarns are high strength and excellent electrical conductivity. This yarn may not be suitable for fabrication processes that require certain flexibility and stretchability, such as knitting or sewing, but it could be a good choice for weaving. Conductive yarns made of metal-plated nylon are widely used commercial conductive yarns. This type of yarn was characterized by maximizing the retention of the mechanical properties of the base material, enabling direct applications in textile products. Depending on the properties of the base material, the mechanical characteristics of this type of conductive yarn can be engineered in a wide range. The low bending length and high elongation indicate that this type of conductive yarn poses high flexibility and deformability. Thus, these yarns could be most versatile in fabrications from weaving, knitting and sewing to embroidery. As for metal core yarns, the multi-layered structures of wrapping and coating make them very stable, which was not likely to untwist during end-product manufacturing. Inevitably, this structure accompanied certain levels of stiffness, resulting in high bending length. The conductivity of copper wire was kept intact, and it had the lowest resistance value among the three conductive yarn types.

Metal-based conductive yarns, such as stainless steel yarn and copper core yarn, had high conductivity because of the intrinsic properties of metal. The thicker the wire, the lower its resistance. Compared to copper core yarn, stainless steel yarn consists of much more stainless-steel filaments (275 filaments for one strand), resulting in higher resistance. In addition, the twisted structure also had a negative effect on conductivity.

3.3. Electromechanical Testing

The continuous resistance data was used to calculate the change in resistance from the baseline resistance ($\Delta R/R_0$) and was then plotted on a secondary Y-axis with the corresponding tenacity-strain plot. Figures 6–8 show the electromechanical results for the three different types of yarns: stainless steel filaments, silver-coated nylon and copper wire core. The measurements were repeated five times for each yarn sample, and one typical result of five tests is shown in the figures. The resistance values of these three conductive yarns all increased with the elongation process. For yarns using metal as a conductive material, with irreversible stretching, the metal became thinner, the cross-sectional area decreased and the resistance increased. For Ag-plated conductive yarn, the conductive layer is broken or defective during the stretching process, resulting in an increase in the resistance value. The effect of the increase in the resistance value caused by the fracture is much greater than that caused by the change in the cross-sectional area.

Conductive yarns using metals as conductive materials (B1–B6 and A4–A8) had very little resistance change with strain. Among them, the resistance change ($\Delta R/R_0$) of stainless-steel yarns was less than 0.05 (Figure 4). The strain of stainless-steel yarn was also very small, which was less than 2.5%. As the number of plies increases, the stretchability of the yarn increases while the change in resistance decreases.

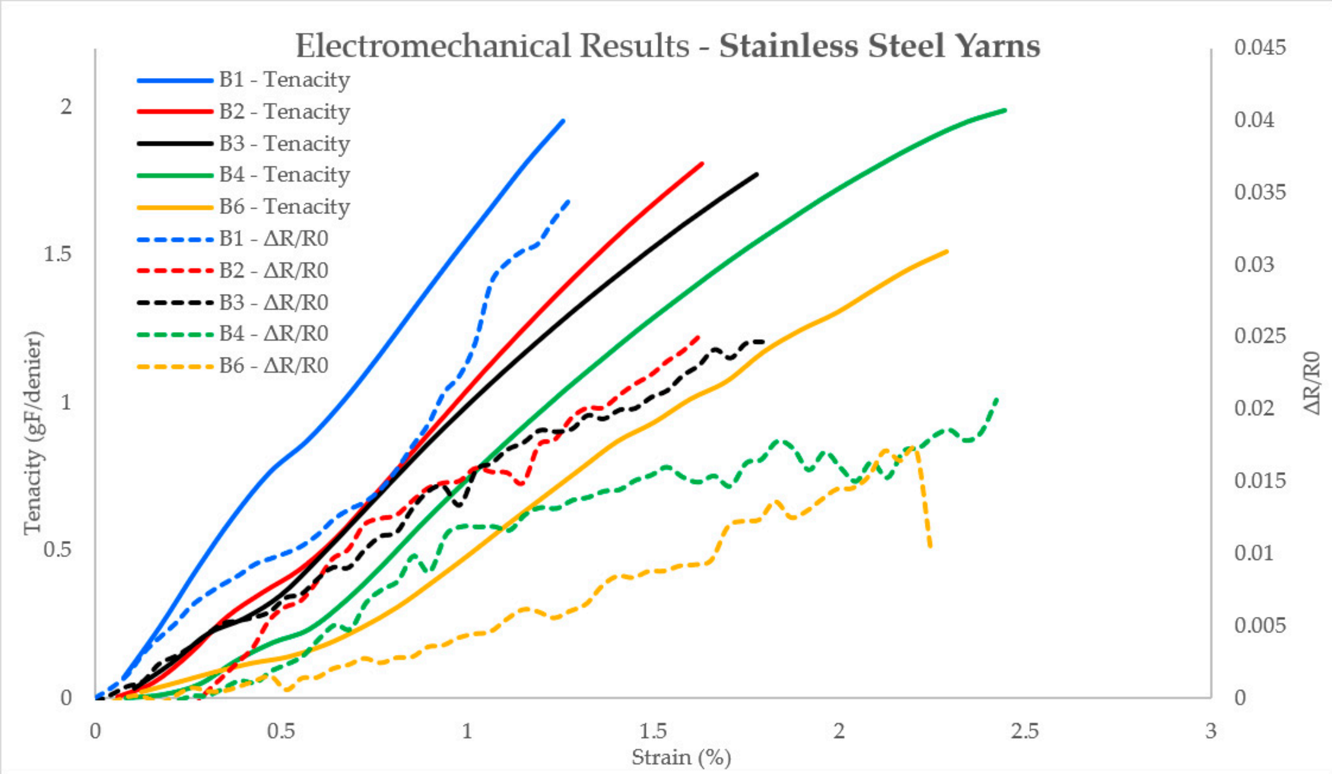

Figure 6. Continuous electromechanical evaluation results for stainless-steel filament yarns.

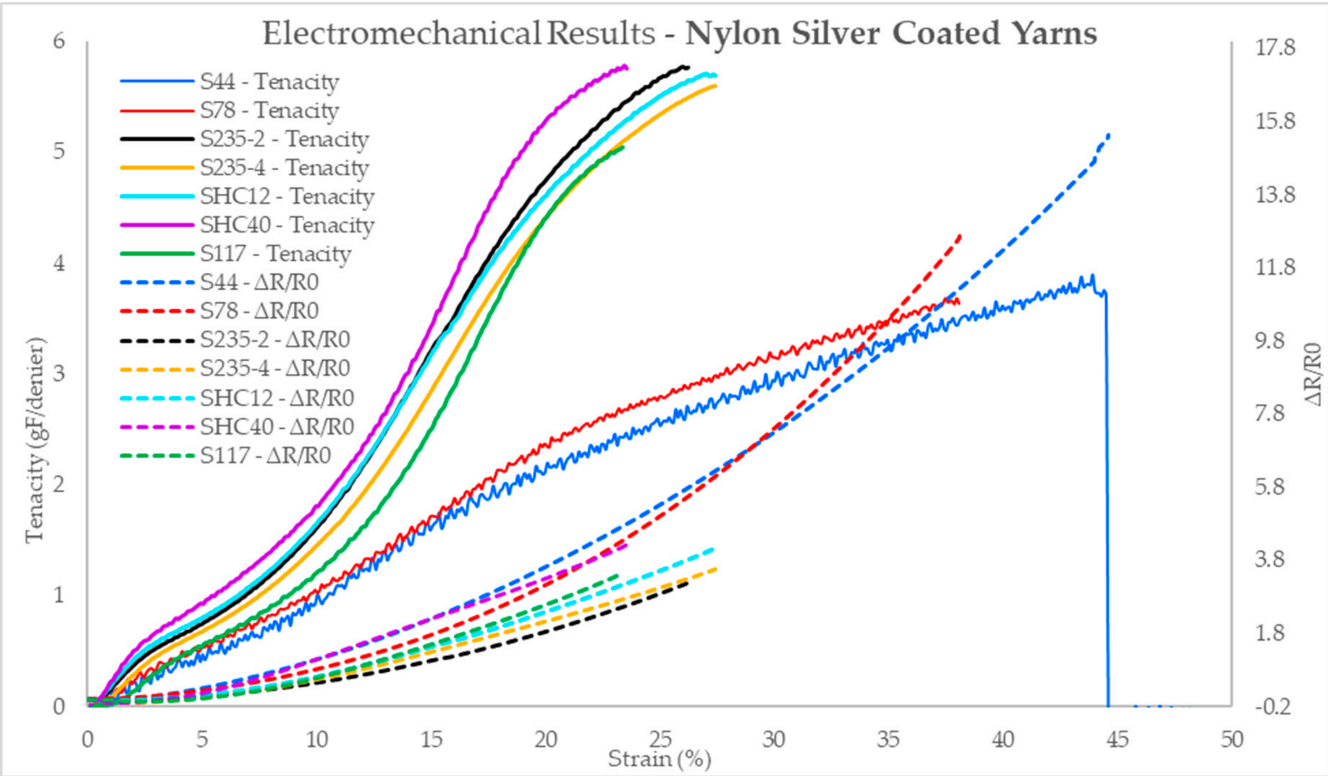

Figure 7. Continuous electromechanical evaluation results for silver-plated yarns.

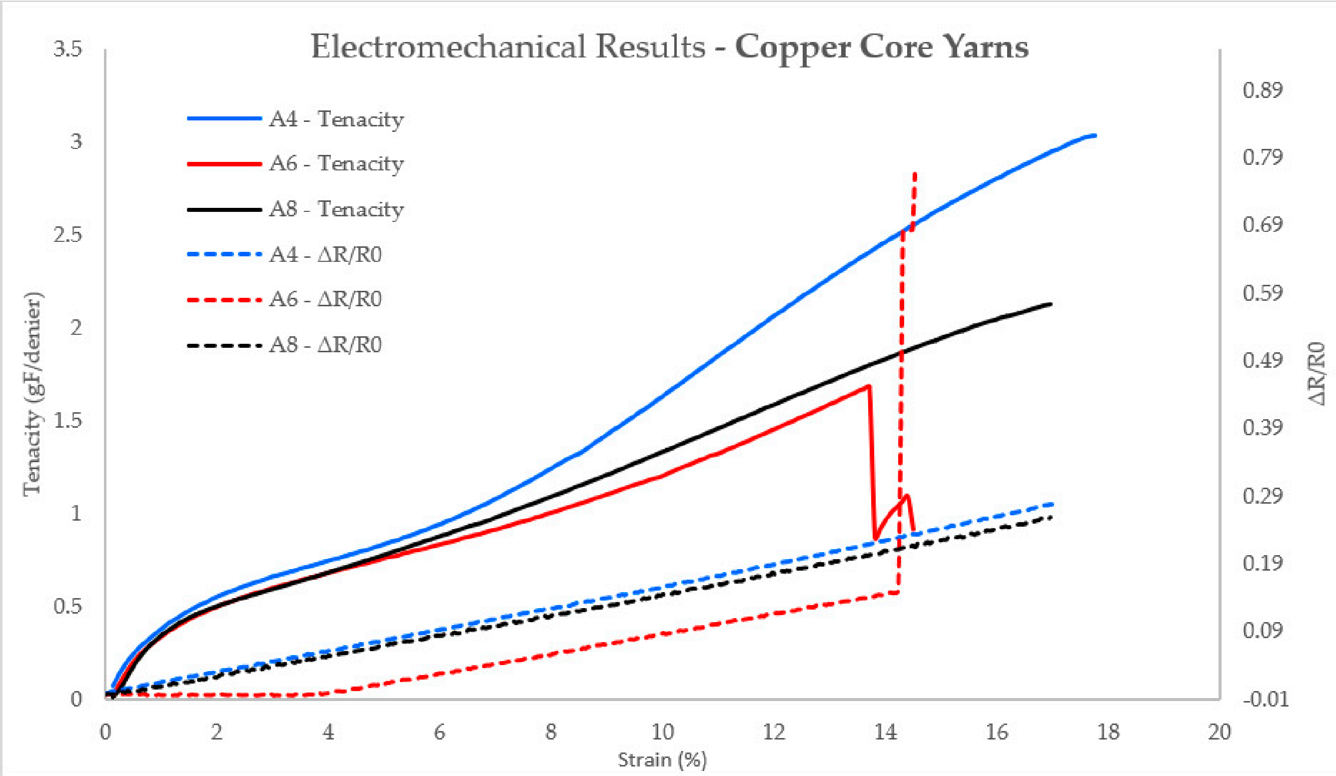

Figure 8. Continuous electromechanical evaluation results for copper core yarns.

In contrast, silver-plated nylon yarns had very good stretchability (>20%), especially the yarns S44 and S78 reached more than 35%. The resistance of this type of yarn also changed greatly with strain, except for S44 and S78; the resistance change stayed between 2 and 4 for the other plated yarns, while the resistance change exceeded 11 with S44 and S78 (Figure 7). Considering the relatively high resistance of such conductive yarns, it would be beneficial to keep in mind how the resistance is impacted by the strain during processing as well as end-user applications. Interestingly, for Ag-plated conductive yarns, the resistance does not always increase with increasing strain (Figure 9). When the low strain occurs (<4%), the conductive material does not break. On the contrary, the Ag-plated nylon monofilaments approached each other under the action of external force, forming a tighter structure. This results in a tighter contact of the conductive layers on the monofilament, reducing the resistance to some extent. As the stretching progresses, the conductive layer begins to show defects, and the resistance value increases. The above data had a certain guiding effect on the tension setting of the conductive yarn during sewing and the application of the finished product.

The resistance change ($\Delta R/R_0$) of the copper core yarn was less than 0.3% (Figure 9). An increased number of copper cores resulted in no change in conductivity but decreased tenacity. Due to the twisted polyester being the outer layer, this type of yarn has a certain stretchability, with a strain of 14% to 18%.

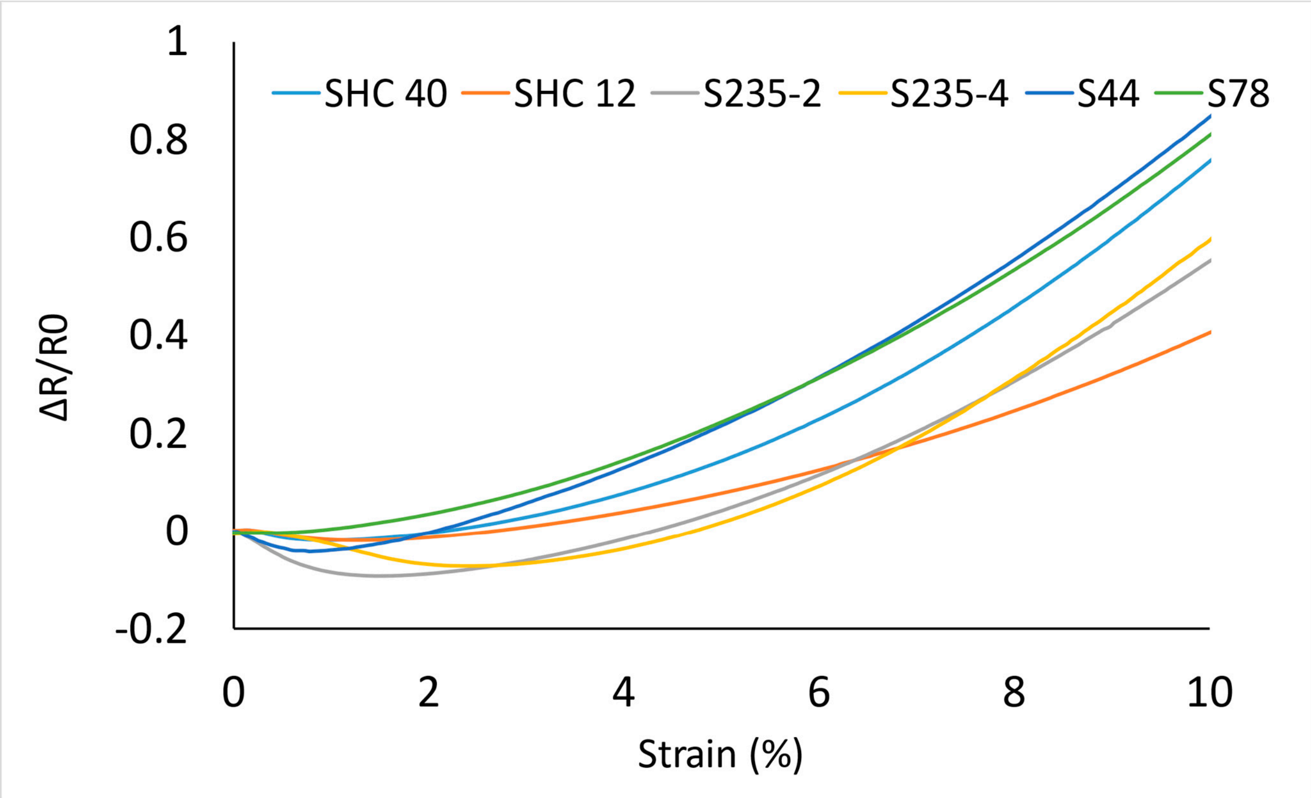

Figure 9. Change of resistance value of Ag-plated yarn under low strain.

4. Conclusions

In this study, we selected three representative types of conductive yarns, analyzed their conductive materials and structures and measured their mechanical and electromechanical properties. For each type of conductive yarn, we picked several different specifications of yarn, and the conclusions are: 1. The stainless-steel yarn showed high linear density (up to 13,500D), high yarn diameter (0.496 mm) and low stretchability (<2% strain); 2. The yarn made of silver-plated nylon showed good mechanical properties, indicating that the conductive yarn produced by this preparation method has good weaving, knitting and sewing potential. However, this type of yarn typically possesses a large inherent resistance (up to 15,000 ohm/m), and the resistance increases substantially with increasing strain or load ($\Delta R/R_0$ can be up to 15). In addition, we found that under low strain, the resistance of Ag-plated conductive yarn decreased first, which may serve as a guide for pretension settings during yarn fabrication; 3. The copper core yarns are made of polyester-wrapped copper/stainless steel filaments. This yarn combines the advantages of pure metal conductive yarns and conductive yarns based on traditional textile materials, maintaining good strength and stretchability, and the resistance is not significantly changed with the strain/load. These three types of conductive yarns are typical of commercially available conductive yarns, and the experimental results can well guide the processability of conductive yarns in weaving, knitting and sewing.

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