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Investigating the Effect of Weave Type and Filament Count on Electrical Conductivity of Polyethylene Terephthalate (PET) Fabrics Coated with PEDOT Polymer

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ABSTRACT

The rapid development of smart and wearable textiles has been driven by the need for smaller and lighter electronic circuits. To make textile surfaces conductive, various methods have been developed, with vapor-phase polymerization being a preferred method due to its smoothness, conductivity, and ease of application. This study investigates the effect of fundamental characteristics of textile fabrics, such as weave type and filament count, on electrical conductivity. Fabrics woven with different filament counts and weave types were coated with PEDOT polymer using vapor-phase polymerization. The results showed that the fabric woven with 150F288 yarns and a 3/1 twill weave exhibited lower electrical resistance, attributed to the microfibrous structure of the yarn and the twill's staggered structure. Despite increases in resistance values after performance tests, the electrical resistance values remained within a sufficient conductivity range. This research contributes to the understanding of how fabric characteristics affect the electrical conductivity of coated textiles, paving the way for the development of smart electronic textiles.

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KEYWORDS

Conductive textiles, PEDOT, vapour phase polymerization

1. INTRODUCTION

As a result of our continuous efforts to be closely intertwined with technology, the need for electronic circuits to be made smaller and lighter to be portable has arisen, leading to the rapid development of the smart and wearable textiles as a new sector. Polymers such as polyester, polyamide, polyolefin, etc., which are used in textile surface production, have high electrical resistance values. Therefore, numerous methods have been developed to make textile surfaces conductive [1], [2].

The process that began with the use of metal wires in fabric production gained new momentum with the discovery of conductive polymers in 1977 [3]–[6]. In 1988, PEDOT Poli(3,4-ethylenedioxythiophene), which was one of the most successful polymers in terms of processability, stability, and conductivity, reached a higher level of production by Bayer AG [7]–[9].
While there are various application methods for coating textile surfaces with conductive polymers, (electrochemical polymerisation, and oxidative chemical polymerization [10], [11]) vapor-phase polymerization is seen as one of the preferred methods due to its smoothness of the surface, conductivity level, and ease of application [12]–[16].

Starting with initial efforts by J. Kim et al. [17] between 2003 and 2005, a novel method for creating highly conductive PEDOT layers through vapor phase polymerization (VPP) was developed . In the polymerization chamber, EDOT was evaporated and polymerized on the substrate, with the oxidant iron (III)-tosylate being deposited by bubbling different gases such as nitrogen, air, and argon through the EDOT reservoir. Winther-Jensen et al. performed the experiments, applying the compound to PET and Pt-coated PET substrates. This was done by mixing the ferric tosylate solution with pyridine in a molar ratio of 1:0.5. [18]
Choi et al. effectively prepared highly conductive and transparent poly(3,4-ethylenedioxythiophene) (PEDOT) thin films through

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vapor-phase polymerization (VPP) with the addition of imidazole (Im) based derivatives [19].

Yang et al. applied the vapor phase polymerization process to coat flexible polyethylene terephthalate (PET) fabrics with a uniform poly(3,4-ethylenedioxythiophene) (PEDOT) film. They systematically investigated the polymerization conditions, including the concentration of the oxidant, reaction time, and temperature. The results indicate that the concentrations of the impregnating oxidant, as well as the temperature and duration of vapor polymerization, significantly impact the surface resistance of the coated fabric [20].

Trindade et al. utilized aqueous oxidant solutions in addition to ethanol-based ones, resulting in textile substrates with high electrical conductance. The sheet resistivity of the samples could be further reduced by a factor of 5 through the application of multiple polymerization layers, with the resistivity being dependent on the conjugated polymer content.[21]

Ala et al. fabricated electrically conductive textiles by vapor-phase polymerizing poly(3,4-ethylenedioxythiophene) (PEDOT) layers on cotton, cotton/poly(ethylene terephthalate) (PET), cotton/Lycra, and PET fabrics. They measured the electrical resistivity of these PEDOT-coated textiles and analyzed the impact of water treatment on their electrical resistivity. They concluded that prolonged exposure of the PEDOT layer to water increases the pH of PEDOT, resulting in reduced conductivity of the coated fabric. [22]

Pires et al. applied a coating of the conductive polymer poly(3,4-ethylenedioxythiophene) (PEDOT) to fibers through vapor-phase polymerization of EDOT at 70 °C over a duration of 2 hours. They used different solvents (ETH, DMF, and THF) as FeTos solvents to investigate their impact on conductivity. They concluded that various solvent systems will affect the redox state of iron species and, consequently, the properties of PEDOT. [23]

In the coating of textile surfaces with conductive polymers, the surface properties of the fabric are one of the important parameters for achieving a homogeneous coating and thus obtaining good conductivity. The weave type of the fabric and the number of filaments in the yarn used are among the most important parameters that alter the fabric surface properties.

The aim of this study is to investigate the effect of fundamental characteristics of textile fabrics, such as weave type and filament count, on electrical conductivity. In this study A polymerization chamber was developed for the purpose of coating textile surfaces with PEDOT to make them conductive. The front of the chamber features a sealed gasketed cover to accommodate the placement of samples. Inside the chamber, needle frames on adjustable suspension legs are designed in a horizontal orientation to prevent the liquid solution applied from flowing unevenly on the fabric surface, ensuring that the fabric is positioned horizontally rather than vertically. The fabrics were woven with the most commonly used Polyethylene Terephthalate (PET) yarns of 48, 144, and 288 filaments using plain and 3/1 twill weaves, without changing the yarn densities. Due to its high conductivity potential, PEDOT polymer and the vapor-phase polymerization (VPP) method were selected for the coating process under laboratory conditions. After performance tests such as washing, dry cleaning, abrasion, elasticity, acid/alkali resistance on PEDOT-coated fabrics, changes in electrical conductivity values were examined, and the effects of weave type and filament count were evaluated. Electrical conductivity measurement was presented as electrical resistance.

In the conducted studies, although the effect of weave and filament count did not show a significant difference, it was determined that the fabric woven with 150F288 yarns and 3/1 twill weave exhibited lower electrical resistance than the others. This is thought to be due to the microfibrous structure of the yarn enlarging the surface area of the coating done with VPP, and thus increasing the contact surface, along with the twill's staggered structure resulting in a less closed fabric. Despite the observed increases in resistance values after performance tests, the electrical resistance values remained between 10^1 and 10^3 Ohms, indicating sufficient conductivity. The electrical resistance values of PET surfaces are above 10^{13} Ohms and are classified as insulating.

2. MATERIAL AND METHOD

2.1 Material

2.1.1 Characteristics of Yarn and Fabric

For the experiments, PET yarns with a yarn count of 150 Denier and 48, 144, and 288 filaments per texture were used. The yarns were used in the warp without being twisted for higher surface coverage. The characteristics of the yarns are provided in Table 1, and the fabric properties with plain and 3/1 twill weaves are presented in Table 2. The charts presented in the results section are labeled in accordance with the codes specified in that tables. Besides the yarn count, the effect of filament count and weave variation on making the fabric conductive through vapor-phase polymerization was investigated while keeping the weft and warp densities constant. The yarns were used with a minimum number of twists in both the warp and weft to enable stable operations.

Plain weave fabrics have the highest intersection of weft and warp yarns, giving them an isotropic structure and a closed surface. In 3/1 twill fabrics, the number of intersections is lower, and the warp yarns make more pronounced jumps on the surface, resulting in a more open surface. High filament count yarns increase the surface area.

2.1.2 Chemicals Used

Details of the chemicals used in the study are provided in Table 3, and the details of the solution prepared to create the conductive surface are presented in Table 4.

Table 1. Properties of the yarns used in the experiment

Yarn Count/ Number of Filament	Filament Thickness (Den)	Breaking Load (cN)	Breaking Elongation (%)	Tensile Strength (cN/dtex)	Twist Count
150F48	159,3	668,9	18,6	3,7	119,8
150F144	163	592,2	18,8	3	115
150F288	164,5	584,5	19,1	3,2	117

Table 2. Fabric properties

Code	Weave Type	Warp Yarns	Weft Yarns	Warp Density (threads/cm)	Weft Density (threads/cm)	Unit Weight (g/m²)	Thickness (mm)
48P	Plain	150F48	150F48	31	31	121	0.21
144P	Plain	150F144	150F144	31	31	118	0.21
288P	Plain	150F288	150F288	31	31	118	0.21
48T	3/1 Twill	150F48	150F48	31	31	120	0.21
144T	3/1 Twill	150F144	150F144	31	31	117	0.21
288T	3/1 Twill	150F288	150F288	31	31	115	0.21

Table 3. Chemicals used in the experiment and their properties

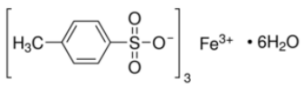
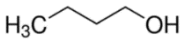
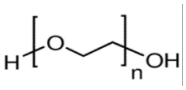
Material	Function	Content	Formula	Molecular Weight (g/mol)
3,4-Ethylenedioxythiophene (EDOT)	Monomer	96.5% (GC)	$C_6H_6O_2S$ 	142,18
Iron(III) p-toluenesulfonate hexahydrate	Dopant (oxidizing agent)	Karbon 30.9-43.5% Sülfür 11.8-16.6% Klorid ≤10 %	$[C_{21}H_{21}FeO_9S_3 \cdot 6(H_2O)]$ 	677,52
n-butanol	Solvent	≥ 99.4 % A.C.S. Reagent	$CH_3(CH_2)_3OH$ 	74,12
PEG	Conductivity enhancer		$H(OCH_2CH_2)_nOH$ 	400
Pyridine	Basic solvent for alkaline environment	≥99.8 A.C.S Reagent	C_5H_5N 	77
Argon	Inert gas	≥99.998%	Ar	39,95
Ethanol	Dissolver	≥ 99.5 A.C.S Reagent	C_2H_5OH	46,069

Table 4. Recipes used for the solution (Dopant)

Iron Weight Ratio (%) (Iron Tosylate/Butanol)	Iron(III) p-toluenesulfonate hexahydrate (g)	Butanol (g)	Pyridine (g)	PEG (4-5%) (g)
40	1.190	1.500	0,067	0,110-0,140

2.1.2 Polymerization Chamber

Bjørn Winther-Jensen spearheaded the creation of the polymerization chamber utilized in vapor-phase polymerization, a milestone referenced in numerous subsequent studies [15]. He considered standard substrates rather than textile materials, resulting in the material being placed vertically in the cabinet. Consequently, when textile surfaces were coated, the dopant flowed downward, leading to agglomerates and inhomogeneous coatings. Thus, a different design was necessary to produce conductive textile materials using the VPP method. In this study polymerization chamber, as depicted in Figure 1, was developed for the purpose of coating surfaces with PEDOT to make them conductive [24]. The front of the chamber features a sealed gasketed cover to accommodate the placement of samples. Inside the chamber, needle frames on adjustable suspension legs are designed in a horizontal orientation to prevent the liquid solution applied from flowing unevenly on the fabric surface, ensuring that the fabric is positioned horizontally rather than vertically. To achieve the desired temperature of the environment, a heating table is centered under the apparatus, with a fan inserted to ensure temperature homogeneity, and thermostat control maintains a constant temperature. The device includes a digital indicator that allows the reading of the target and instantaneous temperatures. The fan, as well as the lamp for illumination and the heater, are controlled by buttons on top of the device. A gas inlet valve is located at the bottom of the chamber for feeding argon gas, and an air outlet valve is placed at the top for air exhaust. Since the chamber requires air ventilation, it is placed within the draft hood. Its dimensions are prepared as 75 cm in width, 50 cm in depth, and 60 cm in height.

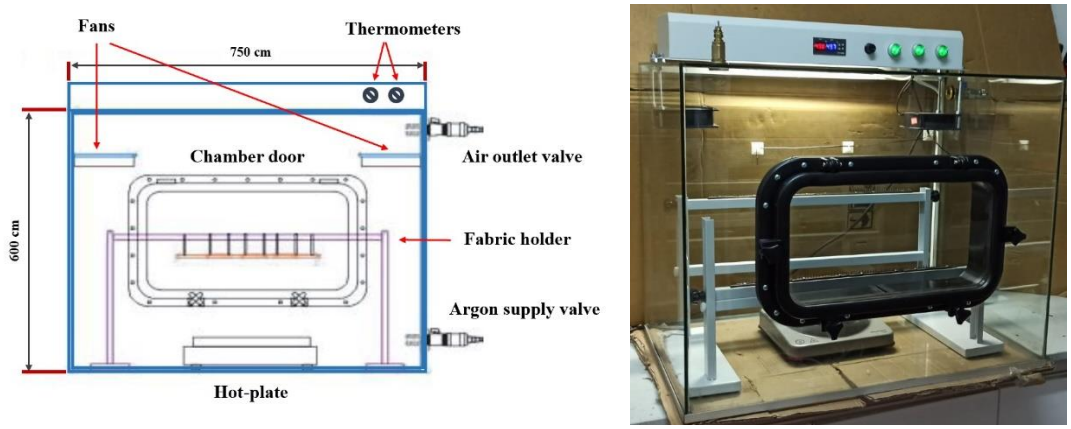


Figure 1. Polymerization chamber design and picture

2.2 Method

2.2.1 Preparation of Samples

The production of yarns, weaving of fabrics, and dyeing processes were carried out at Küçükçalık Tekstil production facilities. To ensure no residues were left on the fabrics and to achieve surface cleanliness, the fabrics were washed with 2 g/L Rucogen DFL oil remover at 80°C and a speed of 10 m/min in the dyeing facility. Fabric samples were cut into dimensions of 6 cm x 30 cm to prepare the samples.

Based on the work of Truong et al. (2008), a Dopant (Iron tosylate) solution was prepared using a mixture of Iron tosylate powder, Butanol, Polyethylene glycol, and Pyridine. The mixture was prepared and homogenized by ultrasonically stirring for approximately 30 minutes until no solid particles remained.

To ensure accurate comparisons between fabric samples, 0.476 g of the prepared DOPANT mixture was applied to each of the 6 fabric samples. The mixtures were prepared daily before each experiment.

While the samples soaked in the Dopant solution were placed horizontally in the polymerization chamber, 0.7 g of EDOT monomer was placed on a petri dish on the heating plate. When the chamber was closed, the argon gas cylinder was opened simultaneously with an air outlet valve at a feed rate of 15 L/min. After 15 minutes, the air outlet valve was closed. Fifteen minutes later, the argon feed rate was reduced to 8 L/min. After another 15 minutes, the argon gas supply was stopped, and the polymerization continued for another 15 minutes. After a total of 1 hour of application within the chamber, the lid was opened, and the samples were removed. The samples were washed with a 50/50 mixture of ethyl alcohol and distilled water and then dried in an oven at 100°C for 15 minutes for the measurement of electrical resistance values.

The polymerization process (VPP) and conductivity measurements were carried out at Uludağ University Textile Engineering Laboratories. Performance tests were also conducted on the conductive fabrics to assess the effects of filament count and weave type on the process.

2.2.1 Applied Tests

Surface Tension: To observe the effect arising from differences in both weave and filament count of the fabrics, Surface Tension Resistances were measured in Contact Angle (Young-Laplace) analysis mode using a Biolin Scientific Attension Theta Flex device at Bursa Technical University Polymer Engineering Laboratory before the polymerization process.

Surface Electrical Resistance: The electrical resistance values of the fabrics were measured using the Entek FPP470 4-Point Conductivity device in accordance with the EN 1149-1 test standard.

SEM Imaging: SEM images of the fabrics before polymerization, after polymerization, and after abrasion were obtained using the ZEISS EVO 40 device at Uludağ University Physics Department Laboratory.

Wash Resistance: To evaluate the suitability for use of the conductive surfaces, the fabrics underwent a gentle wash at 30°C in a home washing machine following the ISO 105 C06 standard, and changes in electrical resistance were measured.

Dry Cleaning Resistance: Fabric samples were subjected to dry cleaning with perchloroethylene solution following the ISO 105 D01 standard after polymerization, and changes in electrical resistance were examined.

Abrasion: The fabrics were tested using the Martindale abrasion tester according to the ISO 12947-2 standard after becoming finished goods, and the impact of friction on electrical resistance values was measured.

Elastic Behavior: To examine changes in flexibility of the fabrics after polymerization, their recovery behaviors were investigated using a Titan Tensile Strength Testing Device in accordance with the Next TM 21a standard used for apparel fabrics. The test involves stretching the sample with a force of 4 kgf, with a jaw separation of 100 mm, and holding it for 10 seconds before releasing it twice. Test results were evaluated after the 20th stretch to represent general usage conditions.

Acid-Alkali Resistance: For assessing the durability of the fabrics with polymerized surfaces for use in garments, a resistance test was conducted following the ISO 105 E04 standard, followed by the measurement of electrical resistance changes to observe their conductivity.

Tensile Strength: To determine whether the tensile strength and behavior of the fabrics were affected after polymerization, tests were conducted using the James H. Heal Titan device in accordance with the TS EN ISO 13934-1 standard.

3. RESULTS AND DISCUSSION

3.1. Contact Angle

To assess the surface properties of fabrics before conducting the conductive coating, measurements of the contact angle of the fabric surfaces were conducted. The results of the contact angle experiment were analyzed based on the weave and filament count characteristics of the fabrics. The values measured at the 5th second, when water droplets were observed, are presented in Table 5. According to the results, in plain weave samples, an increase in filament count led to an increase in the contact angle. However, in twill weaves, the impact of the weave structure was more influential than the effect of filament count, resulting in a decrease in contact angle due to the open structure.

3.2 Electrical Resistance Measurements

3.2.1 Front-Back Surface Comparison

During the application of the Dopant solution, the weft faces of all fabrics were considered as the front surfaces, and the electrical resistance values after polymerization were separately measured from both the front and back surfaces of plain and twill fabrics. When examining the electrical resistance of plain and twill samples in Figure 2 and Figure 3, except for the 48-filament fabric, there was no significant difference between the measured values from the front (F1, F2,… F6) and back (B1, B2,… B6) surfaces. The 48-filament fabrics have the lowest filament count, suggesting they possess the least coverage, leading to a less homogeneous coating. Therefore, variations in electrical resistance values are observed among these samples. The reason for the similarity in values between both sides of the fabrics is attributed to the porous structure allowing the solution to penetrate through to the back surface when dripped, and the vapor-phase polymerization affecting all fabric surfaces. Electrical resistance values vary between 20 and 300 Ohms for all fabrics, indicating their conductivity.

3.2.2 Resistance Change After Washing

After applying the conductive coating to the fabrics using the VPP process, the next step involved subjecting these fabrics to a washing test using a standard home washing machine. The purpose of this test was to assess the durability of the conductive coating under typical washing conditions that garments might experience during regular use.

Upon completing the washing test and measuring the electrical resistance of the fabrics it was observed that the resistance values exceeded 10^5 Ohms. This finding indicated that the electrical conductivity of the fabrics had been compromised due to the washing process. In other words, the conductivity of the coated fabrics decreased significantly after undergoing the washing procedure.

Table 5. Contact angle measurement values

Weaving type	Yarns (Warp/Weft)	Pattern No	Contact Angle (°)
Plain	150F48	38198	16.51
Plain	150F144	38191	21.08
Plain	150F288	38193	23.85
3/1 Twill	150F48	38197	-
3/1 Twill	150F144	38194	-
3/1 Twill	150F288	38195	-

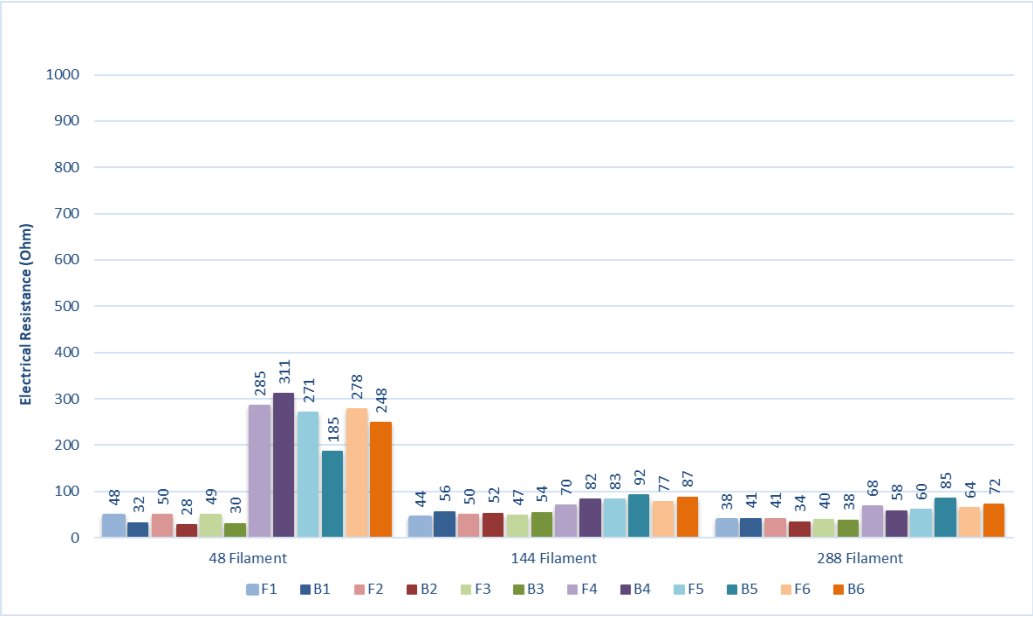


Figure 2. Comparison of surface resistance values for Plain weave samples

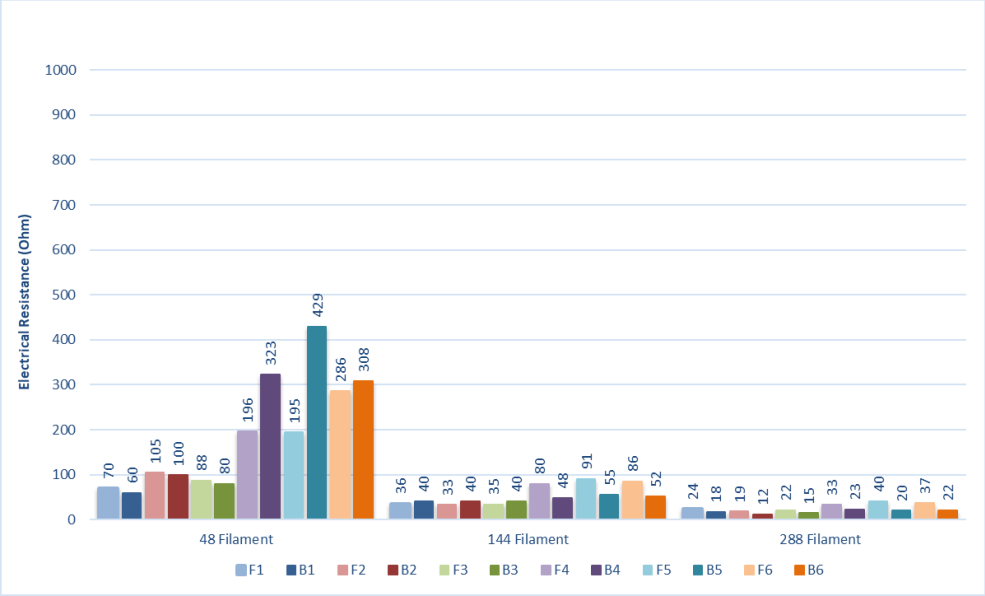


Figure 3. Comparison of surface resistance values for Twill weave samples

This outcome raised concerns about the wash resistance of the conductive coating achieved through the VPP (vapor-phase polymerization) process. The result suggested that the coating might not possess the desired durability to maintain its electrical conductivity through multiple washing cycles in a home washing machine.

This information is crucial for evaluating the practicality and longevity of the developed conductive textiles for real-world applications, as maintaining the functionality of conductive coatings is essential to their usability in wearable technology, smart textiles, and related fields.

3.2.3 Resistance Change After Dry-Cleaning

Since the resistance values after washing mashine were realy high, it was decided to dry clean the samples. After polymerization and ethanol washing, the samples were dry cleaned and the resistance measurements were repeated the results were showed in Figure 4. It was observed that the resistance increased up to 10^4 Ohm in 48 filament samples, but the resistivity level remained below 10^3 Ohm in other samples.

3.2.4 Resistance Change After Abrassion

The electrical resistance values of the fabrics subjected to a 1,000-cycle abrasion test are depicted in Figure 5. While there isn't a substantial difference among the weaves, it's notable that samples with 48 filaments experienced a more adverse impact on resistance values due to the abrasion test. Conversely, as filament count increased, it became apparent that the conductivity of the surface was less affected by abrasion.

This observation indicates that the conductive properties of the fabrics, particularly in terms of electrical resistance, exhibit varying degrees of resilience to abrasion depending on factors such as filament count. Fabrics with higher filament counts appear to better retain their conductivity even after undergoing an abrasion test compared to those with lower filament counts.

These findings are vital for understanding the behavior of conductive coatings in textiles when subjected to wear and tear. Evaluating the resistance changes post-abrasion is crucial to ensure the longevity and reliability of conductive textiles in practical applications.

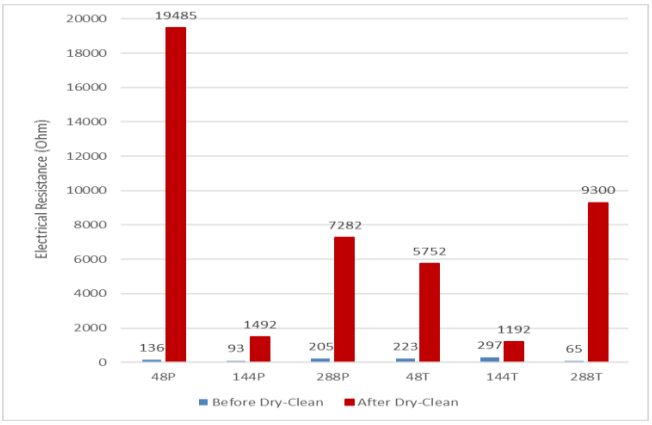


Figure 4. Electrical resistance changes before and after dry-cleaning

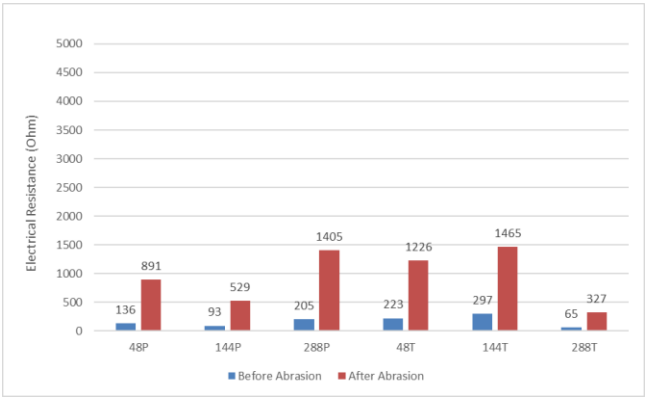


Figure 5. Comparison of electrical resistance values before and after 1000 cycles of abrasion for fabrics

3.2.5 Resistance Change After Elasticity Test

Considering the suitability of fabrics for wearable electronics, an elasticity test was performed with 20 repetitions in the warp direction. This test aimed to assess not only the effect of the created surface's flexibility after polymerization but also the impact of repeated stretching movements on conductivity. It was observed that the VPP process did not significantly alter the fabric's elongation percentages, as the values remained within the range of 99% to 100%. Only a slight decrease was observed in the recovery values in the warp direction.

Following the repetition of the test for 20 sets, the measured resistance changes are presented in Figure 6. For both weave types, as filament count increased, resistance values decreased, with samples made using 150F288 threads exhibiting the lowest resistance values. Among all fabrics, there was a marginal increase in electrical resistance values after repeated stretching in the warp direction, whereas in the weft direction, the 48 and 144 filament fabrics showed an increase in electrical resistance values. In the case of 288 filament fabrics, regardless of the weave type, electrical resistance values remained exceptionally low even after repeated stretching. However, when considering all fabrics collectively, their resistance values remained quite low after 20 stretches, attributed to the dense and homogeneous coverage of fiber surfaces by vapor-phase polymerization.

These observations highlight the behavior of conductive coatings under stretching conditions and emphasize the potential robustness of the developed textiles for wearable applications, especially in terms of maintaining their conductivity during repeated movements.

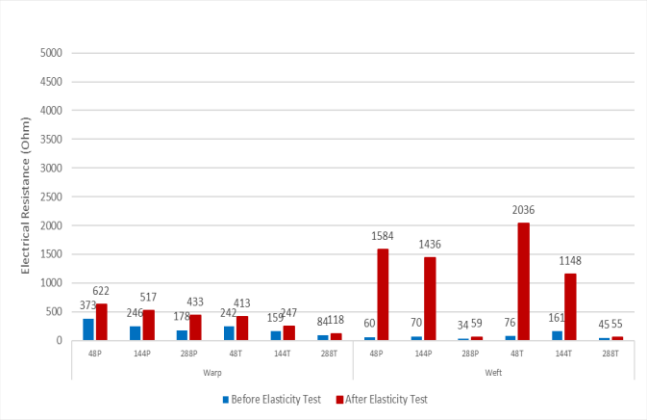


Figure 6. Comparison of electrical resistance change in samples stretched for 20 sets

3.2.6 Resistance Change After After Acid/Alkali Resistance Test

The results of the acid/alkali resistance test on the fabrics indicated that the test chemicals were rated at 4-5 for all fabrics, revealing that the accompanying samples were not stained. As depicted in Figure 7, due to the hydrophilic nature of the twill weave, the test chemicals penetrated the fabric structure more extensively. Consequently, there was a higher increase in resistance values for the twill weave samples. Nonetheless, the final outcomes demonstrated that the resistance values of the samples remained low.

This outcome implies that the developed conductive textiles have a degree of resilience to acid and alkali exposure, showcasing their potential suitability for applications where they might come into contact with various chemicals without compromising their conductive properties.

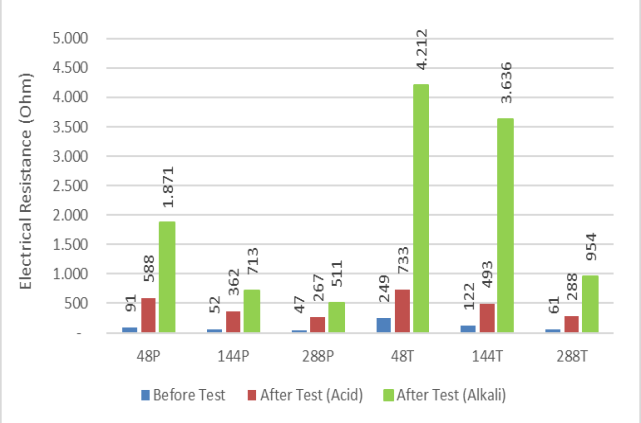


Figure 7. Comparison of electrical resistance before and after acid and alkali perspiration tests

It has been observed that all fabrics were particularly affected by alkaline substances after the VPP process. Moreover, fabrics with lower filament counts were more susceptible to this effect compared to fabrics with 288 filaments.

3.2.7 Time-Dependent Electrical Resistance Change

Following the polymerization process, the fabrics were left exposed to room conditions and re-evaluated on the 60th and 90th days to measure resistance changes. As depicted in Figure 8, it is evident that within three months, the conductivity remained at a satisfactory level under indoor conditions. The figure shows the mean value for all samples.

This observation suggests that the conductive coatings applied through the VPP method exhibited a level of stability and endurance over time, indicating their potential for maintaining effective conductivity for wearable applications even after extended periods of use.

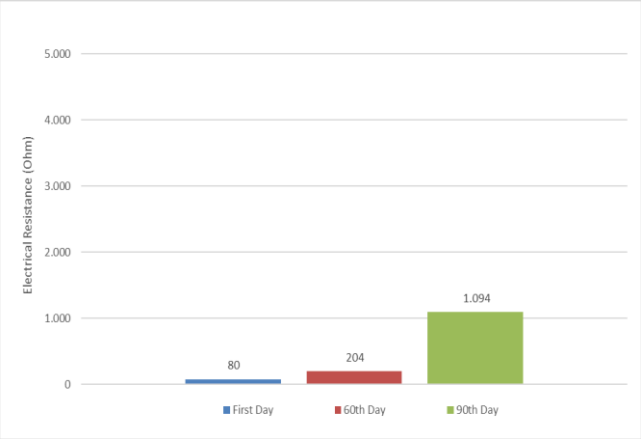


Figure 8. Electrical resistance variation of samples kept under room conditions

3.3 SEM Images

Figure 9 presents SEM images of the fabrics after abrasion. It's noticeable that a film layer formed post-coating, which fills the spaces between the fibers. While the film layer isn't visible in the

images after abrasion, the fact that the measured resistance values remained low suggests that the coating not only persisted on the fabric surface but also enveloped the fiber surfaces.

This observation underscores the effectiveness of the coating process in providing a durable and comprehensive coverage, maintaining conductivity even after undergoing abrasive conditions.

3.4 Strength Analysis

The impact of the coating was investigated by conducting strength tests on the fabrics before and after the VPP process, and the results are shared in Figures 10 and 11. The absence of a significant difference in strength and elongation values can be attributed to the thin and uniform nature of the coating formed on the fiber surfaces post-polymerization.

These findings suggest that the polymerization process and subsequent coating have been managed in a way that doesn't substantially compromise the mechanical strength of the textiles.

When comparing the fabrics before and after VPP coating, there is also no significant alteration in the elongation values shown in Figure 11.

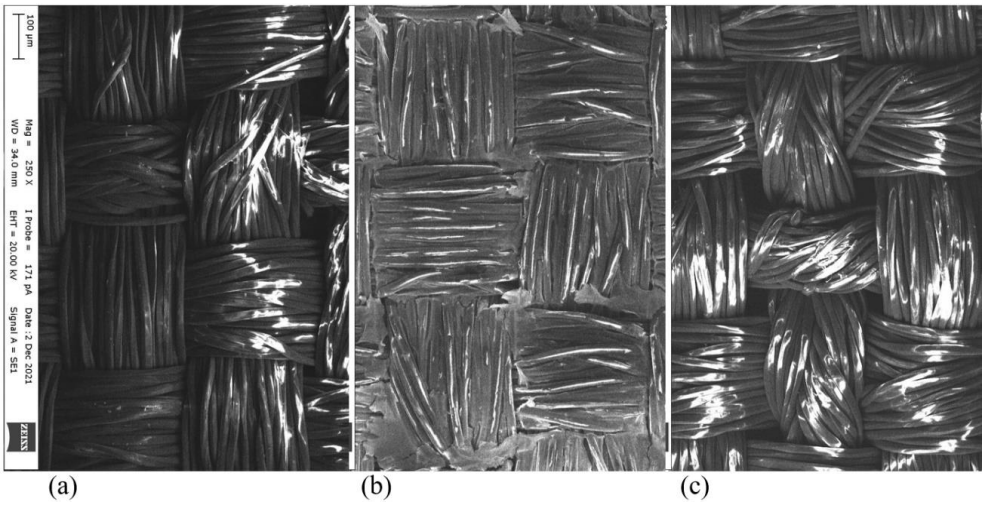


Figure 9. Plain weave a) Raw Fabric, b) PEDOT Coated Fabric, c) PEDOT Coated Fabric After 1000 Rubs of Abrasion

Figure 10. Comparison of tensile strength in fabrics before and after coating

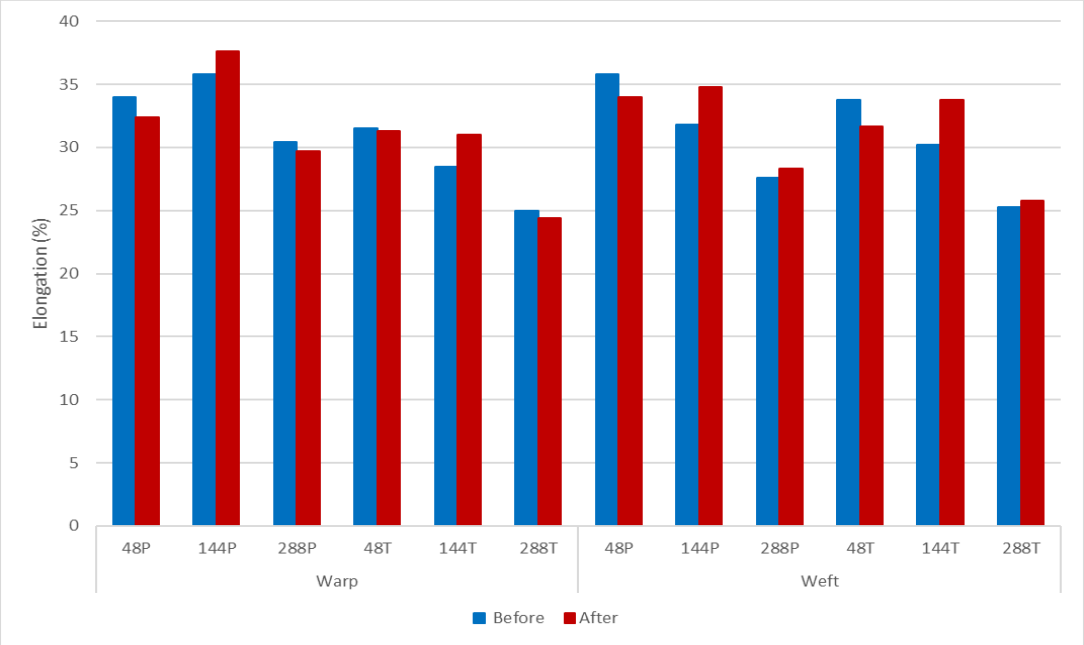


Figure 11. Comparison of percentage elongation at break in fabrics

4. CONCLUSION

When examining the effect of the fabric's weave structure on the polymerization process, it is evident that the performed polymerization process did not significantly alter physical performance parameters such as tensile strength and elongation. Similarly, the impact of polymerization on fabric's recovery behavior was found to be negligible. These findings suggest that the Vapor Phase Polymerization (VPP) process may not have a discernible impact on the performance parameters evaluated through these physical tests. Therefore by utilizing VPP, researchers have been able to fabricate conductive textiles with enhanced electrical conductivity, making them suitable for applications in flexible electronics and wearable devices [25]–[27].

However, as indicated by the measurements of contact angles, it is apparent that 3/1 twill weave fabrics are significantly more hydrophilic compared to plain weave fabrics. This effect is attributed to the more pronounced capillarity of the twill weave structure, allowing a higher amount of solution to penetrate the fabric's structure, ultimately enhancing conductivity. This is consistent with the results of post-abrasion electrical conductivity measurements, where twill weave fabrics exhibited better performance due to the same reason.

In terms of filament count, fabrics woven with higher filament counts exhibited notably lower electrical resistance compared to fabrics woven with lower filament counts. Specifically, fabrics woven with 48 filament yarns displayed a more significant deviation in resistance values compared to those woven with 144 and 288 filament yarns. This trend could be linked to the reduction in surface area associated with fewer filaments, potentially leading to a less conductive structure due to reduced inter-fiber connectivity. Duran and Kadoğlu investigated the electromagnetic shielding effectiveness of woven fabrics influenced by various factors such as yarn count, core filament count, blend ratio, weft density, electrical resistivity, yarn type, and wave frequency [28] They concluded that the results have demonstrated significant differences in the EM shielding characteristics and performance of fabrics produced with different yarn groups. Additionally, it was observed that shielding effectiveness can be controlled by tailoring the yarn and fabric parameters.

In summary, 3/1 twill fabrics woven with 288 filament yarns achieved the lowest electrical resistance values post-polymerization and maintained high performance even after physical tests such as abrasion and elasticity tests. Considering usage conditions, dry cleaning might be recommended post-home washing due to the increase in electrical resistance caused by factors like water, detergent, and mechanical stress. Moreover, despite the greater increase in resistance resulting from alkali exposure compared to acid exposure, electrical conductivity was still retained. Micro filaments in yarns play a crucial role in enhancing the performance of fabrics during vapor phase polymerization. The fineness of filaments significantly impacts the comfort characteristics of fabrics, with finer filaments leading to better wetting, higher wicking, and optimal moisture vapor transmission [29]. Fabrics constructed from micro denier synthetic filament yarns exhibit improved properties by reducing open spaces within the yarn or fabric structure, enhancing overall performance [30].

SEM images and the results of conducted tests collectively suggest that the vapor-phase polymerization process produces robust and effective conductivity. The ability of PEDOT-treated fabrics to achieve resistances below 10^2 Ohms, withstand external factors, and maintain conductivity even after 90 days of exposure to open air and room temperature indicates the potential for further industrial application.

These findings indicate the potential for this method to be implemented in industrial production. It underscores the potential of producing conductive fabrics suitable for wearable electronics and other applications. This research paves the way for refining the production of conductive fabrics and improving their use in various fields.

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REFERENCES

1. T. He et al., "Self-Sustainable Wearable Textile Nano-Energy Nano-System (NENS) for Next-Generation Healthcare Applications," Adv. Sci., vol. 6, no. 24, 2019.
2. A. M. Grancarić et al., Conductive polymers for smart textile applications, vol. 48, no. 3. 2018.
3. A. Schwarz and L. Van Langenhove, "Types and processing of electro-conductive and semiconducting materials for smart textiles," in Multidisciplinary Know-How for Smart-Textiles Developers, 2013.
4. O. Ala and Q. Fan, "Applications of Conducting Polymers in Electronic Textiles," Res. J. Text. Appar., vol. 13, no. 4, pp. 51–68, 2009.
5. C. K. Chiang et al., "Electrical conductivity in doped polyacetylene," Phys. Rev. Lett., vol. 39, no. 17, 1977.
6. C. R. Cork, "Conductive fibres for electronic textiles: An overview," in Electronic Textiles: Smart Fabrics and Wearable Technology, 2015.
7. L. Groenendaal, F. Jonas, D. Freitag, H. Pielartzik, and J. R. Reynolds, "Poly(3,4-ethylenedioxythiophene) and Its Derivatives: Past, Present, and Future."
8. X. Crispin et al., "The origin of the high conductivity of poly(3,4-ethylenedioxythiophene)- poly(styrenesulfonate) (PEDOT-PSS) plastic electrodes," Chem. Mater., vol. 18, no. 18, 2006.
9. A. Elschner, S. Kirchmeyer, W. Lövenich, U. Merker, and K. Reuter, "PEDOT: Principles and applications of an intrinsically conductive polyme," PEDOT Princ. Appl. an Intrinsically Conduct. Polym., pp. 1–380, Jan. 2010.
10. J. F. Serrano-Claumarchirant, R. Muñoz-Espí, A. Cantarero, M. Culebras, and C. M. Gómez, "Electrochemical Deposition of Conductive Polymers on Fabrics," Coatings, vol. 13, no. 2, 2023.
11. T. Bashir, M. Skrifvars, and N. K. Persson, "Synthesis of high performance, conductive PEDOT-coated polyester yarns by OCVD technique," Polym. Adv. Technol., vol. 23, no. 3, pp. 611–617, 2012.
12. B. Karagüzel Kayaoğlu, I. Göcek, H. Kizil, and L. Trabzon, "Functional nano and micro-scale thin film deposition on textiles: Emerging technologies and applications," Journal of Textiles and Engineer, vol. 19, no. 88. 2012.
13. N. Hussain et al., "Synthesis of highly conductive electrospun recycled polyethylene terephthalate nanofibers using the electroless deposition method," Nanomaterials, vol. 11, no. 2, 2021.
14. S. M. Shang and W. Zeng, "Conductive nanofibres and nanocoatings for smart textiles," in Multidisciplinary Know-How for Smart-Textiles Developers, 2013.
15. B. Winther-Jensen, J. Chen, K. West, and G. Wallace, "Vapor phase polymerization of pyrrole and thiophene using iron(III) sulfonates as oxidizing agents," Macromolecules, vol. 37, no. 16, pp. 5930–5935, 2004.
16. T. Le Truong et al., "Surface smoothness and conductivity control of vapor-phase polymerized poly(3,4-ethylenedioxythiophene) thin coating for flexible optoelectronic applications," Thin Solid Films, vol. 516, no. 18, pp. 6020–6027, 2008.
17. J. Kim, E. Kim, Y. Won, H. Lee, and K. Suh, "The preparation and characteristics of conductive poly(3,4-ethylenedioxythiophene) thin film by vapor-phase polymerization," Synth. Met., vol. 139, no. 2, pp. 485–489, 2003.
18. B. Winther-Jensen and K. West, "Vapor-phase polymerization of 3,4-ethylenedioxythiophene: A route to highly conducting polymer surface layers," Macromolecules, vol. 37, no. 12, pp. 4538–4543, 2004.
19. J. S. Choi, K. Y. Cho, and J. H. Yim, "Micro-patterning of vapor-phase polymerized poly(3,4-ethylenedioxythiophene) (PEDOT) using ink-jet printing/soft lithography," Eur. Polym. J., vol. 46, no. 3, pp. 389–396, 2010.
20. X. Yang, S. Shang, L. Li, X. M. Tao, and F. Yan, "Vapor phase polymerization of 3,4-ethylenedioxythiophene on flexible substrate and its application on heat generation," Polym. Adv. Technol., vol. 22, no. 6, 2011.
21. I. G. Trindade, J. Matos, J. Lucas, R. Miguel, M. Pereira, and M. S. Silva, "Synthesis of poly(3, 4-ethylenedioxythiophene) coating on textiles by the vapor phase polymerization method," Text. Res. J., vol. 85, no. 3, 2015.
22. O. Ala, B. Hu, D. Li, C. L. Yang, P. Calvert, and Q. Fan, "Conductive Textiles via Vapor-Phase Polymerization of 3,4-Ethylenedioxythiophene," ACS Appl. Mater. Interfaces, vol. 9, no. 34, 2017.
23. L. S. Pires, D. S. Melo, J. P. Borges, and C. R. Henriques, "PEDOT-Coated PLA Fibers Electrospun from Solutions Incorporating Fe(III)Tosylate in Different Solvents by Vapor-Phase Polymerization for Neural Regeneration," Polymers (Basel)., vol. 15, no. 19, 2023.
24. A. (BUU G. S. of N. and A. S. D. of T. E. Yenice, "Investigation of the effects of number of filaments and weaving structure on polyester textile surfaces made conductive by coating pedot film with vapour phase polymerization method (Master's Thesis).," Bursa Uludag University, 2021.
25. R. Brooke, P. Cottis, P. Talemi, M. Fabretto, P. Murphy, and D. Evans, "Recent advances in the synthesis of conducting polymers from the vapour phase," Prog. Mater. Sci., vol. 86, pp. 127–146, May 2017.
26. H. Moon et al., "Ag/Au/Polypyrrole Core-shell Nanowire Network for Transparent, Stretchable and Flexible Supercapacitor in Wearable Energy Devices," Sci. Rep., vol. 7, no. February, pp. 1–10, 2017.
27. H. R. Lim, H. S. Kim, R. Qazi, Y. T. Kwon, J. W. Jeong, and W. H. Yeo, "Advanced Soft Materials, Sensor Integrations, and Applications of Wearable Flexible Hybrid Electronics in Healthcare, Energy, and Environment," Advanced Materials, vol. 32, no. 15. 2020.
28. D. Duran and H. Kadoğlu, "Electromagnetic shielding characterization of conductive woven fabrics produced with silver-containing yarns," Text. Res. J., vol. 85, no. 10, 2015.
29. M. B. Sampath, S. Mani, and G. Nalankilli, "Effect of filament fineness on comfort characteristics of moisture management finished polyester knitted fabrics," J. Ind. Text., vol. 41, no. 2, 2011.
30. A. Moussa, I. Ben Marzoug, H. Bouchereb, and F. Sakli, "Development and optimisation of waterproof breathable double-sided knitting using a factorial experimental design," J. Ind. Text., vol. 45, no. 3, 2015.