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Development of Highly Stretchable Ag-MWCNT Composite for Screen-Printed Textile Electronics with Improved Mechanical and Electrical Properties

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Introduction: The rapid growth of flexible and wearable electronics has created a need for materials that offer both mechanical durability and high conductivity. Textile electronics, which integrate electronic pathways into fabrics, are pivotal in this field but face challenges in maintaining stable electrical performance under mechanical strain. This study develops highly stretchable silver multi-walled carbon nanotube (Ag-MWCNT) composites, tailored for screen printing and heat-transfer methods, to address these challenges.
Methods: Silver flakes dispersed in a thermoplastic polyurethane (TPU) matrix formed the base composite, which was initially evaluated under tensile and cyclic stretching conditions. Resistance drift observed in these tests prompted the incorporation of multi-walled carbon nanotubes (MWCNTs). Leveraging their high aspect ratio and conductivity, MWCNTs were homogenized into the composite at varying concentrations. The resulting Ag-MWCNT composites were assessed through cyclic stretching and thermal shock tests to evaluate electrical and mechanical performance.
Results: Incorporating MWCNTs improved composite performance, reducing resistance change amplitude by 40% and stabilizing resistance within 2–8 Ohms under mechanical stress. These materials demonstrated superior electrical stability and durability, maintaining consistent performance over extended use compared to Ag/TPU alone.
Discussion: This study highlights the critical role of MWCNTs in enhancing the reliability of conductive composites for textile electronics. By addressing resistance drift and stabilizing electrical properties, these advancements enable more robust and long-lasting wearable technologies. The demonstrated feasibility of combining screen-printing and heat-transfer techniques provides a scalable approach for manufacturing flexible electronics, paving the way for further innovation in industrial applications.
Keywords: stretchable electronics, wearables, Ag-MWCNT composite, screen printing, textile electronics, IoT

Introduction

With the advancement of personal electronics, there is a growing demand for mechanically durable and flexible electronic systems and stretchable conductors and signal pathways.[1–4] Over the years, numerous methods have been developed for manufacturing stretchable electronic systems. Based on a review of the existing solutions, two leading concepts for producing stretchable structures can be observed.

The first method involves a design-oriented approach to impart complex shapes to a structure in 3D or 2D form, such as spirals, accordions, coils, or meanders.[5–13] These shapes aim to mitigate and temporally offset the adverse effects of material stress. However, this approach has a significant drawback in that it consumes more space and material, which is

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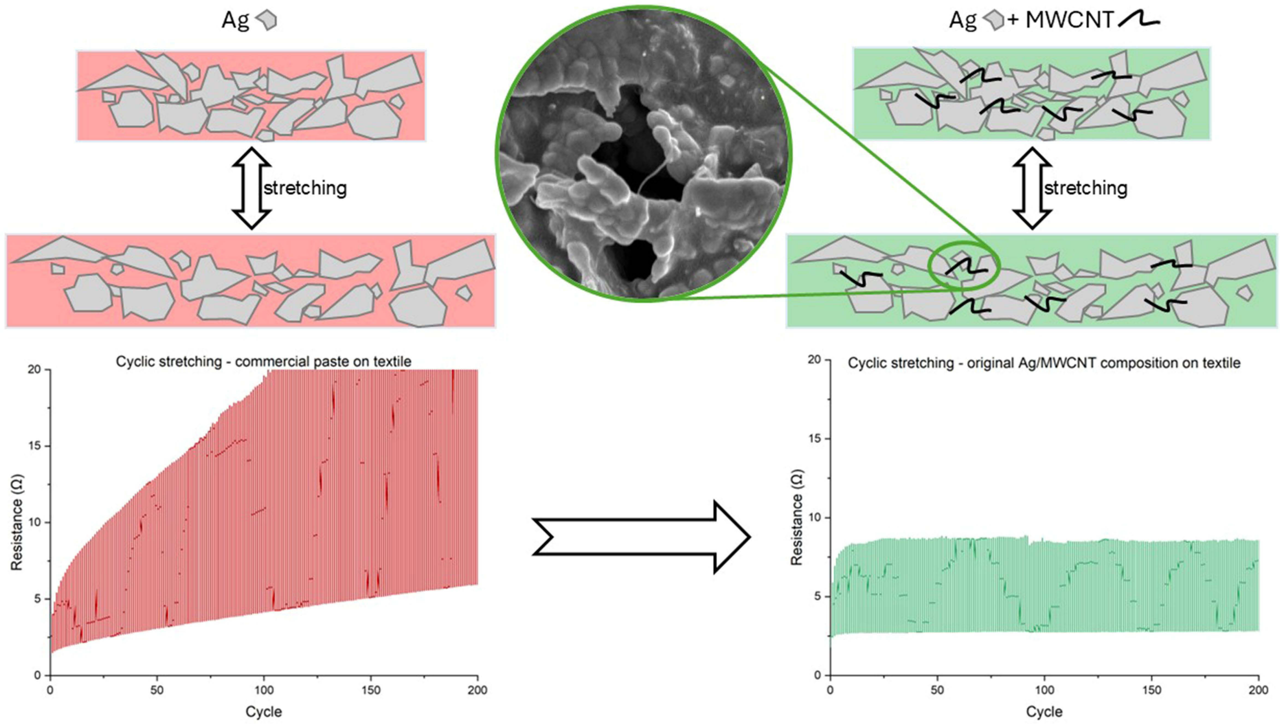
Graphical Abstract



undesirable given the increasing demand for mass reduction, cost efficiency, and component integration in electronic systems.

The second method focuses on applying, developing, and modifying material properties, primarily composite materials, to ensure appropriate electrical and mechanical properties in response to longitudinal deformation.[14–20] These methods can be combined to improve mechanical strength, electric properties, and longevity.

In recent years, carbon-based nanostructures, such as carbon nanotubes (CNTs), have gained significant attention as additives in conductive pastes. These materials are known for their exceptional electrical conductivity, mechanical strength, and high aspect ratios, making them ideal for enhancing the performance of composites under mechanical stress. By forming secondary conductive networks within composites, carbon nanotubes bridge gaps between conductive fillers such as silver flakes, improving both the conductivity and mechanical resilience of the material.[21,22] However, achieving uniform dispersion and functionalization of these nanomaterials remains a critical challenge. Inadequate dispersion can result in agglomeration, reducing the efficiency of the conductive network and compromising mechanical properties.

Creating electrically conductive pastes faces several challenges, including balancing conductivity with mechanical flexibility, ensuring stability under mechanical deformation, and minimizing resistance drift over time. Additionally, conductive pastes often require high curing temperatures, which limit their compatibility with heat-sensitive substrates like textiles. Variability in paste formulation and manufacturing processes can also result in inconsistent performance, further complicating large-scale adoption in wearable and flexible electronics.[22–24]

Considering the continuous evolution of the Internet of Things (IoT) and the Fourth Industrial Revolution (4IR), coupled with the emergence of textile and stretchable electronics,[25–28] there is a notable gap in the literature regarding manufacturing such electronics using intermediate printing with thermal transfer.[29–32] This method can offset the drawbacks of direct printing by increasing the reliability and ease of manufacturing. Therefore, this study aims to address this gap by developing novel composites for stretchable electronics on textiles and conducting research to analyze the influence of different compositions on electrical and mechanical parameters. It aims to devise methods to improve mechanical properties without compromising electrical conductivity.

Materials and Methods

Materials

This study examined six conductive printing pastes: five commercial pastes, NR_1-5, and a custom composition, NR_6. Table 1 summarizes the key characteristics of the composites, with the custom composition highlighted in bold. The developed printing composition was fabricated using commercial silver flakes AX 20LC with an average diameter of approximately 2 µm (Amepox Microelectronics, Poland) and thermoplastic polyurethane (TPU) Elastollan 1170A with a density of 1.18 g/cm^3 (BASF, Germany). TPU was dissolved in a 1:2 mixture of tetrahydrofuran (THF) and N, N-dimethylformamide (DMF) (Carl Roth GmbH + Co. KG, Germany).

Multi-walled carbon nanotubes (MWCNTs) were produced using the floating catalyst chemical vapor deposition (FC CVD) method using a reactor at the Center for Advanced Materials and Technologies (CEZAMAT, Warsaw University of Technology, Poland)), with Ferrocene serving as catalyst material. The MWCNTs had diameters ranging from 40 to 180 nm and a length of 160 µm. Carbon nanotubes were deagglomerated using a MALIALIM® SC-0505K surfactant (NOF EUROPE GmbH, Germany).

SPTN 150 Sicoplast Plastisol paint (SICO, Poland) was used as a transfer layer on a textile substrate during the heat-transfer process. Using direct screen printing, the samples were printed on stretchable TPU foil (Adhesive Films, Inc., USA). This substrate consisted of a laminated layered structure developed to produce stretchable medical sensory devices. In the lamination process, a high-quality TPU film with a constant thickness and smooth surface with low roughness was layered on a rigid PET foil, which allowed defect-free, repeatable patterns to be printed in a controlled manner. After curing the composite layers, low-temperature delamination of the substrate allowed for the formation of conductive layers on the highly elastic films. The method of indirect screen printing with a heat-transfer process uses two types of substrate: matte 2C-CP transfer film (Texo Trade Services, The Netherlands) and cotton textiles with 140 g/m^2 of grammage.

Methods

Fabrication of Custom Ag/TPU Composition

A custom Ag/TPU paste was prepared by combining silver flakes with TPU and dissolving it in a 1:2 ratio mixture of THF and DMF. The solution was homogenized using a speed mixer Kakuhunter SK-350TII (Shashin Kagaku Co., Ltd., Japan) and rolled in a three-roll mill (Exakt 80E, EXAKT Advanced Technologies, Germany) with silicon carbide (SiC) rolls with a gap of 5 µm between the rolls as displayed in diagram in Figure 1. The composition of the paste ensured that the rheological properties were appropriate for the selected printing technique, that is, screen printing.

Fabrication of Ag+CNT/TPU Compositions and Samples

Carbon nanotubes (CNTs) are nanomaterials with good electrical conductivity, excellent mechanical properties, and a high aspect ratio. Therefore, they are used in polymer composites that undergo significant mechanical deformations to

Table 1 A Summary of the Key Characteristics of Silver Conducting Pastes Applied Using Indirect Printing

Silver Conducting Paste	Viscosity [mPa s]	Functional Phase Content [%]	Sheet Resistance [Ω/sq.]	Density [kg/l]	Minimum Curing Temperature [°C]	Curing Time [min]
NR_1	14,500	69.0	<0.01	2.08	120	10
NR_2	12,000	74.6	<0.02	2.56	93	15
NR_3	12,500	60.0	≤0.015	2.14	120	15
NR_4	10,000–50,000	70–80	<0.03	1.5–2.5	100–120	15–30
NR_5	26,000–30,000	>82.0	0.025	ND	125	15–30
NR_6	**12,000–18,000**	**70.0**	**<0.03**	**2.1**	**120**	**15**

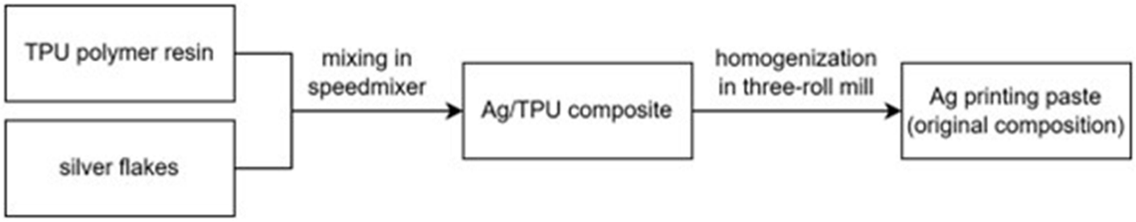


Figure 1 The diagram of the Ag/TPU composition manufacturing process.

act as additional conductive network elements. This increases the number of connections between silver flakes and accelerates the flow of electrons.[33–35]

The motif described in the literature of bridging silver flakes with carbon nanotubes has been employed to stabilize the electrical parameters (by eliminating unfavorable resistance drift) of conductive silver composites produced by indirect printing on textile substrates.[36]

A paste with a hybrid functional phase consisting of commercially available silver microflakes AX 20LC (Amepox Microelectronics, Poland) combined with carbon nanotubes (µAg + CNT) was developed. Carbon nanotubes have been functionalized by the addition of 5% by weight of MALIALIM® SC-0505K surface-active agents. In the conductive composition, which consisted of a TPU matrix with 70% by weight silver flakes, functionalized multi-walled carbon nanotubes were incorporated at concentrations of 0.05%, 0.1%, and 0.2% by weight of the entire composite mixture.The compositions were then homogenized using three roll mill as displayed on Figure 2. Afterwards, the composition was printed on cotton fabrics using an indirect printing method involving a heat-transfer process.

Application of Composite Layers

The composite layers were fabricated using a screen-printing technique with an Aurel C920 screen printer (Aurel Automation, Italy) on polyester screens with a purposed design with a density of 77T and using a squeegee with 75H hardness. First, the conducting layers were printed onto the transfer film and dried at 120 °C for 20 min in an SLW 115 STD dryer (POL-EKO Aparatura sp.k., Poland). The transferred plastisol layer was then printed and dried at 130 °C for 5 min. The heat-transfer process was conducted using a Secabo TC7 membrane heat press (Nepata Vertrieb GmbH, Germany) with medium pressure at 180 °C for 30s onto the textile substrate. Once the structure had cooled, the transfer film was removed, leaving the layer intact and well-combined with the textile substrate. The whole process was displayed in Figure 3.

Using polyester screens with a density of 70T and the same silver pastes, the samples were printed directly on to stretchable TPU foils and dried at 120 °C for 15 min as shown on Figure 4.

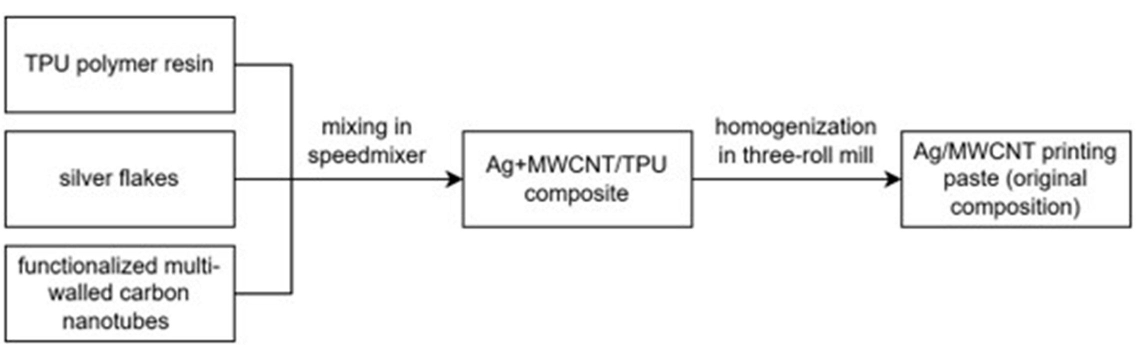


Figure 2 The diagram of the Ag/MWCNT composition manufacturing process.

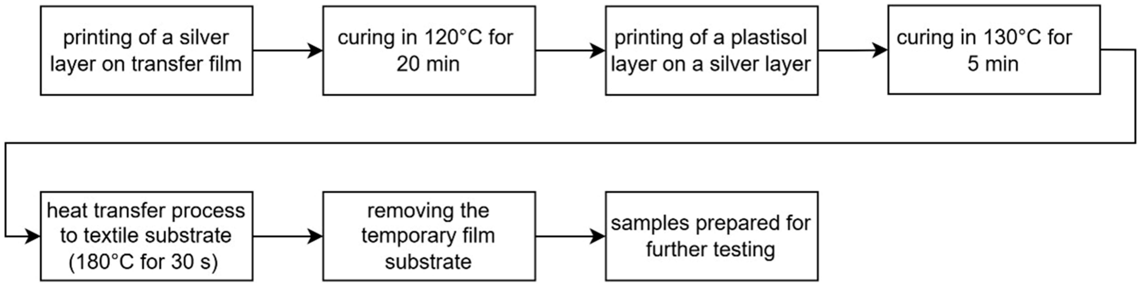


Figure 3 The diagram of the process of manufacturing samples on textile substrate.

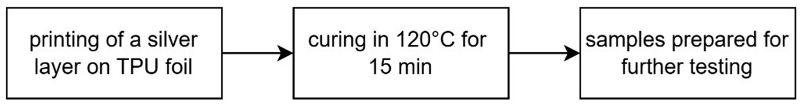


Figure 4 The diagram of the process of manufacturing samples on TPU substrate.

Characterization

Scanning electron microscopy (SEM) was conducted using a Hitachi SU8230 (Hitachi High-Tech Europe GmbH, Krefeld, Germany) instrument with an accelerating voltage of 7.0 kV and an upper secondary electron detector.

Transmission electron microscopy (TEM) was conducted using an LEO 912 Omega (LEO Elektronenmikroskopie GmbH, Oberkochen, Germany) instrument. Samples were prepared by diluting 0.1 g of carbon nanotubes functionalized with surface-active agents in 10 mL of acetone and shaking vigorously by hand until evenly distributed.

Electrical measurements were performed using a digital meter with a range of up to 40 MΩ. As an unambiguous measurement of electrical parameters, the sheet resistance expressed in ohms per square (Ω/□) was calculated by multiplying the measured resistance by the ratio of the width to length of the measured track.

Mechanical measurements are essential for the application of printed polymer composites as signal paths in personal electronics and wearable devices.

The mechanical properties were assessed by establishing the influence of tensile testing and cyclic stretching on the electrical parameters of the structure, and tests were conducted using a fatigue-testing machine. Tensile testing involved stretching the sample at a rate of 0.9 cm/min until rupture, with simultaneous measurement of the resistance of the sample. Cyclic stretching consisted of subjecting the sample to 200 cycles of 10% elongation at a stretching speed of 30 cm/min without stopping at the ends while concurrently measuring the resistance.

An accelerated aging process in a thermal shock chamber was induced to assess the stability of the obtained results over time. Conductive paths created using direct and indirect screen printing were subjected to 400 h of alternating cycles in chambers set at –40°C and +120 °C. Subsequently, the mechanical properties of the samples were re-examined.

Results and Discussion

SEM and TEM Imaging

The SEM images in Figure 5 depict the layers printed with composites NR_1–6. In all these composites, silver flakes were utilized as conductive particles. The functional phase consisted of silver flakes with sizes ranging from 0.5 to 10 µm. Large flakes, approximately 10 µm in size, dominate in all compositions, forming a dense and effective conductive network. Additionally, smaller flakes, with an average diameter of 2–5 µm, are present in significant quantities. These smaller flakes play a crucial role in enhancing the layer's conductivity.

In the image of composition NR_2, a fine fraction of particles smaller than 1 µm with irregular shapes can also be observed. Differences in the shape and size of the functional materials used, likely resulting from variations in the manufacturing processes of the silver fillers, may contribute to differences in the conductivity of the composite layer and

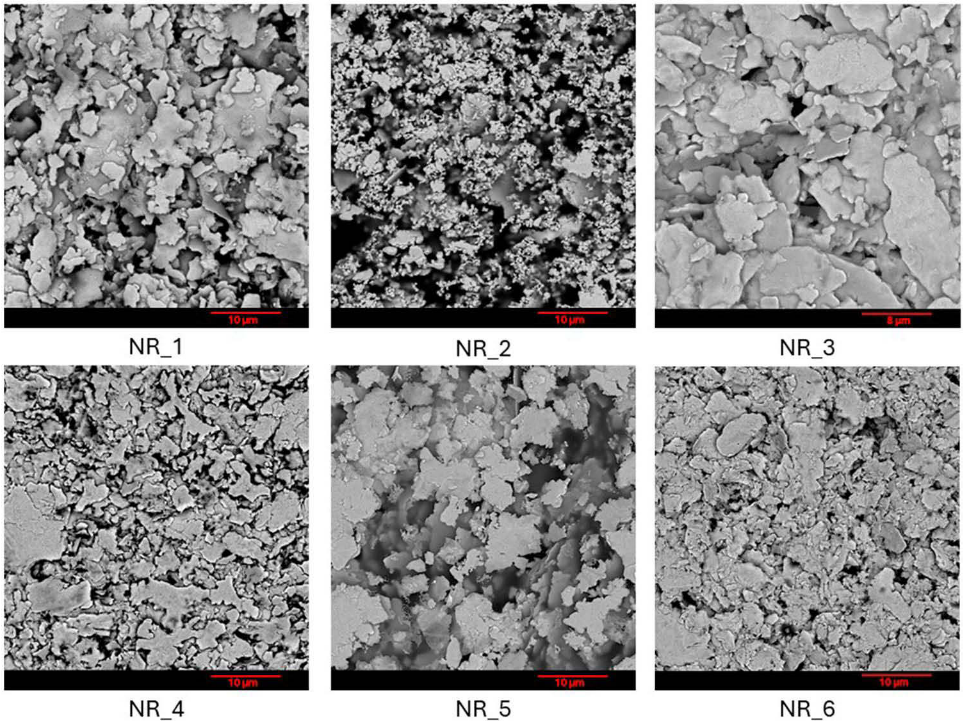


Figure 5 The SEM images of layers printed with NR_1–6 pastes.

the amplitude of changes in its conductivity during stretching. The images also confirm that the silver flakes are homogeneously distributed throughout the composites.

Samples printed with a composite consisting of 70% by weight of silver flakes and 0.2% by weight of multi-walled carbon nanotubes were subjected to cyclic stretching. The structure of the layer after these tests is shown in the SEM images in Figure 6. In the 10 µm scale SEM image in Figure 6(A), there are some visible cracks, which are the result of cyclic mechanical loads of low intensity. However, the fractures and gaps do not result in a loss of conductivity due to bridge formation between silver flakes by carbon nanotubes, as depicted in the 1 µm scale SEM image shown in Figure 6(B).

Small flakes present in used silver microflakes improve the electrical conductivity of the composite but do not necessarily enhance its stretchability, as larger flakes play a crucial role in maintaining the electrical network during deformation. Therefore, a multimodal distribution of flakes within the composite increases the number of electric

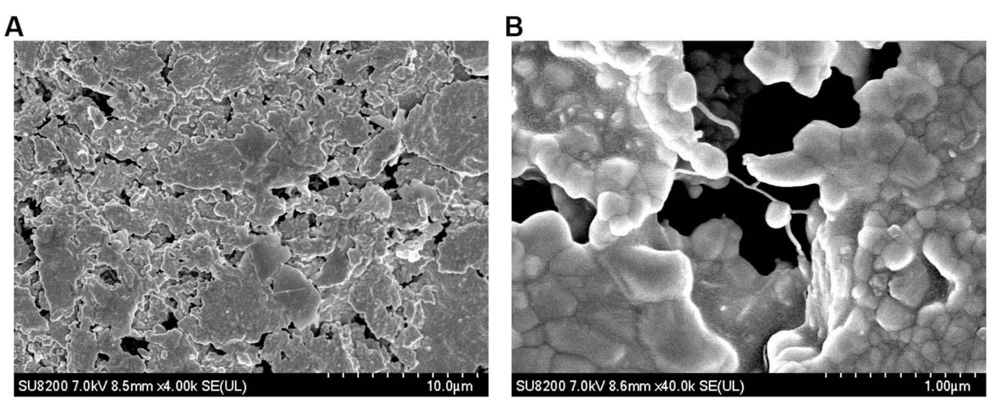


Figure 6 The SEM images of layers printed with Ag/CNT paste; (**A**) structure of the layer printed with Ag/CNT paste in 10 µm scale; (**B**) SEM image showing CNT bridge formation between silver flakes.

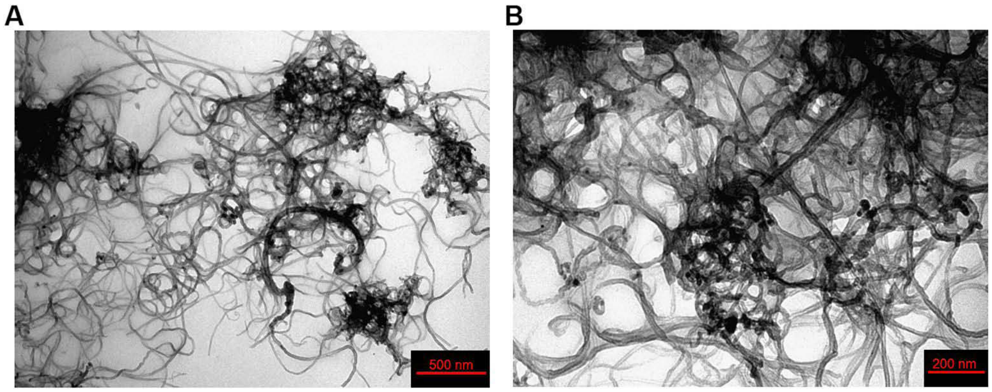


Figure 7 The TEM images of CNT samples in (**A**) 500 nm and (**B**) 200 nm scale.

connections while also enhancing packing density. This effect is further strengthened by the inclusion of CNTs, which act as bridging elements between conductive particles.

The TEM images in Figure 7 depict the carbon nanotubes used in preparing the Ag-MWCNT composites. Despite functionalization with a surfactant agent, the nanotubes still form clumps of agglomerates, which can hinder their even dispersion within the Ag/TPU composite. However, a sufficient number of untangled CNTs are present to function effectively within the prepared composite. Employing a more effective deagglomeration method could further improve the formation of connections between the silver flakes, enhancing the composite's overall performance.

Sheet Resistance Results

Surface resistance measurements of layers made on a transfer substrate and, after the heat-transfer process, onto a textile substrate revealed that this process is not noninvasive for all investigated compositions. As Table 2 reveals, pastes numbered 1, 2, 4, and 5 exhibited an increase in measured resistance ranging from 29–310% after the heat-transfer process. Composition NR_3 proved to be insensitive to the high temperature and pressure involved in transfer to the textile substrate. In the case of custom composition based on thermoplastic PU (NR_6 – highlighted in bold in Table 2), a decrease in resistance of over 60% was observed after the heat-transfer process. The measurement results indicate that, by using a plastisol transferring layer and heat-transfer process, it is possible to consistently create prints on textile substrates that are characterized by good flexibility, and electrical properties.

Tensile Testing

The effect of sample elongation on the resistance of the layer was examined using tensile testing. The research revealed that, for each of the investigated compositions, the resistance exponentially increased with an increase in elongation, as shown in Figure 8.

Table 2 The Impact of the Heat Transfer Process on the Resistance of Conductive Paths Applied on Textile Substrate

Silver Conducting Paste	Sheet Resistance on Transfer Film [Ω/sq.]	Sheet Resistance on Textile [Ω/sq.]	Change in Resistance [%]
NR_1	0.042±0.003	0.054±0.004	+29
NR_2	0.058±0.002	0.098±0.005	+69
NR_3	0.044±0.002	0.044±0.002	0
NR_4	0.043±0.002	0.069±0.004	+60
NR_5	0.056±0.002	0.23±0.02	+310
NR_6	**0.27±0.03**	**0.10±0.01**	**–63**

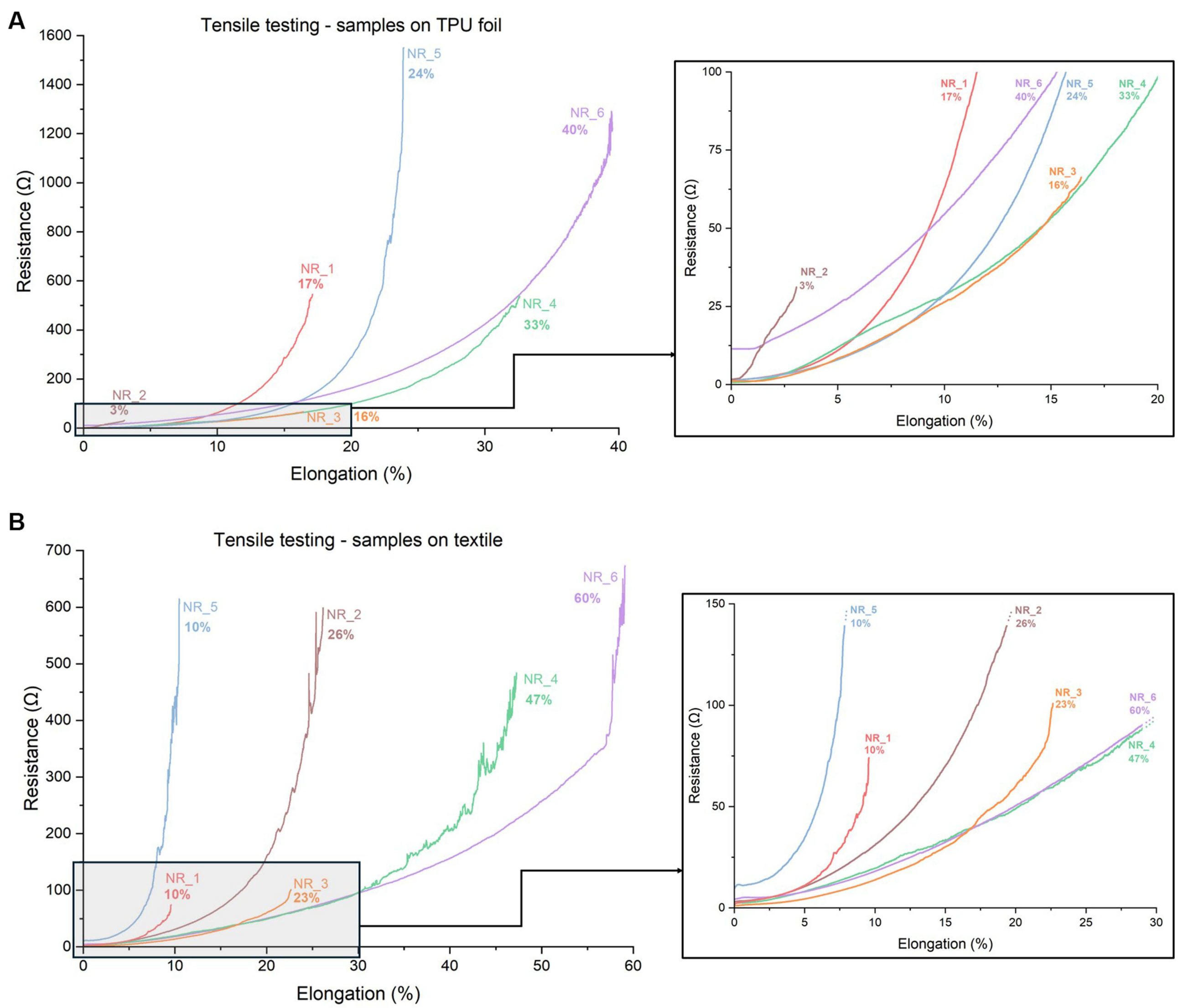


Figure 8 Graphs showing the result of tensile testing – the correlation between the elongation and the resistance of conductive paths printed on (**A**) TPU foil and (**B**) textile substrate.

During stretching, both the number of contacts between conductive particles and the cross-section and length of the conductive pathway undergo significant changes. These changes collectively influence the shape and behaviour of the resistance curve as a function of elongation. Typically, the resistance curve exhibits an exponential trend, driven by the increasing distance between particles in the functional phase as elongation progresses. The objective, however, is to achieve a resistance change that remains linear over selected ranges of elongation, ensuring predictable and stable electrical performance under mechanical stress in such area.

The maximum elongation values and dynamics of the resistance changes depend on the composition type and layer printing method. The maximum elongation values were determined as the elongations above which a rapid increase in path resistance occurred, and these values for each composition are presented in Table 3.

An analysis of the obtained results shows that, for the four investigated pastes, including the custom composition, the mechanical resistance of the layer increases owing to the application of thermocompression. The most significant difference in maximum elongation, from 3% to 26%, was observed for paste NR_2. The highest value of maximum elongation on both substrates (40% on TPU film and 60% on cotton substrate) was exhibited by the custom composition NR_6 (highlighted in bold in Table 3).

Table 3 Comparison of Maximum Elongation Values for Composite Layers Applied with Indirect and Direct Screen-Printing Methods

Silver Conducting Paste	Maximum Elongation Value [%]	
	Direct Screen Printing on TPU Foil	Indirect Screen Printing on Cotton Textile
NR_1	17	10
NR_2	3	26
NR_3	16	23
NR_4	33	47
NR_5	24	10
NR_6	**40**	**60**

Cyclic Stretching

The results of fatigue testing demonstrated that the types of composition and printing method significantly influenced the electrical parameters of the layers subjected to cyclic stretching. The dependencies obtained for the TPU films are shown in Figure 9. For clarity, pastes with maximum elongation during tensile testing of less than 20% were not included in the graph. Layers printed with paste NR_2 (maximum elongation, 5%) were damaged in the initial cycles, whereas layers from paste NR_3 (maximum elongation, 17%) experienced damage after approximately 10–15 fatigue test cycles. For the remaining samples, an increase in resistance amplitude was observed in successive cycles. The most stable results were achieved for NR_1, and the least stable for the custom composition NR_6. Thus, it was demonstrated that, in the case of compositions fabricated by the direct printing method on a stretchable TPU film, a high value of maximum elongation does not ensure stable electrical parameters under low-intensity cyclic loads.

Resistance graphs during cyclic stretching of the samples heat transferred to the cotton substrate are shown in Figure 10. Based on these results, it can be concluded that, for pastes NR_1 and NR_4, the thermal compression process had a minimal impact on the resistance change of the composite layers compared with the samples on the TPU foil. However, for paste NR_5, a significant acceleration of the layer degradation process was observed. In the case of other

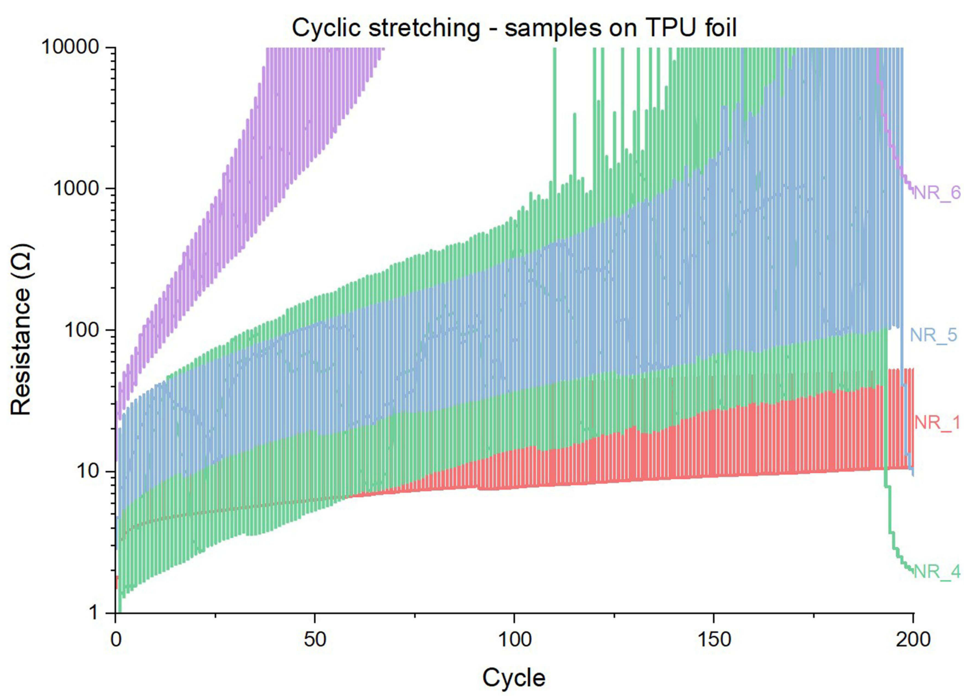


Figure 9 Graph showing the resistance of conductive paths printed on the TPU foil during cyclic stretching.

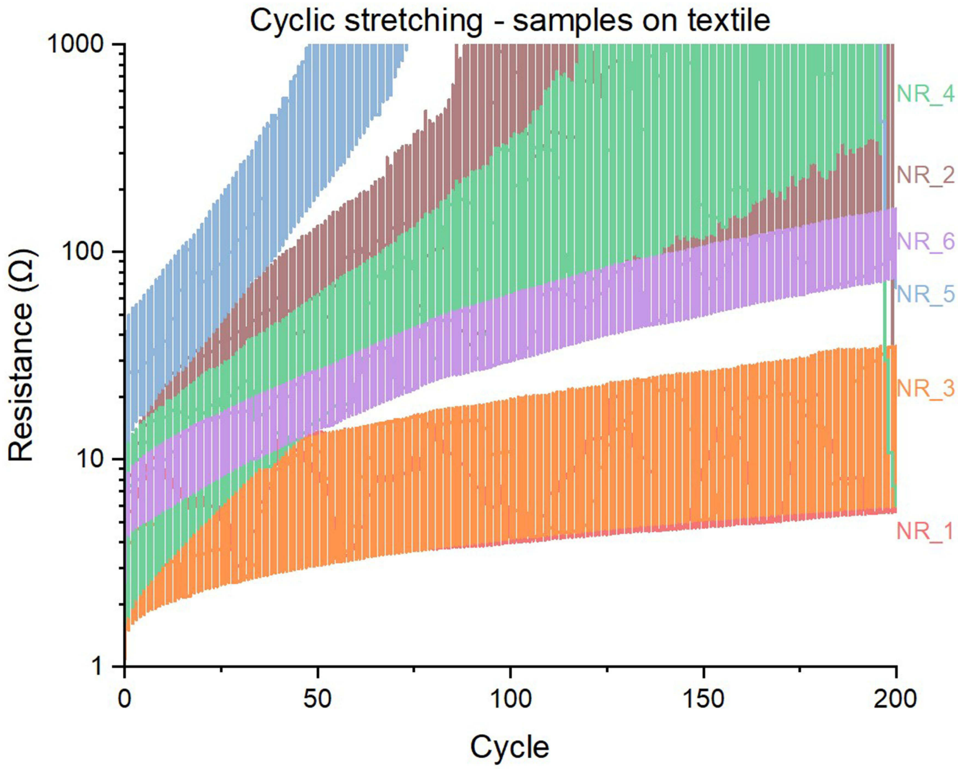


Figure 10 Graph showing the resistance of conductive paths printed on the textile substrate during cyclic stretching.

compositions, a positive effect of changing the printing method on fatigue durability was observed. Composition NR_2, with a very low resistance to cyclic stretching on the TPU foil, exhibited a significant improvement on the textile substrate, undergoing damage after approximately 80–90 cycles, but was still characterized by high and increasing amplitude of resistance changes over time. The best results and significant improvement compared to the layers on TPU foil were observed for the commercial compositions NR_3 and NR_1, as well as for the custom composition NR_6. For all tested pastes, after completing fatigue testing, a stabilization of resistance over time was observed at a level much lower than the readings in the last cycle but significantly higher than the initial values. The custom composition NR_6 based on silver flakes in a TPU matrix showed a higher resistance drift over time; however, the upward trend stabilized, and the layer exhibited a visibly smaller amplitude of resistance change compared with commercial compositions, making it a promising material for further research.

Mechanical Measurements After Aging in a Thermal Shock Chamber

Tensile testing was repeated after accelerated aging in the thermal shock chamber. The obtained results, along with a comparison with the initial values of maximum elongation, are presented in Table 4. Based on these results, it can be

Table 4 Comparison of Maximum Elongation Values for Composite Layers Applied with Indirect and Direct Screen-Printing Methods After Aging in a Thermal Shock Chamber

Silver Conducting Paste	Maximum Elongation Value [%] (Change [%])	
	Direct Screen Printing on TPU Foil	Indirect Screen Printing on Cotton Textile
NR_1	22 (+30)	12 (+20)
NR_2	3 (0)	17 (–34)
NR_3	<5 (–70)	29 (+25)
NR_4	40 (+20)	3 (–90)
NR_5	28 (+16)	5 (–50)
NR_6	75 (+87)	70 (+16)

concluded that, in most cases, commercial pastes are susceptible to changes resulting from cyclic thermal shocks. It was also demonstrated that, depending on the applied composition, the chosen printing method significantly influenced the observed changes in the maximum elongation values due to material aging. At the same time, it was noted that there is no regularity in the observed changes in maximum elongation values.

Composites NR_2, NR_4, and NR_5 exhibited a slight influence of the aging process on the change in the maximum elongation values of the samples made on the TPU film. However, in the case of samples prepared using the indirect method, significant deterioration of this parameter was observed. For composition NR_3, we observed the opposite situation—samples made on the textile substrate remained insensitive to tests in the thermal shock chamber, while samples made by the direct printing method showed a decrease in maximum elongation value by 70%. The custom-composition NR_6 exhibited the highest elongation values before the loss of conductivity. The observed improvement in the parameters for paste NR_6 may have resulted from the heating of the composite layers, causing the moisture absorbed from the surroundings by the TPU matrix to evaporate. The custom composition based on silver flakes and TPU matrix exhibited a maximum elongation more than 240% greater than the best among investigated commercial pastes, confirming the potential for further research.

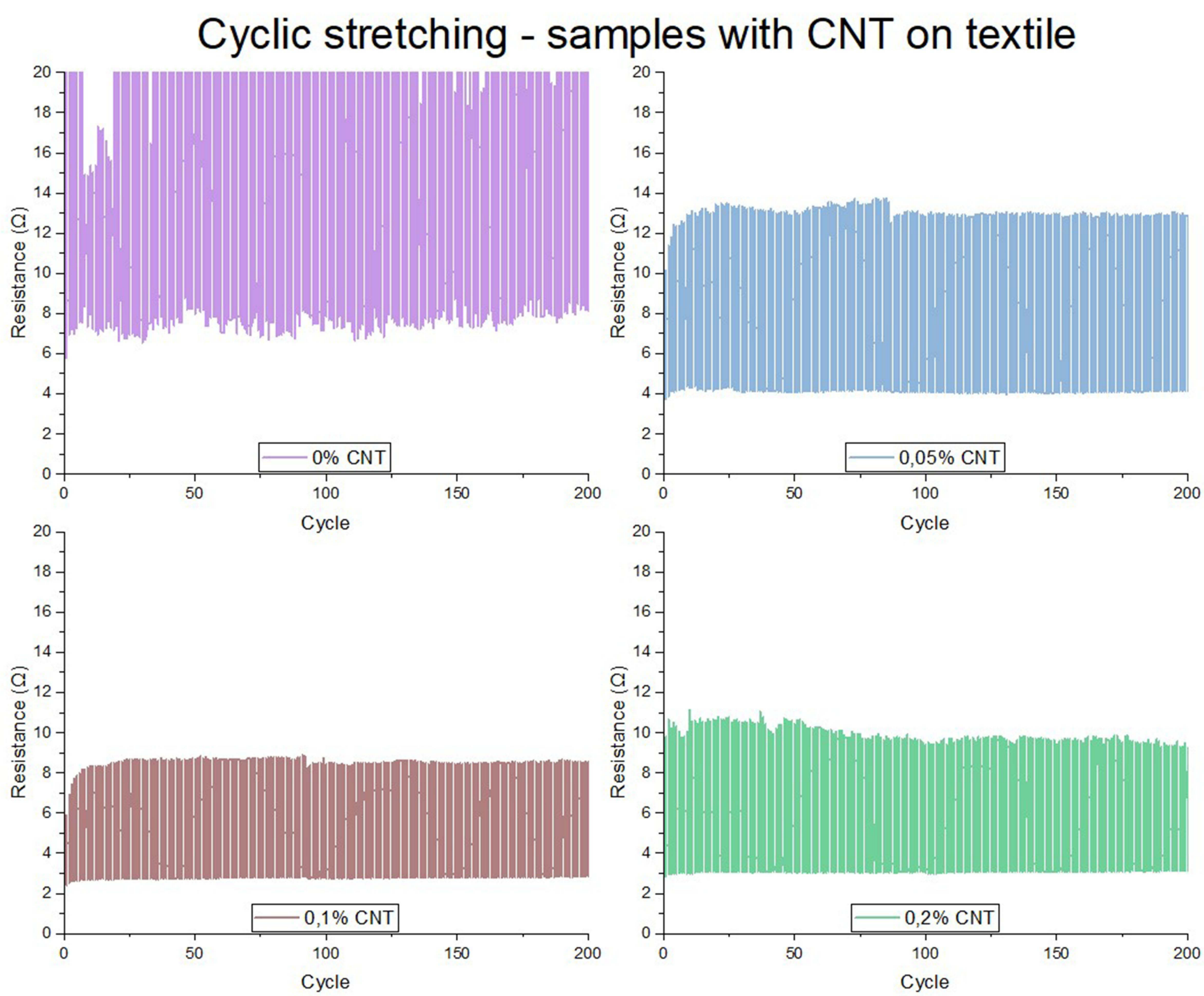


Figure 11 Graphs showing the resistance during cyclic stretching of conductive paths printed with Ag+CNT composites on the textile substrate.

Cyclic Stretching for Ag+CNT Samples

Samples indirectly screen-printed with a composite based on silver flakes with the addition of multi-walled carbon nanotubes (MWCNTs) underwent cyclic mechanical exposure, and the results are shown in Figure 11. The analysis of the results indicates that even a small addition of functionalized MWCNTs in the amount of 0.05% by weight allows for the stabilization of the electrical parameters of the composite over time. It was also demonstrated that the content of MWCNTs at the level of 0.2% by weight allowed for the complete elimination of resistance drift and reduced the amplitude of resistance changes by up to 40%. A literature review revealed a lack of reports on composites designed for printing conductive paths on textile substrates with similar electrical parameter stability, fully compatible with the indirect printing technique and heat-transfer process.

Conclusions

Based on initial testing, a set of Ag/TPU composites with different amounts of Ag microflakes was prepared. Each composite was characterized in terms of suitability for screen printing and homogeneity. The composites were then printed on textiles using two different methods: direct printing and heat transfer printing. In both methods, the electrical and mechanical properties were tested during rest, single stretching, and cyclic stretching.

From all tested samples, the best results were achieved for composite NR_6, which contained 70% wt. of Ag. It achieved maximum elongation of 60%, while maintaining sheet resistance of 0.100 Ω/sq. However, although the developed composite was applicable to stretchable electronics, it exhibited a noticeable drift during cyclic stretching.

A new composite was proposed and prepared by adding MWCNTs to improve the stability and reliability of MWCNTs. This modification eliminated the drift of resistance values during cyclic stretching, while also lowering the amplitude of resistance changes by 40%, to 2–8 Ohm. The study demonstrated the feasibility of creating electrically stable conductive paths on textile substrates. The use of screen printing combined with the heat-transfer method allowed the process to be automated and significantly reduced the number of defects and waste. The use of small amounts of MWCNT as reinforcing additives stabilized the properties of the layer and extended its lifespan.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used ChatGPT to improve the readability and clarity of the article. After using this tool, the authors reviewed and edited the content as required, and took full responsibility for the content of the published article.

Data Sharing Statement

Data available upon request.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors declare no conflicts of interest. The funders had no role in the study design, collection, analyses, interpretation of data, writing of the manuscript, or decision to publish the results.

References

1. Wang B, Facchetti A. Mechanically flexible conductors for stretchable and wearable E-skin and E-textile devices. *Adv Mater*. 2019;31 (28):1901408. doi:10.1002/adma.201901408
2. Nguyen T, Khine M. Advances in materials for soft stretchable conductors and their behavior under mechanical deformation. *Polymers*. 2020;12 (7):1454. doi:10.3390/polym12071454
3. Qiu S, La TG, Zheng L, et al. Mechanically and electrically robust stretchable e-textiles by controlling the permeation depth of silver-based conductive Inks. *Flex Print Electron*. 2019;4(2):025006. doi:10.1088/2058-8585/ab2797
4. Khan Y, Thielens A, Muin S, Ting J, Baumbauer C, Arias AC. A new frontier of printed electronics: flexible hybrid electronics. *Adv Mater*. 2020;32 (15):1905279. doi:10.1002/adma.201905279
5. Marasco I, Niro G, Lamanna L, et al. Compact and flexible meander antenna for surface acoustic wave sensors. *Microelectron Eng*. 2020;227:111322. doi:10.1016/j.mee.2020.111322
6. Salo T, Halme A, Lahtinen J, Vanhala J. Enhanced stretchable electronics made by fused-filament fabrication. *Flex Print Electron*. 2020;5 (4):045001. doi:10.1088/2058-8585/abb931
7. Maddipatla D, Narakathu BB, Atashbar M. Recent progress in manufacturing techniques of printed and flexible sensors: a review. *Biosensors*. 2020;10(12):199. doi:10.3390/bios10120199
8. Fan JA, Yeo W-H, Su Y, et al. Fractal design concepts for stretchable electronics. *Nat Commun*. 2014;5(1):3266. doi:10.1038/ncomms4266
9. Yun G, Tang SY, Lu H, Zhang S, Dickey MD, Li W. Hybrid-filler stretchable conductive composites: from fabrication to application. *Small Sci*. 2021;1(6):2000080. doi:10.1002/smsc.202000080
10. Lim T, Kim HJ, Zhang H, Lee S. Screen-printed conductive pattern on spandex for stretchable electronic textiles. *Smart Mater Struct*. 2021;30 (7):075006. doi:10.1088/1361-665X/abfb7f
11. Gillan L, Hiltunen J, Behfar MH, Rönkä K. Advances in design and manufacture of stretchable electronics. *Jpn J Appl Phys*. 2022;61:SE0804. doi:10.35848/1347-4065/ac586f
12. Kim DW, Kong M, Jeong U. Interface design for stretchable electronic devices. *Adv Sci*. 2021;8(8):2004170. doi:10.1002/advs.202004170
13. Lee J, Llerena Zambrano B, Woo J, Yoon K, Lee T. Recent advances in 1D stretchable electrodes and devices for textile and wearable electronics: materials, fabrications, and applications. *Adv Mater*. 2020;32(5):1902532. doi:10.1002/adma.201902532
14. Boda U, Strandberg J, Eriksson J, Liu X, Beni V, Tybrandt K. Screen-printed corrosion-resistant and long-term stable stretchable electronics based on agau microflake conductors. *ACS Appl Mater Interfaces*. 2023;15(9):12372–12382. doi:10.1021/acsami.2c22199
15. Zavanelli N, Yeo WH. Advances in screen printing of conductive nanomaterials for stretchable electronics. *ACS Omega*. 2021;6(14):9344–9351. doi:10.1021/acsomega.1c00638
16. Yoon S, Kim HK. Cost-effective stretchable Ag nanoparticles electrodes fabrication by screen printing for wearable strain sensors. *Surf Coat Technol*. 2020;384:125308. doi:10.1016/j.surfcoat.2019.125308
17. Shang Y, He X, Li Y, et al. Super-stretchable spring-like carbon nanotube ropes. *Adv Mater*. 2012;24(21):2896–2900. doi:10.1002/adma.201200576
18. Zhao X, Chen F, Li Y, Lu H, Zhang N, Ma M. Bioinspired ultra-stretchable and anti-freezing conductive hydrogel fibers with ordered and reversible polymer chain alignment. *Nat Commun*. 2018;9(1):3579. doi:10.1038/s41467-018-05904-z
19. Eom J, Lee YR, Lee JH, et al. Highly conductive and stretchable fiber interconnections using dry-spun carbon nanotube fibers modified with ionic liquid/poly(vinylidene fluoride) copolymer composite. *Compos Sci Technol*. 2019;169:1–6. doi:10.1016/j.compscitech.2018.10.035
20. Yang Y, Duan S, Zhao H. Advances in constructing silver nanowire-based conductive pathways for flexible and stretchable electronics. *Nanoscale*. 2022;14(32):11484–11511. doi:10.1039/D2NR02475F
21. Lim KM, Lee JH. Electrical conductivity and compressive strength of cement paste with multiwalled carbon nanotubes and graphene nanoplatelets. *Appl Sci*. 2022;12(3):1160. doi:10.3390/app12031160
22. Wang Y, Jing D, Xiong Z, et al. Ag-MWCNT composites for improving the electrical and thermal properties of electronic paste. *Polymers*. 2024;16 (8):1173. doi:10.3390/polym16081173
23. Lim HS, Kim SN, Lim JA, Park SD. Low temperature-cured electrically conductive pastes for interconnection on electronic devices. *J Mater Chem*. 2012;22(38):20529–20534. doi:10.1039/C2JM33168C
24. Li Y, Gan G, Huang Y, Yu X, Cheng J, Liu C. Ag-NPs/MWCNT composite-modified silver-epoxy paste with improved thermal conductivity. *RSC Adv*. 2019;9(36):20663–20669. doi:10.1039/C9RA03090E
25. Chen G, Xiao X, Zhao X, Tat T, Bick M, Chen J. Electronic textiles for wearable point-of-care systems. *Chem Rev*. 2022;122(3):3259–3291. doi:10.1021/acs.chemrev.1c00502
26. Ismar E, Kurşun Bahadir S, Kalaoglu F, Koncar V. Futuristic clothes: electronic textiles and wearable technologies. *Global Challenges*. 2020;4 (7):1900092. doi:10.1002/gch2.201900092
27. Yin L, Lv J, Wang J. Structural innovations in printed, flexible, and stretchable electronics. *Adv Mater Technol*. 2020;5(11):2000694. doi:10.1002/admt.202000694
28. Choudhry NA, Arnold L, Rasheed A, Khan IA, Wang L. Textronics—a review of textile-based wearable electronics. *Adv Eng Mater*. 2021;23 (12):2100469. doi:10.1002/adem.202100469
29. Pulanthran K, Jizat NM, Islam Md S. A low-cost textile antenna using thermal-transfer printing.2020 16th IEEE International Colloquium on Signal Processing & Its Applications(CSPA); 2020:162–165 doi:10.1109/CSPA48992.2020.9068726.
30. Maheshwari N, Abd-Ellah M, Goldthorpe IA. Transfer printing of silver nanowire conductive ink for e-textile applications. *Flex Print Electron*. 2019;4(2):025005. doi:10.1088/2058-8585/ab2543
31. Kim Y, Park JB, Kwon YJ, Hong JY, Jeon YP, Lee JU. Fabrication of highly conductive graphene/textile hybrid electrodes via hot pressing and their application as piezoresistive pressure sensors. *J Mater Chem C*. 2022;10(24):9364–9376. doi:10.1039/D2TC00165A
32. Raczyński T, Janczak D, Szałapak J, et al. Influence of the heat transfer process on the electrical and mechanical properties of flexible silver conductors on textiles. *Polymers*. 2023;15(13):2892. doi:10.3390/polym15132892
33. Luo J, Cheng Z, Li C, et al. Electrically conductive adhesives based on thermoplastic polyurethane filled with silver flakes and carbon nanotubes. *Compos Sci Technol*. 2016;129:191—197. doi:10.1016/j.compscitech.2016.04.026

34. Chun KY, Oh Y, Rho J, et al. Highly conductive, printable and stretchable composite films of carbon nanotubes and silver. *Nat Nanotechnol*. 2010;5(12):853–857. doi:10.1038/nnano.2010.232
35. Ma R, Kwon S, Zheng Q, et al. Carbon-nanotube/silver networks in nitrile butadiene rubber for highly conductive flexible adhesives. *Adv Mater*. 2012;24(25):3344–3349. doi:10.1002/adma.201201273
36. Luo X, Yang G, Schubert DW. Electrically conductive polymer composite containing hybrid graphene nanoplatelets and carbon nanotubes: synergistic effect and tunable conductivity anisotropy. *Adv Compos Hybrid Mater*. 2022;5(1):250–262. doi:10.1007/s42114-021-00332-y