

Constructing Electrospun 3D Liquid Metal Adhesion Channel on Stretchable Yarns for Broad-Range Strain-Insensitivity Smart Textiles

Corresponding Author: Professor Dongxiao Ji

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This manuscript presents an adhesion channeling strategy to facilitate the liquid metal (LM) flow along the yarn surface, enabling the simultaneous deformation of both the LM and the yarn. The resulting yarn exhibits outstanding electrical conductivity, moderate stretchability, and notably, stable electrical performance that is insensitive to strain. These characteristics hold significant promise for applications in stretchable electronics. Nevertheless, the reviewer has expressed reservations regarding the novelty of the study concerning the formation mechanism and potential applications. The manuscript currently may not meet the standards for publication in Nature Communications. Below are specific concerns regarding the content:

1. The structural design rationale needs to be further elaborated. Why TPU must be used as the core for stretchable yarn? In principle, SBS can also be directed spun into a yarn. Is the stretchability limited by the PU core fiber or SBS microfiber shell? What is the importance of the SBS microfiber? How does SBS microfiber overperform compared to SBS coating?
2. The adhesion of LM to yarns lacks sufficient experimental evidence. Although the X-ray diffraction (XRD) spectra suggest that LM reacts with Ag on the yarn, reaction does not necessarily equate to adhesion. Furthermore, the cross-sectional energy-dispersive X-ray spectroscopy (EDS) mapping of SLMAS yarns in Figure 1h shows almost no overlap with the carbon elements. The adhesion force of the resultant AgIn₂ still needs to be tested and supported with additional data.
3. There are no scale bars for Figures 1j and 1k.
4. How is the LM loading content controlled? What is the quantitative relationship between the silver precursor solution and the LM loading content? Does the immersion time affect the LM loading content?
5. Recommend conducting cycling stability tests with a significantly higher number of cycles (for example: >10,000 cycles). Testing up to 1100 cycles does not provide sufficient evidence to claim long-term electrical stability, which is crucial for practical applications.
6. The authors state that the SBS microfiber encapsulation layer forces LM into the pores of the adherent microchannel layer during stretching. However, Figures 2d and 2e show no encapsulation layer. It appears that LM flows directly into the pores of the PU-SBS yarn without an encapsulation layer.
7. Why does a negative resistance change occur during the stretching process of the SLMAS yarn (Supplementary Figure 9)?
8. The Hue value decreases after just 10 cycles of switching the voltage on and off (Figure 5c). Additional cycling tests are required to confirm stability.
9. How about the integration ability of these yarns into fabrics?

Reviewer #2

(Remarks to the Author)

In this manuscript, the authors report the development of an elastic conductive yarn through a layer-by-layer assembly of SBS microfibers, Ag nanoparticles and liquid metal on commercial spandex yarn by an adhesion channeling strategy that enables three-dimensional control of liquid metal flow on the yarn surface. This research offers a new strategy to achieve conductive yarn with ultra-low resistance and extraordinary conductivity stability over a large strain range. I believe the manuscript is possible to be accepted for publishing after carefully addressing the following issues:

1. The authors only provided stress-strain curves for SLMAS yarns and whether the absorption of LM has an effect on the mechanical properties of the yarns, so stress-strain curves for SBS-PU yarns should also be provided and discussed.
2. I noticed that the encapsulating SBS layer seems to play a very important role, how does the SBS fiber encapsulation layer on the yarn surface affect the electromechanical behavior of the yarn?
3. I suggest to include a video to further improve the clarity and understanding of the research methodology. The video could show the production of SBS-PU yarn using conjugated electrostatic spinning to visualize the electrospinning process. This video will provide the reader with valuable additional material to visualize the experimental process and better understand the research.
4. The loading of liquid metal significantly influences the electrical conductivity and electromechanical properties of SLMAS yarns. What is the liquid metal loading in the SLMAS yarn used to measure the electromechanical properties in Figure 3?
5. The direct use of "SBS-PU yarn" and "Ag-SBS yarns" in the manuscript without a clear definition by the author may cause confusion to the reader.
6. There is confusion in the author's description of the yarn in Figure 1b in terms of "SBS/PU yarn" as well as "SBS-PU yarn". Please clarify the terminology and ensure consistency.
7. There are some details that have not been noticed, such as the location of the scale bar "10 μ m" in Figure 1g should be adjusted.
8. There are still some grammatical errors and typos in the manuscript; please check carefully. For example, in the caption of Figure 2f, "Metal" should be in lowercase.
9. The long-range electro-thermochromic property of the yarn is critical. Therefore, please specify the value of the scale bar in Figure 5b that represents the length of the electro-thermochromic yarn.

Reviewer #3

(Remarks to the Author)

The paper "Constructing Electrospun 3D Liquid Metal Adhesion Channel on Stretchable Yarns for Broad-Range Strain-Insensitivity Smart Textiles" discusses the development of stretchable conductive yarn through the electrospinning of elastomer (SBS) microfibers onto a stretchable substrate of TPU microfibers. Additionally, the yarn is treated with silver nanoparticles (Ag NPs) and liquid metal (LM) to create a stretchable conductor. There have been several papers that report coating stretchable fibers with liquid metal, but this one achieves it by using Ag NPs. I provide here two examples - in the former, the metal is coated just by spreading it across the fabric, and in the latter, the metal is coated by dip coating into a solution of LM particles (neither of which requires Ag):

<https://www.nature.com/articles/s41563-020-00902-3>

<https://onlinelibrary.wiley.com/doi/10.1002/admt.202202183>

I have several questions about the work:

What is the size distribution of silver nanoparticles (Ag NPs), and how are they attached to the styrene-butadiene-styrene (SBS) polymer chains? If the Ag NPs are within the polymer structure, how might this confinement affect their function?

Although both thermoplastic polyurethane (TPU) and SBS polymers are stretchable, their recoverability during stress-strain cyclic tests appears to be quite different, which could lead to deformation in the entire yarn after testing. I suggest conducting more experiments using neat TPU fibers and neat electrospun SBS fibers, and comparing their mechanical properties.

Additionally, please examine how the incorporation of Ag NPs affects the mechanical properties of neat SBS fibers in the absence of TPU fibers. What would happen to the mechanical properties of the SBS/Ag NP composite after treatment with liquid metal (LM), again without TPU fibers?

Have the authors considered the effect of oxidation on the conductivity of the resulting yarn during cyclic testing? If LM can freely flow inside the three-dimensional channel being discussed, why does it not leak out during the stretching process? Or does the LM solidify due to alloy formation with Ag NPs (in which case, perhaps it comes off the fabric)?

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have addressed the review's concerns in this revised version of the manuscript well.

Reviewer #2

(Remarks to the Author)

I believe the authors have cleared all my concerns and the revised manuscript can be accepted for publication now.

Reviewer #3

(Remarks to the Author)

Thank you for addressing the prior concerns.

In regard to the response to question 4, it seems that running multiple cyclic tests should lead to the accumulation of oxide during cycling, which may affect both mechanical and electrical properties in the long term. Is that possible?

Version 2:

Reviewer comments:

Reviewer #3

(Remarks to the Author)

Thank you for addressing the prior concerns. I look forward to seeing this published.

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In cases where reviewers are anonymous, credit should be given to 'Anonymous Referee' and the source.

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We sincerely appreciate the pertinent suggestions of editors and reviewers. The quality of the manuscript has been significantly improved following reviewers' comments. All modifications have been highlighted with yellow shading in the revised manuscript.

REVIEWER COMMENTS

To Reviewer 1:

This manuscript presents an adhesion channeling strategy to facilitate the liquid metal (LM) flow along the yarn surface, enabling the simultaneous deformation of both the LM and the yarn. The resulting yarn exhibits outstanding electrical conductivity, moderate stretchability, and notably, stable electrical performance that is insensitive to strain. These characteristics hold significant promise for applications in stretchable electronics. Nevertheless, the reviewer has expressed reservations regarding the novelty of the study concerning the formation mechanism and potential applications. The manuscript currently may not meet the standards for publication in Nature Communications. Below are specific concerns regarding the content:

Replay: Thank you very much for a careful evaluation of our manuscript. We really appreciate your comments and constructive suggestions, which are very helpful for us to improve the quality of this manuscript.

In this study, we present an adhesion-channel strategy that synergistically integrates silver nanoparticles (Ag NPs) grown on a yarn substrate with the capillary wicking effect of microfibers on the yarn surface, enabling the spontaneous infiltration of liquid metal (LM) into the Ag-modified microfiber channels while maintaining strong interfacial adhesion. The design attains ultra-high LM adhesion through multiscale structural interlocking: the Ag NPs are embedded within the microfibers, generating a physical anchoring effect; under capillary action, the LM penetrates to the surface of the Ag-modified microfibers, forming a continuous conductive network and creating a dynamic self-adapting interface during stretching via the metallurgical bonding between Ag NPs and LM (through In-Ag intermetallic phases); the synergistic and macroscopic deformation of the fibers and LM promotes the dynamic rearrangement of the LM. This multiscale structural interlocking structure surpasses conventional LM composites in interfacial stability and exhibits excellent electrical properties (Table R1-1, Fig. R1-1). Exhibiting strain - insensitive conductivity (with a resistance change of less than 0.703 at 600% strain), this yarn is an ideal candidate for next-

generation stretchable electronics, and its inherent textile compatibility further allows for direct integration into industrial weaving processes, providing a scalable approach.

Table R1-1. Comparison of electrical performance among the currently reported liquid metal-based stretchable conductive yarns.

Strategy	Low initial resistance	Conductivity stability under large strain	Conductivity stability under long-term cyclic strain
Coating liquid metal on fiber ¹⁻⁵	√	X	X
Liquid metal in tube ⁶⁻⁹	√	X	X
Liquid metal particle treated yarn ¹⁰⁻¹²	X	√	X
LM three-dimensional adhesion channel structure (This work)	√	√	√

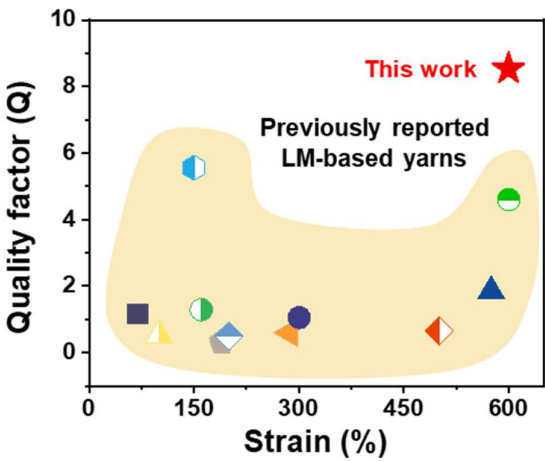


Fig. R1-1. Quality factor Q of SLMAS yarns compared to previously reported LM-based conductive yarns.

1. Uzabakiriho, P. C., Wang, M., Wang, K., Ma, C. & Zhao, G. High-strength and extensible electrospun yarn for wearable electronics. *ACS Appl. Mater. Interfaces* **14**, 46068–46076 (2022).
2. Zhang, Y. et al. Liquid metal enabled elastic conductive fibers for self-powered wearable sensors. *Adv. Mater. Technol.* **8**, 2202030 (2023).
3. Yuan, M. et al. Fabrication of a twisted sensing yarn for multifunctional wearable applications. *Prog. Org. Coat.* **186**, 108082 (2024).
4. Chen, G. et al. Superelastic EGaIn composite fibers sustaining 500% tensile strain with superior electrical

- conductivity for wearable electronics. *ACS Appl. Mater. Interfaces* **12**, 6112-6118 (2020).
5. Ma, Z. et al. Permeable superelastic liquid-metal fibre mat enables biocompatible and monolithic stretchable electronics. *Nat. Mater.* **20**, 859-868 (2021).
 6. Wu, Y. et al. Highly integrated, scalable manufacturing and stretchable conductive core/shell fibers for strain sensing and self-powered smart textiles. *Nano Energy* **98**, 107240 (2022).
 7. Gu, W. et al. Wireless smart gloves with ultra-stable and all-recyclable liquid metal-based sensing fibers for hand gesture recognition. *Chem. Eng. J.* **460**, 141777 (2023).
 8. Yu, X. et al. A one-step fabricated sheath-core stretchable fiber based on liquid metal with superior electric conductivity for wearable sensors and heaters. *Adv. Mater. Technol.* **7**, 2101618 (2022).
 9. Qi, X. et al. Underwater sensing and warming E-textiles with reversible liquid metal electronics. *Chem. Eng. J.* **437**, 135382 (2022).
 10. Ning, C. et al. Scalable one-step wet-spinning of triboelectric fibers for large-area power and sensing textiles. *Nano Res.* **16**, 7518-7526 (2023).
 11. Zheng, L. et al. Conductance-stable liquid metal sheath-core microfibers for stretchy smart fabrics and self-powered sensing. *Sci. Adv.* **7**, eabg4041 (2021).
 12. Yang, J. et al. Liquid metal coated textiles with autonomous electrical healing and antibacterial properties. *Adv. Mater. Technol.* **8**, 2202183 (2023).

Q1: The structural design rationale needs to be further elaborated. Why TPU must be used as the core for stretchable yarn? In principle, SBS can also be directed spun into a yarn. Is the stretchability limited by the PU core fiber or SBS microfiber shell? What is the importance of the SBS microfiber? How does SBS microfiber overperform compared to SBS coating?

A1: We appreciate the feedback provided by the reviewer. For effective comparison, we prepared pure SBS microfiber yarns (pSBS yarns) by electrospinning process (Fig. R1-2). As highlighted in Fig. R1-3, we systematically evaluated the mechanical performance of pSBS yarns and SBS-PU yarns. It was found that the elastic PU as core yarn played a key role in achieving synergistic mechanical enhancement, with the SBS-PU yarn exhibiting a 26-fold higher tensile strength and 1.42-fold higher elongation at break compared to the pSBS yarn. This design strategically combines the high compliance of the SBS microfiber shell (providing interfacial adaptability and porous architecture for conductive material integration) with the high mechanical robustness of the PU core yarn (resisting catastrophic fracture under large deformations). It is worth noting that the observed “breakage” of SBS-PU yarn specifically refers

to the breakage of the SBS microfibers in the surface layer of the yarn, while the core structure remains intact. This core-shell architecture decouples mechanical robustness (core-dominated) from electrical functionality (shell-dominated), aligning with industrial requirements for durable smart textiles.

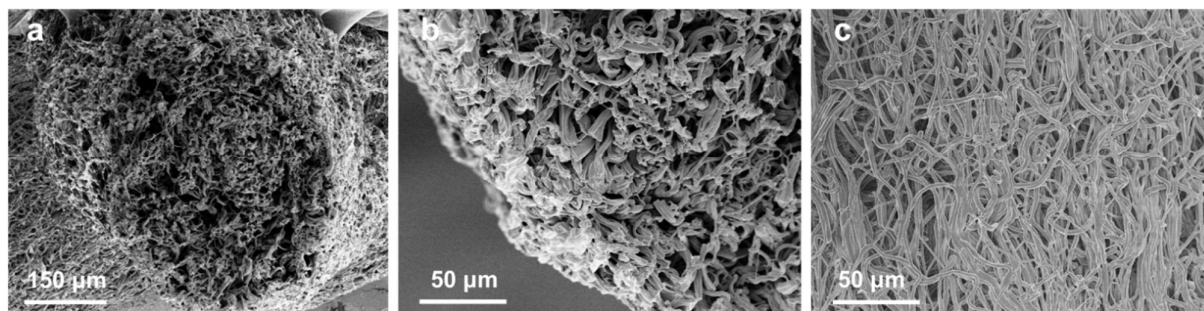


Fig. R1-2. SEM of pSBS yarns. **a-b** Cross-sectional SEM image of pSBS yarns. **c** Surface morphology of pSBS yarns.

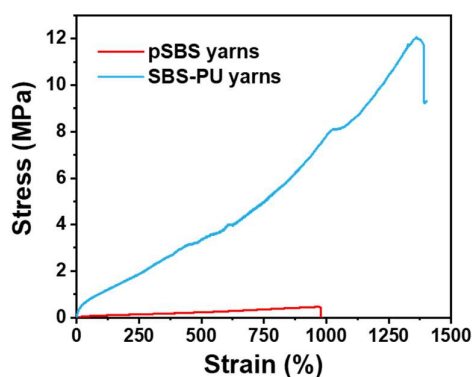


Fig. R1-3. Stress-strain curves of pSBS yarns and SBS-PU yarns.

SBS microfibers form a three-dimensional porous network structure through electrospinning process, which provides space for three-dimensional distribution of LM, enhances the wetting effect between LM and substrate, and reduces the risk of interfacial delamination. In contrast, SBS coatings have smooth surfaces, lack porosity, and have poor LM wetting (Fig. R1-4).

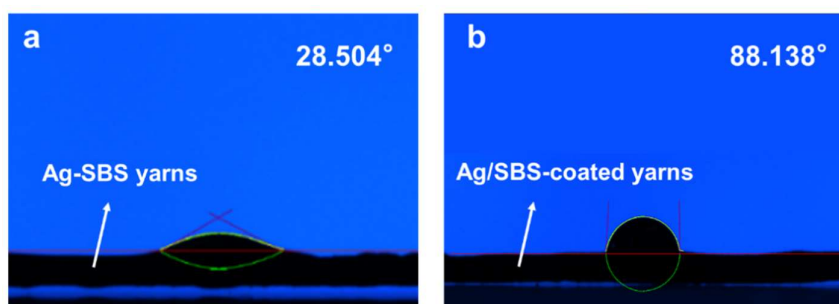


Fig. R1-4. **a** The contact angle between LM and Ag-SBS yarns. **b** The contact angle between LM and Ag modified

SBS-coated yarns (Ag/SBS-coated yarns).

Q2: The adhesion of LM to yarns lacks sufficient experimental evidence. Although the X-ray diffraction (XRD) spectra suggest that LM reacts with Ag on the yarn, reaction does not necessarily equate to adhesion. Furthermore, the cross-sectional energy-dispersive X-ray spectroscopy (EDS) mapping of SLMAS yarns in Figure 1h shows almost no overlap with the carbon elements. The adhesion force of the resultant AgIn_2 still needs to be tested and supported with additional data.

A2: We thank the reviewers for their insightful comments on the distinction between alloying reactions and adhesion. Our structural design indeed establishes a three-dimensional adhesion channel for robust LM adhesion. This efficient adhesion is achieved by a multiscale interlocking mechanism.

First, Ag NPs were firmly anchored to the substrate fibers to provide the basis for effective LM adhesion. This is because during the growth of Ag NPs, the trifluoroacetic acid anion (CF_3COO^-) forms an ion-dipole interaction with the hydroxyl group (-OH) of the alcohol, which facilitates the rapid uptake of precursors and alcohols into the fibers. During the absorption of the silver precursors, they diffuse towards the center of the fiber, thus fixing the silver firmly to the fiber¹⁻².

Second, the intermetallic phases Ag_9In_4 and AgIn_2 phases detected at the LM/Ag interface by XRD confirm the generation of metallic bonds (Fig. 1f in the revised manuscript). Ag NPs deposition induced a shift in wettability (Fig. 1g in the revised manuscript), with the contact angle decreasing from 115.780° (non-wetting) to 28.504° (super-wetting), resulting in a shift of the LM from an interlayer coating of fiber layers to penetrates to the fibers surface (Fig. R1-5 a-b). When LM touches the super-wettable Ag-SBS fiber, the capillary force instantly penetrates LM into the fiber pores and spreads it out, and Ag NPs on the fiber surface retains LM on the surface after alloying reaction with LM, so that LM remains penetrated in the fiber pores (Fig. R1-6). This synergy between the bonding mechanism and the capillary wicking effect of microfibers on the yarn surface is the fundamental reason for the excellent adhesion properties of our yarns to LM. More importantly, the fiber surface still maintains complete LM coverage after 5000 cycles of high-strain cyclic stretching of the SLMAS yarns, reflecting the dynamic bonding mechanism of our structure to LM, which indicates a stable and long-lasting adhesion between our yarns and LM (Fig. R1-5c).

Third, the macroscopic deformation of the fibers drives the dynamic rearrangement of LM, and more LM penetrates into the pores of the Ag-SBS fibers with higher wettability and are firmly bonded to the fiber surface after stretching, which leads to stronger adhesion and control of LM (Fig. R1-7; Fig. R1-8).

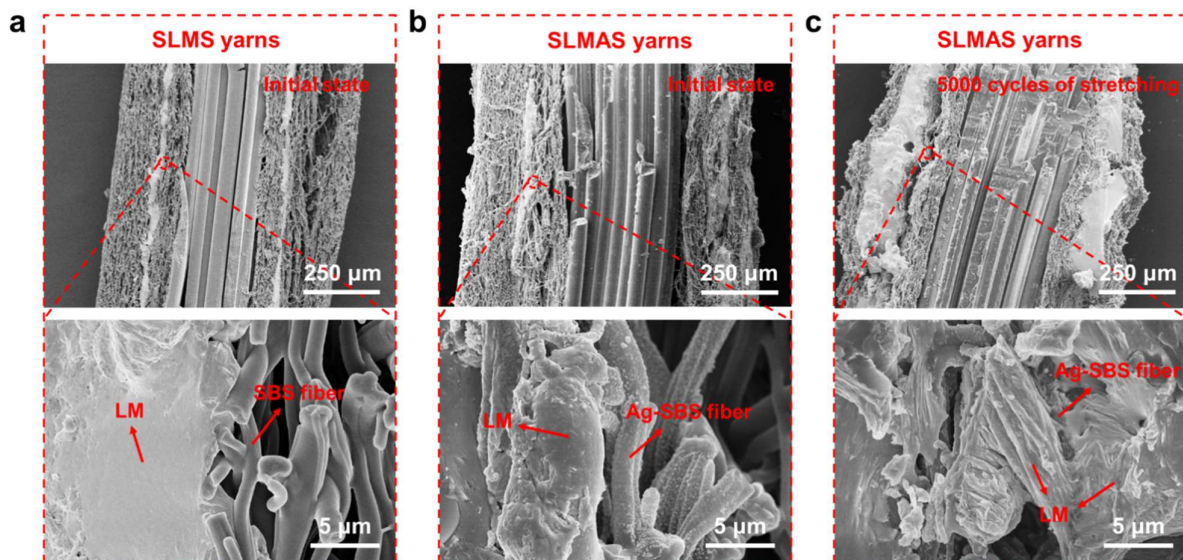


Fig. R1-5. **a** Longitudinal-sectional SEM image of SLMS yarns (yarns obtained by coating LM directly onto SBS-PU yarns and encapsulating them), showing that LM is distributed between fiber layers without being drawn into the fiber pores. **b** Longitudinal-sectional SEM image of SLMAS yarns, showing that LM is absorbed into the fiber pores and completely wraps around the fibers. **c** Longitudinal-sectional SEM image of SLMAS yarns after 5000 cycles of stretching (500% strain) showing the morphology of the LM firm coating on the surface of SBS fibers after cyclic stretching.

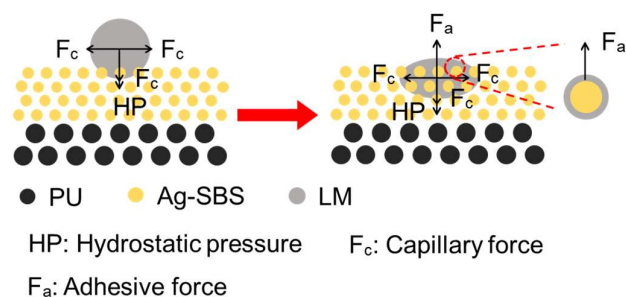


Fig. R1-6. Schematic diagram of the mechanism of LM penetration into the fiber channel and maintaining adhesion.

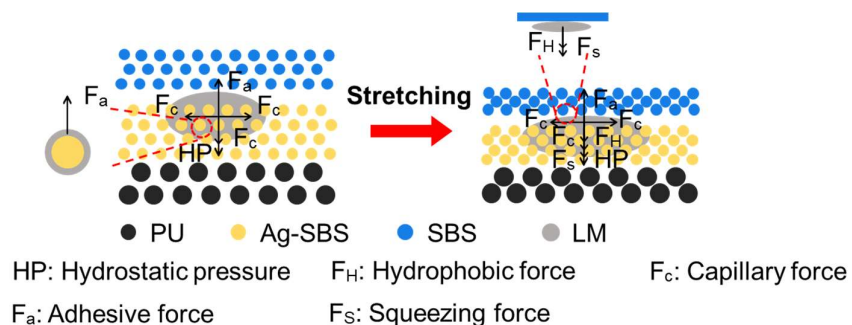


Fig. R1-7. Schematic of the mechanism by which the SBS fiber layer squeezes the LM under stretching, allowing more LM to immerse into the Ag-SBS fiber channel with higher wettability. The encapsulation layer compresses the LM during the stretching process, and at the same time, the LM is subject to reverse hydrophobic forces due to the non-wettability of the encapsulation layer.

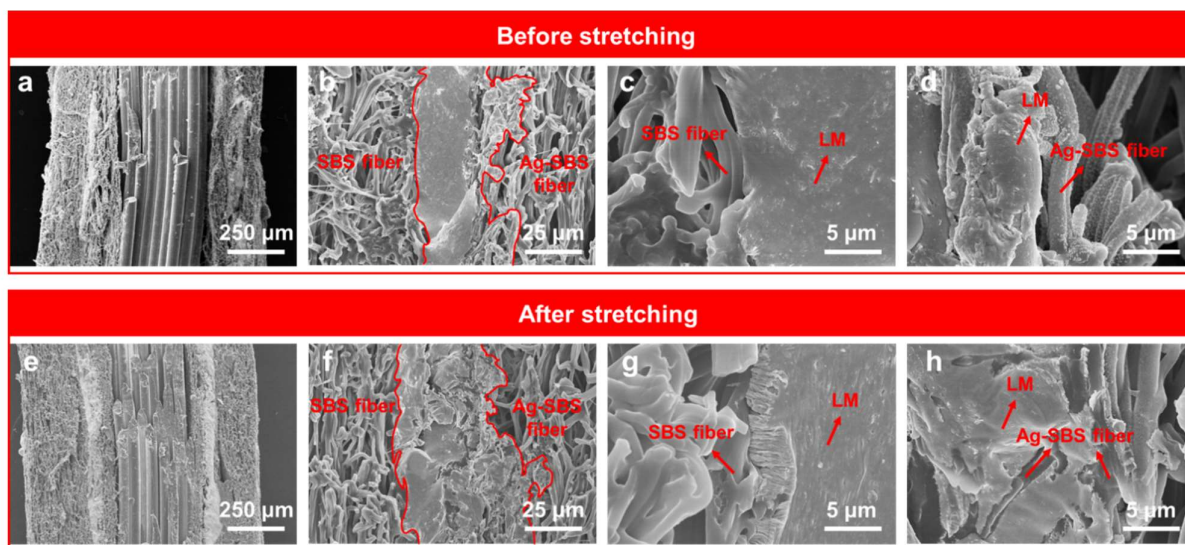


Fig. R1-8. **a-d** Longitudinal cross-section SEM images of SLMAS yarns at different magnifications showing the distribution of LM within the yarns. **e-h** Longitudinal cross-section SEM images of SLMAS yarns after stretching at different magnifications, showing variation in the distribution of LM.

1. Park, M. et al. Highly stretchable electric circuits from a composite material of silver nanoparticles and elastomeric fibres. *Nature Nanotech.* **7**, 803-809 (2012).
2. Ma, Z. et al. Stretchable and conductive fibers fabricated by a continuous method for wearable devices. *Cell Rep. Phys. Sci.* **4**, 101300 (2023).

Q3: There are no scale bars for Figures 1j and 1k.

A3: Thank you for pointing this out. We apologize for the oversight. We have added the appropriate scale bars to Figures 1j and 1k in the revised manuscript.

Q4: How is the LM loading content controlled? What is the quantitative relationship between the silver precursor solution and the LM loading content? Does the immersion time affect the LM loading content?

A4: We appreciate the feedback provided by the reviewer. We varied the loading of the Ag NPs on the yarn by controlling the concentration of the silver precursor solution, which in turn regulated the loading of LM. The LM wettability on the yarn increased significantly when the silver precursor concentration was increased from 2 wt% to 10 wt%, with the contact angle decreasing from 83.081° to 28.504° (Supplementary Fig. 6 in the revised Supplementary Information). This resulted in an increase in LM loading from 1.00 mg/cm to 6.88 mg/cm (Fig. R1-9a). Due to the strong metallic bonding between the LM and the Ag NPs on the fibers as well as the capillary penetration of the microscale fibers, there is an extraordinarily high wettability between the LM and the substrate fibers, and thus the yarn absorbs the saturated LM (6.88 mg/cm) immediately after immersion in the LM bath. As shown in Fig. R1-9b, when the yarn was submerged in the LM bath for 30 minutes, there was almost no change in the amount of LM loading.

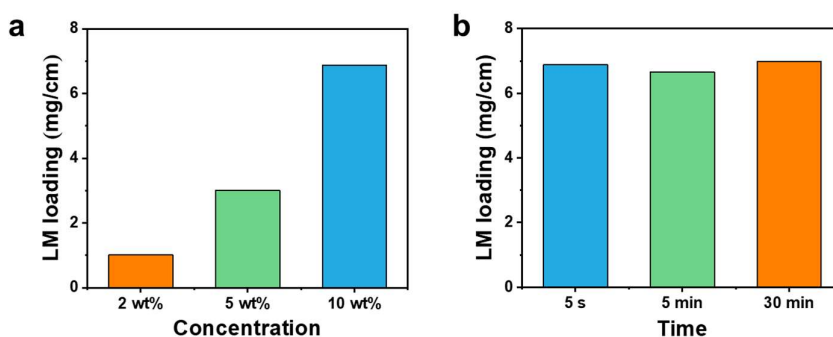


Fig. R1-9. a LM loading on yarns after treatment with different concentrations of silver precursor solutions. **b** LM loading on the yarns for different immersion time.

Q5: Recommend conducting cycling stability tests with a significantly higher number of cycles (for example: >10,000 cycles). Testing up to 1100 cycles does not provide sufficient evidence to claim long-term electrical stability, which is crucial for practical applications.

A5: Thank you for your valuable suggestion. We recognize that long term cycling stability is critical for practical applications, so we test the resistance change of the SLMAS yarns at a higher number of cycles. It was found that the yarns exhibited stability over long-term stretch cycling, maintaining essentially constant resistance over 10,000 stretch cycles at 200% strain, while the yarns maintained stable resistance over 5,000 cycles at a large strain of 500% (Fig. R1-10).

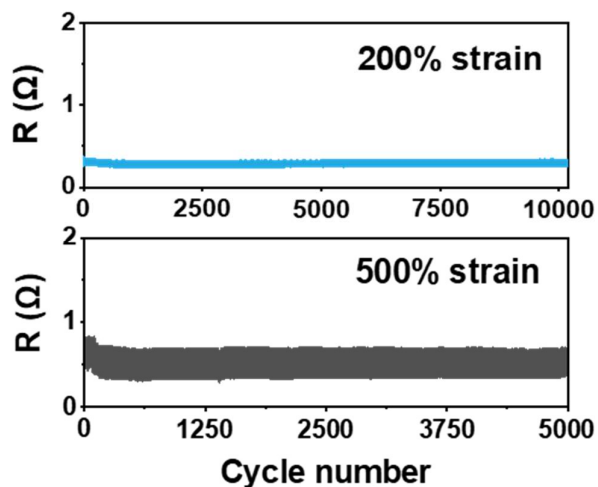


Fig. R1-10. Resistance changes of the SLMAS yarns during the stretching-releasing cycling test (200% strain and 500% strain).

Q6: The authors state that the SBS microfiber encapsulation layer forces LM into the pores of the adherent microchannel layer during stretching. However, Figures 2d and 2e show no encapsulation layer. It appears that LM flows directly into the pores of the PU-SBS yarn without an encapsulation layer.

A6: We thank the reviewers for their comments. Figures 2d and 2e (in the revised manuscript) depict the distribution of LM on yarns without encapsulating layers in the initial and stretched states, aiming to confirm the successful construction of three-dimensional adhesion channels for LM. As shown in Fig. 2d, in the initial state, the LM tightly coats individual tortuous microfibers or bridges several microfibers, forming a three-dimensional network of LM. When the LM loading reaches 3.03 mg/cm, it fills the surface pores. With the further increase of LM content, part of the LM penetrated into the pores of the fibers, and part of the LM was free in the surface layer of the yarn, which is in full agreement with the conclusion of our supplementary longitudinal cross-section SEM images (Fig. R1-11 a-d). Due to the ultra-high adhesion caused by the reaction of Ag NPs grown on the fibers with the LM, the LM remained firmly attached to the microfibers in the stretched state (Fig. 2e) and stretched along with the microfibers, thus maintaining a straight and highly connected conductive channel.

In order to better maintain the stable electrical properties, we used electrospinning SBS microfibers to encapsulate the yarn. When the encapsulated yarn is stretched, the encapsulation layer compresses the LM, allowing more LM to enter the Ag-SBS microchannel. To further confirm this, we compared the distribution of LM before and after stretching the yarn with encapsulation layer. It is very obvious from the SEM images that after stretching,

more free LM penetrates into the adhesion channels constructed by Ag-SBS fibers and remains in tight contact with the fibers (Fig. R1-11).

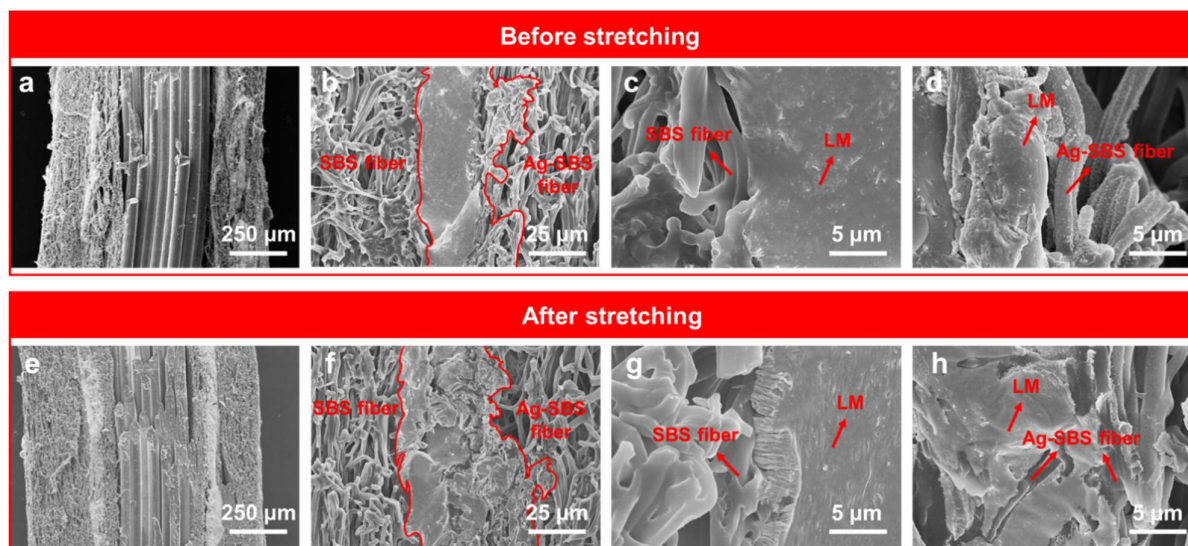


Fig. R1-11. **a-d** Longitudinal cross-section SEM images of SLMAS yarns at different magnifications showing the distribution of LM within the yarns. **e-h** Longitudinal cross-section SEM images of SLMAS yarns after stretching at different magnifications, showing variation in the distribution of LM.

Q7: Why does a negative resistance change occur during the stretching process of the SLMAS yarn (Supplementary Figure 9)?

A7: Thanks to the reviewer's comments. As shown in Supplementary Figure 9 (Supplementary Fig. 21 in the revised Supplementary Information), the negative resistance change observed in the SLMAS yarn during the stretching cycle is due to a slight decrease in resistance after stretching. This resistance decrease is attributed to the stretch-induced LM rearrangement (Fig. R1-11). The compression of the surface SBS encapsulation layer forces the LM to penetrate deeper into the pores of the core fibers, and the LM connects the stretch-induced cracks between the Ag NPs on the surface of the fibers¹, which leads to the decrease in resistance during the stretching cycle.

1. Park, M. et al. Highly stretchable electric circuits from a composite material of silver nanoparticles and elastomeric fibres. *Nature Nanotech.* **7**, 803-809 (2012).

Q8: The Hue value decreases after just 10 cycles of switching the voltage on and off (Figure 5c). Additional cycling tests are required to confirm stability.

A8: Thanks to the reviewers for the feedback provided. Additional cycling tests to confirm the stability of the electro-thermochromic yarns are important for their application in practice. Therefore, we conducted 100 switching voltage cycling tests and found that our electro-thermochromic yarn continues to exhibit stable color-changing capabilities (Fig. R1-12).

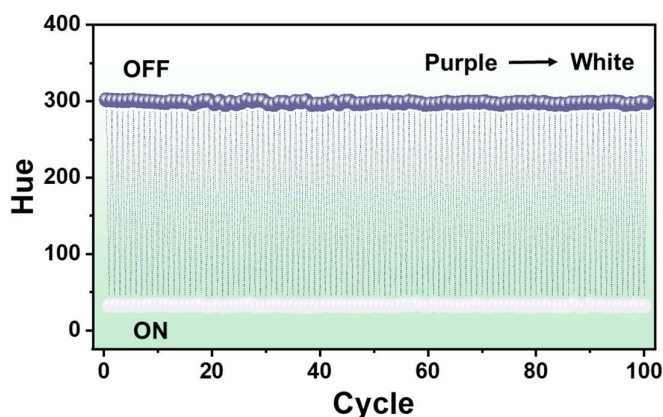


Fig. R1-12. Hue value during switching voltage on and off (100 cycles).

Q9: How about the integration ability of these yarns into fabrics?

A9: We appreciate the feedback provided by the reviewer. We conducted research on the textile process of the prepared conductive yarn. The prepared conductive yarn has good structural stability and can be made into flat and stable fabrics through classic weaving techniques. (Fig. R1-13).



Fig. R1-13. **a-b** Photographs showing the weaving process of the conductive fabric, which is woven from commercial yarns and SLMAS yarns. **c** Photomicrograph of a conductive fabric woven from a mixture of commercial yarns and SLMAS yarns.

To Reviewer 2:

In this manuscript, the authors report the development of an elastic conductive yarn through a layer-by-layer assembly

of SBS microfibers, Ag nanoparticles and liquid metal on commercial spandex yarn by an adhesion channeling strategy that enables three-dimensional control of liquid metal flow on the yarn surface. This research offers a new strategy to achieve conductive yarn with ultra-low resistance and extraordinary conductivity stability over a large strain range. I believe the manuscript is possible to be accepted for publishing after carefully addressing the following issues:

Replay: We thank the reviewer for the positive evaluation of our manuscript. We have carefully revised the manuscript according to your valuable comments and suggestions.

Q1: The authors only provided stress-strain curves for SLMAS yarns and whether the absorption of LM has an effect on the mechanical properties of the yarns, so stress-strain curves for SBS-PU yarns should also be provided and discussed.

A1: We appreciate the feedback provided by the reviewer. In order to illustrate more precisely the effect of LM uptake on the mechanical properties of the yarns, we compared the yarns obtained in each step, including SBS-PU yarn, Ag-SBS yarn, LM/Ag-SBS yarn and SLMAS yarn (Fig. R2-1a).

First of all, SBS-PU yarns as base yarns have high mechanical strength and excellent tensile properties, with a breaking strength of about 12 MPa and a breaking strain of about 1360%. Typically, the addition of solid or liquid fillers usually affects the mechanical properties of the material¹. The growth of Ag NPs as a rigid filler on the SBS-PU yarn decreases the elasticity, but the modulus of the yarn increases². In contrast, when the LM is absorbed into the yarn as a fluid, the modulus of the yarn decreases and the tensile properties increase slightly. Finally, the encapsulated layer of microfibers on the surface resulted in a slight reduction in the modulus of the SLMAS yarn (Fig. R2-1b).

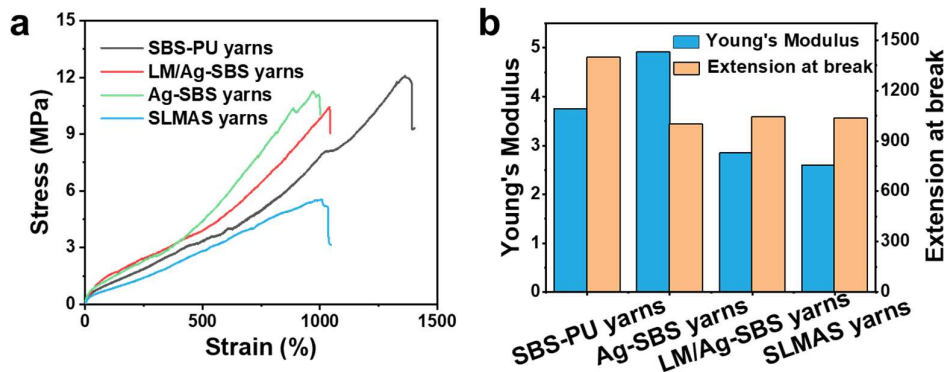


Fig. R2-1. **a** Stress-strain curves of SBS-PU yarns, Ag-SBS yarns, LM/Ag-SBS yarns and SLMAS yarns. **b** Comparison of extension at break and Elastic modulus of these yarns during stretching.

1. Eristoff, S. et al. Liquid metal + x: a review of multiphase composites containing liquid metal and other (x) fillers. *Adv. Funct. Mater.* **34**, 2309529 (2024).
2. Bhattacharyya, S. et al. Improving reinforcement of natural rubber by networking of activated carbon nanotubes. *Carbon* **46**, 1037-1045 (2008).

Q2: I noticed that the encapsulating SBS layer seems to play a very important role, how does the SBS fiber encapsulation layer on the yarn surface affect the electromechanical behavior of the yarn?

A2: Thanks to the reviewers for the feedback provided. In order to investigate the effect of the encapsulation layer on the electromechanical properties of the yarns, we compared the resistance changes of unencapsulated and encapsulated yarns during stretching. Compared to the unencapsulated yarn, the encapsulated yarn has less resistance change during stretching, indicating that encapsulation is beneficial for the yarn to maintain stable electromechanical properties (Fig. R2-2). This occurs because the encapsulation layer compresses the LM during stretching, and the LM experiences reverse hydrophobic forces due to the non-wettability of the encapsulation layer. As a result, more free LM enters the Ag-SBS fiber channels, which have higher wettability to the LM, thereby maintaining a highly connected three-dimensional conductive network (Fig. R2-3; Fig. R2-4).

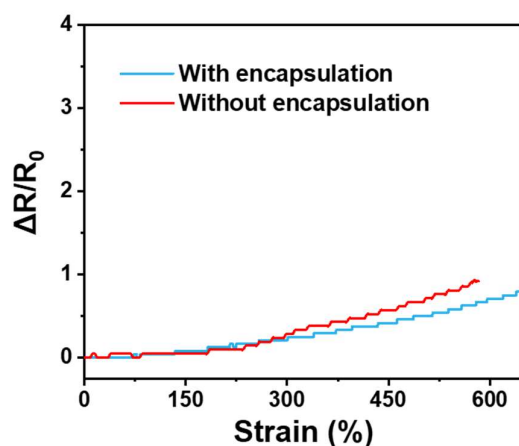


Fig. R2-2. Resistance changes of the yarns with encapsulation and without encapsulation.

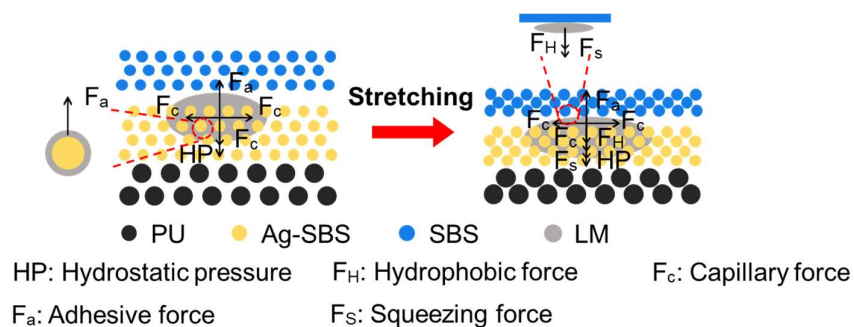


Fig. R2-3. Schematic of the mechanism by which the SBS fiber layer squeezes the LM under stretching, allowing more LM to immerse into the Ag-SBS fiber channel with higher wettability.

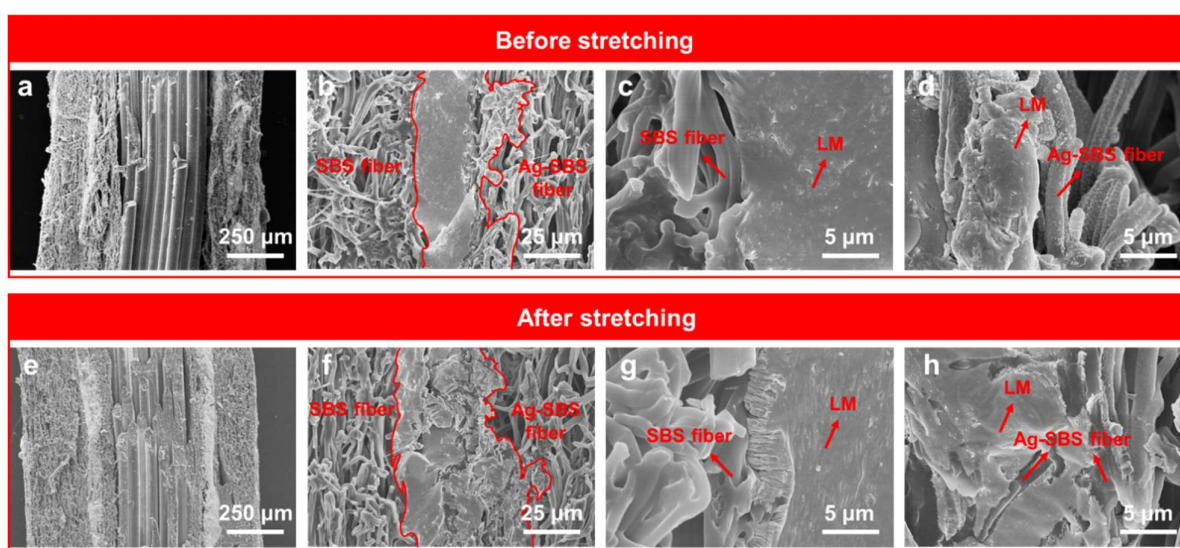


Fig. R2-4. **a-d** Longitudinal cross-section SEM images of SLMAS yarns at different magnifications showing the distribution of LM within the yarns. **e-h** Longitudinal cross-section SEM images of SLMAS yarns after stretching at different magnifications, showing variation in the distribution of LM.

Q3: I suggest to include a video to further improve the clarity and understanding of the research methodology. The video could show the production of SBS-PU yarn using conjugated electrostatic spinning to visualize the electrospinning process. This video will provide the reader with valuable additional material to visualize the experimental process and better understand the research.

A3: Thank reviewer for the valuable suggestion. We have added a video showcasing the preparation process of SBS-PU yarn (Supplementary Movie 1) into the supplementary information.

During the yarn formation process, a voltage of opposite polarity is applied to two needles placed opposite each

other, which supply the solution. Under the influence of a high-voltage electric field, the solution is drawn, the solvent volatilizes, the jet cures, and the fibers are formed. The oppositely charged fibers are attracted to each other, neutralizing the charges. The fibers are then collected and twisted using rotating metal discs positioned between the needles, with the nanofibers ultimately being deposited onto the core yarn.

Q4: The loading of liquid metal significantly influences the electrical conductivity and electromechanical properties of SLMAS yarns. What is the liquid metal loading in the SLMAS yarn used to measure the electromechanical properties in Figure 3?

A4: Thank reviewer for the valuable suggestion. SLMAS yarns with a loading of 6.88 mg/cm were used to test various mechanical properties in Fig. 3 (in the revised manuscript). This loading was chosen because the yarn exhibits superior electromechanical stability at 6.88 mg/cm compared to other loading amounts, making it more suitable for practical applications in strain-insensitive smart fabrics. We have added this information in the revised manuscript for clarity.

Q5: The direct use of "SBS-PU yarn" and "Ag-SBS yarns" in the manuscript without a clear definition by the author may cause confusion to the reader.

A5: Thank you for your constructive comments. In the revised manuscript, we have provided clear definitions when these terms are first introduced. Specifically, we explain that "SBS-PU yarn" refers to a yarn with a core-sheath structure obtained by electrospinning of styrene-butadiene-styrene (SBS) microfibers deposited on polyurethane (PU) yarn. Meanwhile, "Ag-SBS yarn" refers to a yarn obtained by Ag NPs deposition onto SBS-PU yarn. These definitions ensure that the reader can easily understand the composition and structure of the materials discussed in the manuscript.

Q6: There is confusion in the author's description of the yarn in Figure 1b in terms of "SBS/PU yarn" as well as "SBS-PU yarn". Please clarify the terminology and ensure consistency.

A6: Thank you for pointing out the inconsistency in the terminology used to describe the yarn in Fig. 1b. We apologize for the confusion. To clarify, "SBS/PU yarn" and "SBS-PU yarn" refer to the same material: a yarn with a core-sheath structure, created by electrospinning styrene-butadiene-styrene (SBS) microfibers onto polyurethane (PU) yarn. In the revised manuscript, we have standardized the terminology and consistently refer to it as "SBS-PU yarn" throughout the text to eliminate any confusion.

Q7: There are some details that have not been noticed, such as the location of the scale bar "10 μm " in Figure 1g should be adjusted.

A7: Thank you for pointing out the problem with the scale location in Figure 1g. We apologize for the oversight. In the revised manuscript, we have adjusted the position of the "10 μm " scale to ensure that it is clearly visible and appropriately positioned so as not to obscure important details in the image. And we carefully reviewed all the diagrams to make sure that all the scales were properly positioned.

Q8: There are still some grammatical errors and typos in the manuscript; please check carefully. For example, in the caption of Figure 2f, "Metal" should be in lowercase.

A8: Thank you for your careful review of the manuscript. We apologize for the grammatical errors and typos you have pointed out. We have adjusted the caption of Figure 2f as you suggested by changing "metal" to lowercase. In addition, we have double-checked the entire manuscript to ensure that all grammatical errors and typos are resolved before resubmission.

Q9: The long-range electro-thermochromic property of the yarn is critical. Therefore, please specify the value of the scale bar in Figure 5b that represents the length of the electro-thermochromic yarn.

A9: Thank you for your valuable feedback. In Fig. 5b, when the yarn is woven into a fabric with the "LMY" pattern with the size of 5 cm $\times$ 12 cm, the color of the yarn obviously changes from light to dark, which fully illustrates the long-range electrothermochromic properties of our yarn as well as its inherent weaving adaptability. In the revised manuscript, we have clearly marked the scale bar in Figure 5b showing the length of the electrothermochromic yarn to ensure that readers can accurately interpret the image.

To Reviewer 3:

The paper "Constructing Electrospun 3D Liquid Metal Adhesion Channel on Stretchable Yarns for Broad-Range Strain-Insensitivity Smart Textiles" discusses the development of stretchable conductive yarn through the electrospinning of elastomer (SBS) microfibers onto a stretchable substrate of TPU microfibers. Additionally, the yarn is treated with silver nanoparticles (Ag NPs) and liquid metal (LM) to create a stretchable conductor. There have been several papers that report coating stretchable fibers with liquid metal, but this one achieves it by using Ag NPs.

I provide here two examples - in the former, the metal is coated just by spreading it across the fabric, and in the latter, the metal is coated by dip coating into a solution of LM particles (neither of which requires Ag):

<https://www.nature.com/articles/s41563-020-00902-3>

<https://onlinelibrary.wiley.com/doi/10.1002/admt.202202183>

Replay: We appreciate the reviewer's insightful and helpful comments on our manuscript. The reviewers' suggestions and criticisms have significantly improved the quality of our manuscript. In this work, we innovatively achieved spontaneous infiltration of liquid metal (LM) and in-situ construction of three-dimensional interpenetrating conductive pathways by establishing super-adhesive LM channels through silver nanoparticle (Ag NPs) growth on microfiber surfaces of yarns. Compared with conventional surface coating techniques, this approach enhances the interfacial bonding strength between LM and substrate, enabling the conductive yarn to maintain a resistance variation below 0.703 under 600% tensile strain with long-term stability, demonstrating marked advantages over the post-processed wrinkle structures reported in literature (literature 1 provided by the reviewer). Notably, our system exhibits an unprecedentedly low initial resistance of 0.082 Ω/cm without pre-activation, effectively overcoming the technical limitation of mechanical activation dependency inherent in traditional LM particle processing methods (literature 2 provided by the reviewer). The structural properties of our yarns endow the yarns with unique electromechanical properties (Table R3-1, Fig. R3-1), demonstrating significant technological advantages in the fields of wearable electronics and smart textiles.

Table R3-1. Comparison of electrical performance among the currently reported liquid metal-based stretchable conductive yarns.

Strategy	Low initial resistance	Conductivity stability under large strain	Conductivity stability under long-term cyclic strain
Coating liquid metal on fiber ¹⁻⁵	√	X	X
Liquid metal in tube ⁶⁻⁹	√	X	X
Liquid metal particle treated yarn ¹⁰⁻¹²	X	√	X
LM three-dimensional adhesion channel structure (This work)	√	√	√

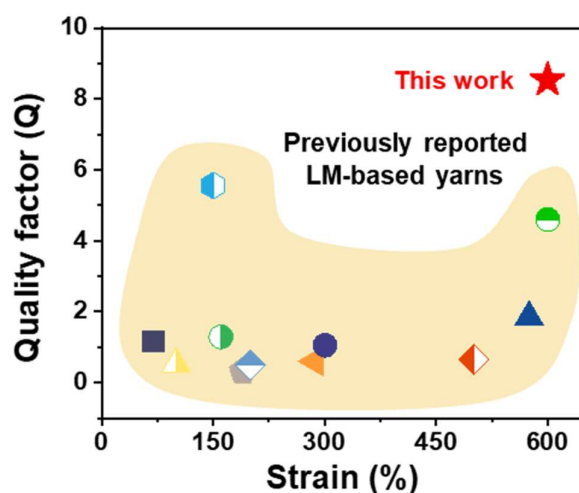


Fig. R3-1. Quality factor Q of SLMAS yarns compared to previously reported LM-based conductive yarns.

1. Uzakiriho, P. C., Wang, M., Wang, K., Ma, C. & Zhao, G. High-strength and extensible electrospun yarn for wearable electronics. *ACS Appl. Mater. Interfaces* **14**, 46068–46076 (2022).
2. Zhang, Y. et al. Liquid metal enabled elastic conductive fibers for self-powered wearable sensors. *Adv. Mater. Technol.* **8**, 2202030 (2023).
3. Yuan, M. et al. Fabrication of a twisted sensing yarn for multifunctional wearable applications. *Prog. Org. Coat.* **186**, 108082 (2024).
4. Chen, G. et al. Superelastic EGaIn composite fibers sustaining 500% tensile strain with superior electrical conductivity for wearable electronics. *ACS Appl. Mater. Interfaces* **12**, 6112-6118 (2020).
5. Ma, Z. et al. Permeable superelastic liquid-metal fibre mat enables biocompatible and monolithic stretchable electronics. *Nat. Mater.* **20**, 859-868 (2021).
6. Wu, Y. et al. Highly integrated, scalable manufacturing and stretchable conductive core/shell fibers for strain sensing and self-powered smart textiles. *Nano Energy* **98**, 107240 (2022).
7. Gu, W. et al. Wireless smart gloves with ultra-stable and all-recyclable liquid metal-based sensing fibers for hand gesture recognition. *Chem. Eng. J.* **460**, 141777 (2023).
8. Yu, X. et al. A one-step fabricated sheath-core stretchable fiber based on liquid metal with superior electric conductivity for wearable sensors and heaters. *Adv. Mater. Technol.* **7**, 2101618 (2022).
9. Qi, X. et al. Underwater sensing and warming E-textiles with reversible liquid metal electronics. *Chem. Eng. J.* **437**, 135382 (2022).

10. Ning, C. et al. Scalable one-step wet-spinning of triboelectric fibers for large-area power and sensing textiles. *Nano Res.* **16**, 7518-7526 (2023).
11. Zheng, L. et al. Conductance-stable liquid metal sheath-core microfibers for stretchy smart fabrics and self-powered sensing. *Sci. Adv.* **7**, eabg4041 (2021).
12. Yang, J. et al. Liquid metal coated textiles with autonomous electrical healing and antibacterial properties. *Adv. Mater. Technol.* **8**, 2202183 (2023).

Q1: What is the size distribution of silver nanoparticles (Ag NPs), and how are they attached to the styrene-butadiene-styrene (SBS) polymer chains? If the Ag NPs are within the polymer structure, how might this confinement affect their function?

A1: We appreciate the feedback provided by the reviewer. SBS-PU yarns are immersed in a silver precursor solution (AgCF_3COO in ethanol). The precursor and solvent are absorbed by the fibers, causing the fiber to swell. After drying, the precursors are reduced by a hydrazine hydrate solution, which results in Ag NPs being embedded and tightly attached in the SBS fibers¹. In general, the diameter of the Ag NPs formed on the fiber surface increased with the concentration of the silver precursor solution. When the concentration increased from 2 wt% to 10 wt%, the diameter of the silver particles grew from 139 nm to 241 nm (Fig. R3-2 a-d).

Ag NPs were tightly distributed on the fibers and embedded in the fiber substrate to form Ag NPs-SBS composite fibers. This is due to the formation of ion-dipole interactions between the trifluoroacetic acid anion (CF_3COO^-) and the hydroxyl group (-OH) of the alcohol, which promotes the rapid absorption of precursors and alcohols into the fiber. During the absorption of silver precursors, they diffuse towards the center of the fibers, thus anchoring the Ag NPs to the fibers²⁻³.

The growth of Ag NPs affects both mechanical and electrical properties of the yarn. It is well known that hard fillers with a conformal interface in an elastic matrix increase the elastic modulus of the composite^{1,4}. Fig. R3-2e compare the mechanical properties of Ag-SBS yarns with SBS-PU yarns. The elastic modulus of Ag-SBS yarns ($E = 4.913 \text{ MPa}$) is higher than that of SBS-PU yarns ($E = 3.758 \text{ MPa}$). As well, the addition of Ag NPs also resulted in a lower strain at break for the Ag-SBS yarns than for the SBS-PU yarns (Fig. R3-2f). For electrical properties, the conductivity of the Ag-SBS yarn is attributed to the penetration of silver nanoparticles within the fibers as well as the electrical connection of the silver shells on the surface. Meanwhile, the combination of Ag NPs and LM provides SLMAS yarns with ultra-low initial resistance (Fig. 2a in the revised manuscript).

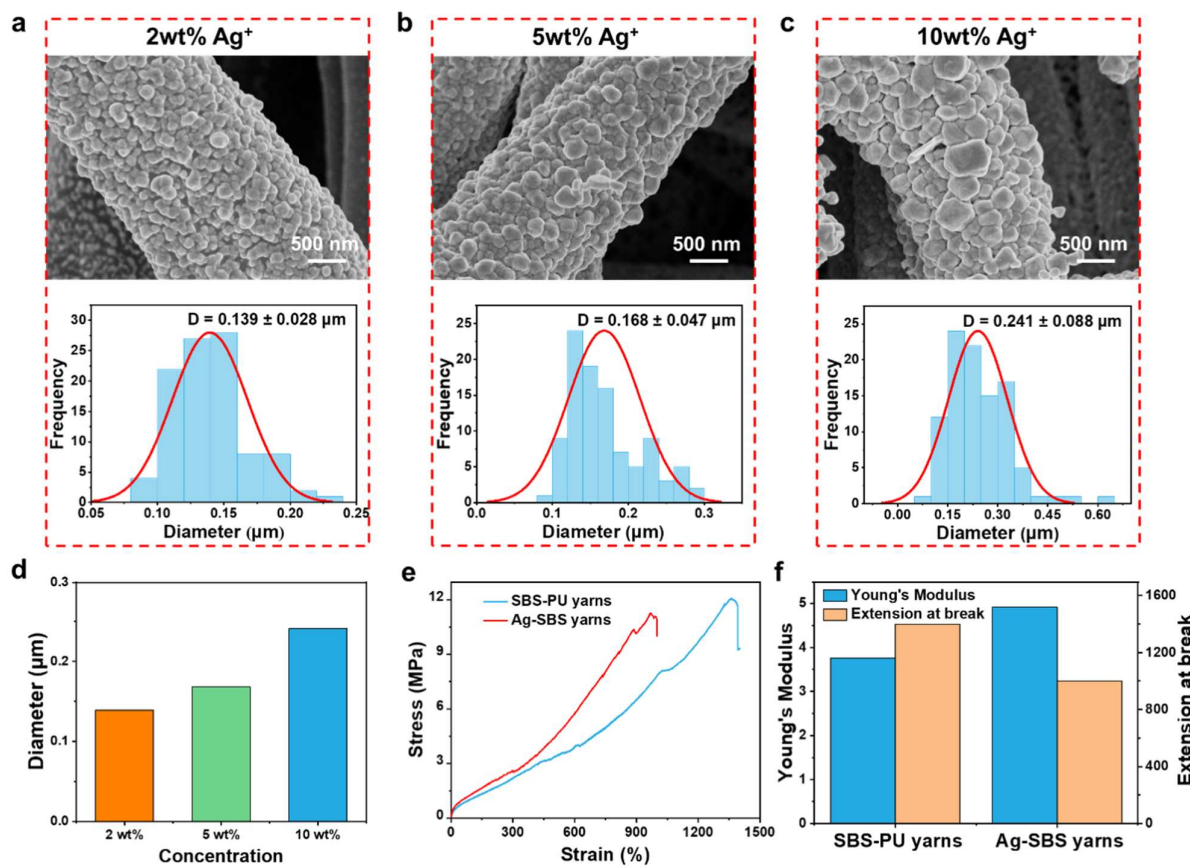


Fig. R3-2. **a-c** High magnification SEM images of SBS-PU yarns treated with different concentrations of silver precursor solutions (**a** 2wt%, **b** 5wt%, **c** 10wt%) and the corresponding Ag NPs diameter distribution curves. **d** Comparative chart of Ag NPs diameters treated with different concentrations of silver precursors. **e** Stress-strain curves of Ag-SBS yarns and SBS-PU yarns. **f** Comparison of extension at break and Elastic modulus of Ag-SBS yarns and SBS-PU yarns during stretching.

1. Park, M. et al. Highly stretchable electric circuits from a composite material of silver nanoparticles and elastomeric fibres. *Nature Nanotech.* **7**, 803-809 (2012).
2. Ma, Z. et al. Stretchable and conductive fibers fabricated by a continuous method for wearable devices. *Cell Rep. Phys. Sci.* **4**, 101300 (2023).
3. Lee, J. et al. Conductive fiber-based ultrasensitive textile pressure sensor for wearable electronics. *Adv. Mater.* **27**, 2433-2439 (2015).
4. Bhattacharyya, S. et al. Improving reinforcement of natural rubber by networking of activated carbon nanotubes. *Carbon* **46**, 1037-1045 (2008).

Q2: Although both thermoplastic polyurethane (TPU) and SBS polymers are stretchable, their recoverability during stress-strain cyclic tests appears to be quite different, which could lead to deformation in the entire yarn after testing. I suggest conducting more experiments using neat TPU fibers and neat electrospun SBS fibers, and comparing their mechanical properties.

A2: We appreciate the feedback provided by the reviewer. In textile materials, the elastic recovery of the yarn is defined as the percentage of the recoverable portion of the yarn deformation to the total deformation of the yarn. For comparison, we directly prepared pure SBS microfiber yarns (pSBS yarn) by conjugated electrospinning process (Fig. R3-3). We added tensile cycle tests for pSBS yarns, commercial PU yarn, and SBS-PU yarn, and found that the elastic recovery of these yarns was essentially the same (Fig. R3-4 a-d). It indicates that our yarn structures have good adaptability.

In addition, from the stress-strain curves of PU yarns and pSBS yarns, it is found that the breaking strength of PU yarns is much higher than that of pSBS yarns, which is 48.5 times higher than that of the pSBS yarn (0.46 MPa) (Fig. R3-4e). Therefore, the SBS-PU yarn as a base yarn can retain the interfacial adaptability and porous structure provided by microfibers while maintaining high mechanical robustness, which can better meet the actual needs of textiles.

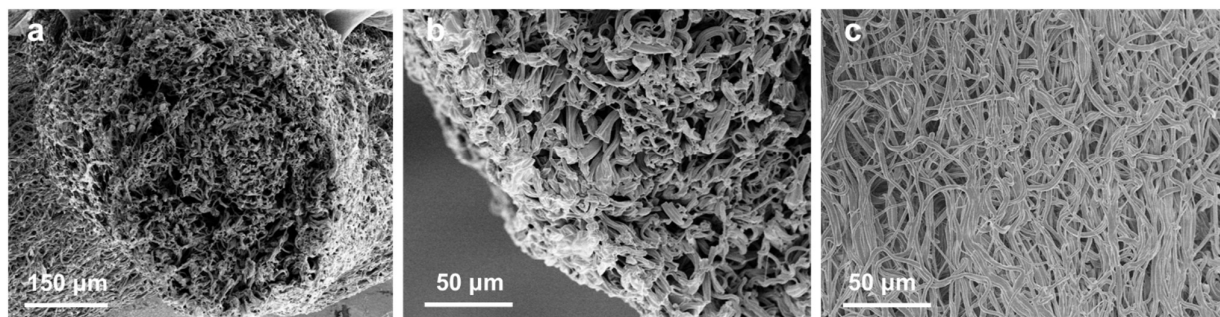


Fig. R3-3. SEM of pSBS yarns. **a-b** Cross-sectional SEM image of pSBS yarns. **c** Surface morphology of pSBS yarns.

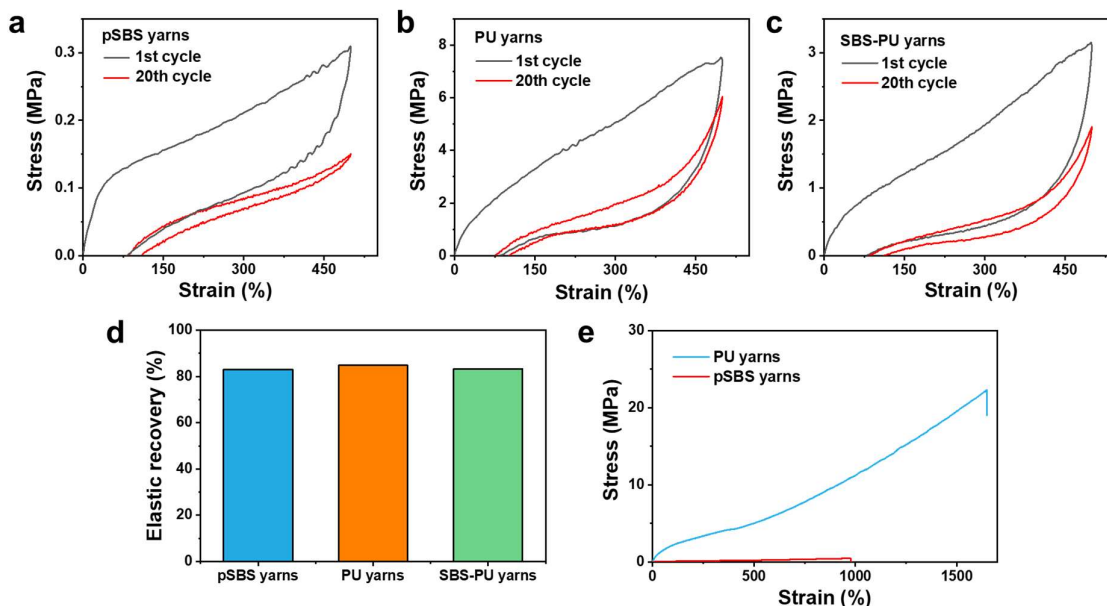


Fig. R3-4. **a** Cycling tensile curves of pSBS yarns at 500% strain (20 cycles). **b** Cycling tensile curves of PU yarns at 500% strain (20 cycles). **c** Cycling tensile curves of SBS-PU yarns at 500% strain (20 cycles). **d** Comparative diagram of elastic recovery of pSBS yarns, PU yarns and SBS-PU yarns after 20 tensile cycles. **e** Stress-strain curves of PU yarns and pSBS yarns.

Q3: Additionally, please examine how the incorporation of Ag NPs affects the mechanical properties of neat SBS fibers in the absence of TPU fibers. What would happen to the mechanical properties of the SBS/Ag NP composite after treatment with liquid metal (LM), again without TPU fibers?

A3: We appreciate the feedback provided by the reviewer. We prepared pure SBS microfiber yarns (pSBS yarns), pure SBS microfiber yarns with Ag-coated (Ag-pSBS yarns), as well as pure SBS microfiber yarns with Ag-coated and LM-absorbing (LM/Ag-pSBS yarns), and compared their mechanical properties (Fig. R3-5a).

The addition of solid or liquid fillers usually affects the mechanical properties of the material¹. With the growth of AgNPs as solid filler, the modulus of the yarn shows a substantial increase from 0.152 MPa to 0.561 MPa, while the strain at break decreases from 976% to 731%. However, after adsorption of LM as liquid filler, the modulus of the yarn has decreased from 0.561 MPa to 0.374 MPa (Fig. R3-5b).

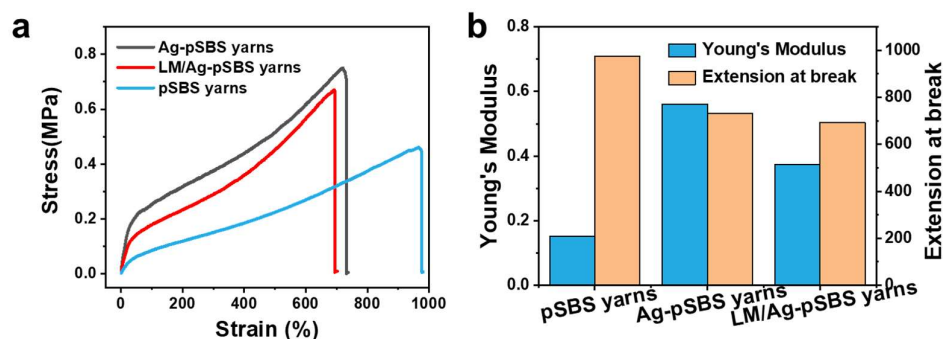


Fig. R3-5. a Stress-strain curves of Ag-pSBS yarns, LM/Ag-pSBS yarns and pSBS yarns. **b** Comparison of extension at break and Elastic modulus of pSBS yarns, Ag-pSBS yarns and LM/Ag-pSBS yarns during stretching.

1. Eristoff, S. et al. Liquid metal + x: a review of multiphase composites containing liquid metal and other (x) fillers. *Adv. Funct. Mater.* **34**, 2309529 (2024).

Q4: Have the authors considered the effect of oxidation on the conductivity of the resulting yarn during cyclic testing? If LM can freely flow inside the three-dimensional channel being discussed, why does it not leak out during the stretching process? Or does the LM solidify due to alloy formation with Ag NPs (in which case, perhaps it comes off the fabric)?

A4-1: Have the authors considered the effect of oxidation on the conductivity of the resulting yarn during cyclic testing?

We appreciate the feedback provided by the reviewer. We compared the state of LM in SLMAS yarns unstretched, after 1 stretching cycle and after 5000 stretching cycles by observing longitudinal cross-section SEM images of the SLMAS yarns. It was clearly found that the surface of the LM in contact with the SBS fibers in the unstretched yarn is completely smooth; after 1 cycle of stretching, the LM surface shows a visible wrinkled structure; and after 5000 cycles of stretching, the wrinkled structure at the interface is still present (Fig. R3-6).

This is attributed to the fact that when the fibers are stretched, the oxide layer formed on the LM surface coated on the fiber surface breaks down and a new oxide layer is formed due to the increase in the total surface area of the LM. Since the oxide layer is much stiffer than the LM, when the stretched fiber relaxes to 0% strain, the LM buckles due to the mechanical competition between the rigid oxide layer on the top and the softer substrate on the bottom. The wrinkled structure formed by the LM oxide layer during cyclic stretching is important for the yarn to maintain stable electrical properties because the strain during stretching is readily released by the extension of the LM wrinkles.

This result is consistent with that previously reported for LM-based conductors (*Adv. Funct. Mater.* 2024, 34, 2308120; *ACS Appl. Mater. Interfaces* 2021, 13, 19254-19262; *Adv. Mater.* 2025, 2417799)¹⁻³. This effect facilitates the long-term stabilization of the electromechanical properties of our yarns, which maintain an essentially constant electrical resistance after 5,000 cycles of high-strain stretching (Fig. R3-7).

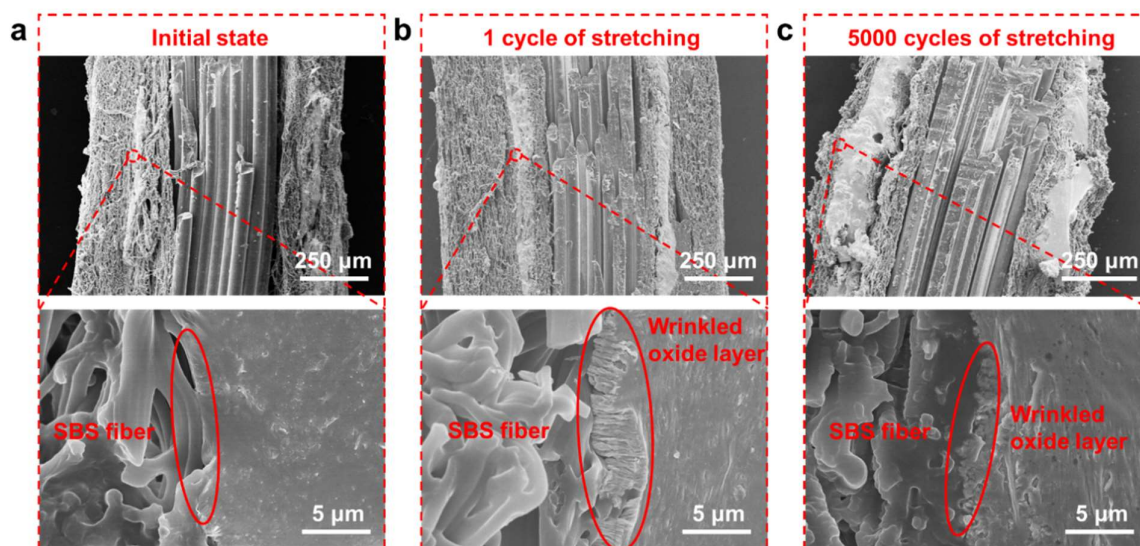


Fig. R3-6. **a** Longitudinal cross-section SEM image of SLMAS yarn in the initial state. **b** Longitudinal cross-section SEM image of SLMAS yarn after 1 stretching cycle (500% strain). **c** Longitudinal cross-section SEM image of SLMAS yarn after 5000 stretching cycles (500% strain).

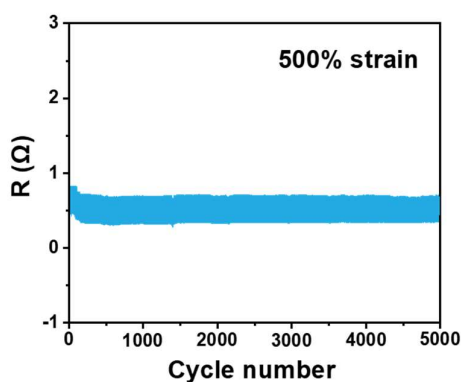


Fig. R3-7. Resistance changes of the SLMAS yarns during the stretching-releasing cycling test.

1. Li, H. et al. Permeable and patternable super-stretchable liquid metal fiber for constructing high-integration-density multifunctional electronic fibers. *Adv. Funct. Mater.* **34**, 2308120 (2024).
2. Zhou, N. et al. A superstretchable and ultrastable liquid metal–elastomer wire for soft electronic devices. *ACS*

Appl. Mater. Interfaces **13**, 19254-19262 (2021).

3. Wang, Q. et al. Stretchable and permeable liquid metal micromeshes featuring strain-insensitive resistance through in situ structural transformations. *Adv. Mater.* 2417799 (2025).

A4-2: If LM can freely flow inside the three-dimensional channel being discussed, why does it not leak out during the stretching process?

The SLMAS yarn provides a robust sealing effect on the LM, preventing leakage even under repeated stretching over an extended period. As shown in Fig. R3-8 a-b, after 5000 tensile cycles, the LM remains completely isolated by the SBS fiber encapsulation layer. This is attributed to the difference between the super-wettability of LM with the Ag-SBS fiber layer and the non-wettability of LM with the encapsulated SBS fiber layer (Fig. R3-9). During stretching, the encapsulant layer compresses the LM, subjecting it to reverse hydrophobic forces due to the non-wettability of the encapsulant. Therefore, as the yarn stretches, the LM flows directionally into the pores of the Ag-SBS fibers under force, effectively preventing leakage (Fig. R3-8c; Fig. R3-10).

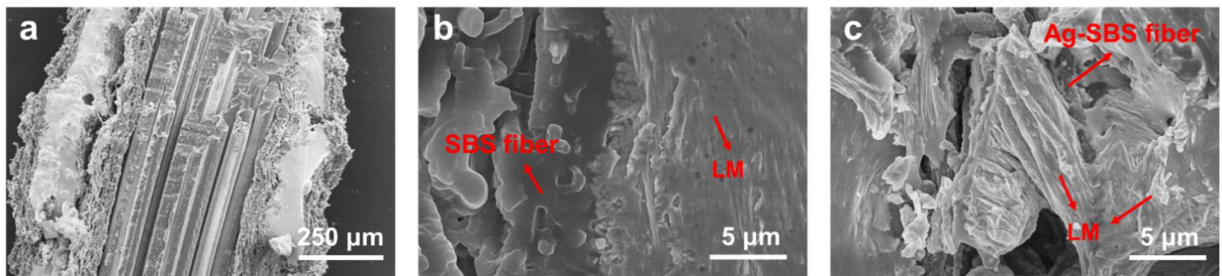


Fig. R3-8. Longitudinal cross-section SEM image of SLMAS yarn after 5000 stretching cycles (500% strain).

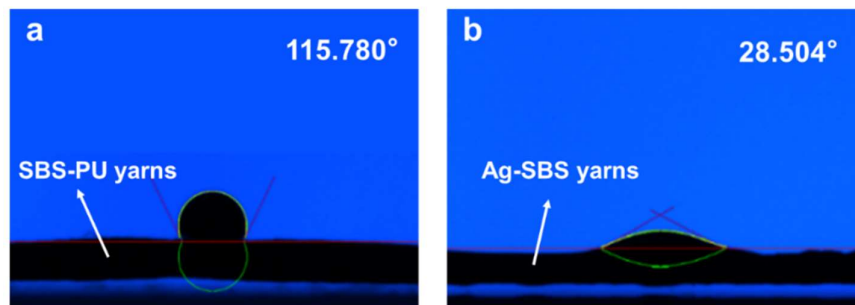


Fig. R3-9. **a** The contact angle between LM and SBS-PU yarns. **b** The contact angle between LM and Ag-SBS yarns.

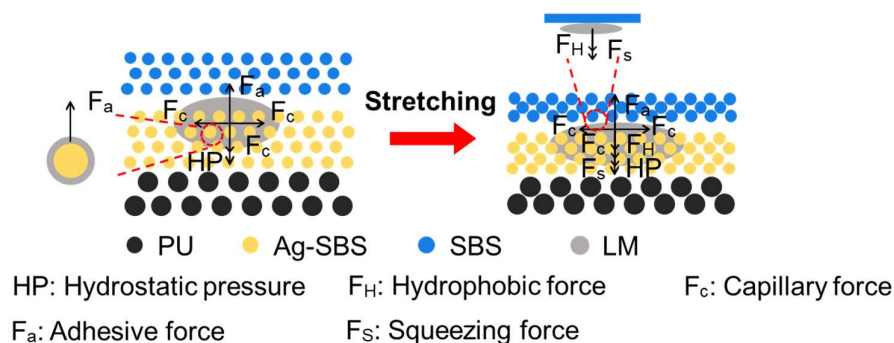


Fig. R3-10. Schematic of the mechanism by which the SBS fiber layer squeezes the LM under stretching, allowing more LM to immerse into the Ag-SBS fiber channel with higher wettability.

A4-3: Or does the LM solidify due to alloy formation with Ag NPs (in which case, perhaps it comes off the fabric)? Compared to the paste or particle form of LM mixed with metal particles, the morphology of LM in our structure is identical to the flow state of pure bulk LM (Fig. R3-8)¹. This is a good indication that LM in our structure does not solidify due to reaction with Ag NPs. In addition, our yarns have extremely strong dynamic adhesion to LM, which remains fully adhered to the Ag-SBS fiber surface after repeated stretching over a long-term cycle and does not detach from the fiber (Fig. R3-8c).

1. Tang, J. et al. Gallium-based liquid metal amalgams: transitional-state metallic mixtures (TransM²ixes) with enhanced and tunable electrical, thermal, and mechanical properties. *ACS Appl. Mater. Interfaces* **9**, 35977-35987 (2017).

At last, we wish to thank the Editor and the Reviewers again for the very constructive comments and suggestions to improve the quality of our manuscript. Thank you very much!

Point-by-Point Response to Review Comments

We sincerely appreciate the pertinent suggestions of reviewers. The quality of the manuscript has been significantly improved following reviewers' comments. All modifications have been highlighted with yellow shading in the revised manuscript.

REVIEWER COMMENTS

To Reviewer 3:

Thank you for addressing the prior concerns.

In regard to the response to question 4, it seems that running multiple cyclic tests should lead to the accumulation of oxide during cycling, which may affect both mechanical and electrical properties in the long term. Is that possible?

We appreciate the feedback provided by the reviewer. The oxide layer spontaneously formed on liquid metal (LM) surfaces at room temperature exhibits self-limiting growth characteristics¹. Functioning as a passivation layer, it effectively suppresses further oxidation of the bulk LM through a mechanism analogous to the protective oxide layer on aluminum². Although not intentionally removed, the ultrathin nature of this oxide layer renders its additional electrical resistance negligible in contact applications³.

As shown in Fig. R3-1, the cyclic strain-induced wrinkled microstructure of the LM surface layer is clearly observed in our structure. The LM surface oxide layer demonstrates a characteristic dynamic rupture-remodeling behavior during initial cyclic stretching processes. Specifically, applied tensile strains induce the rupture of the oxide layer, thereby promoting the formation of a fresh oxide layer on the extended LM surface area. The significant mechanical contrast between the oxide layer (with relatively high hardness) and the substrate (possessing a relatively low modulus) facilitates the development of a stable wrinkled microstructure when the fiber transitions from tensile strain back to its relaxed state. This structural evolution modifies the deformation mechanism of the surface oxide layer, inducing a gradual transition from a stretch-dominated deformation mode to an unfolding-folding dominated mechanical response. Remarkably, the newly generated oxide layer from the altered surface microstructure exerts minimal influence on the electrical properties of bulk LM due to their abundant flowable phases⁴⁻⁶. As a result, this unique structure facilitates the excellent electromechanical stability of our yarns, which maintain essentially unchanged resistance under uninterrupted extreme deformation conditions over long periods of time (continuous high strain cycles in 77.5 h, Fig. R3-2).

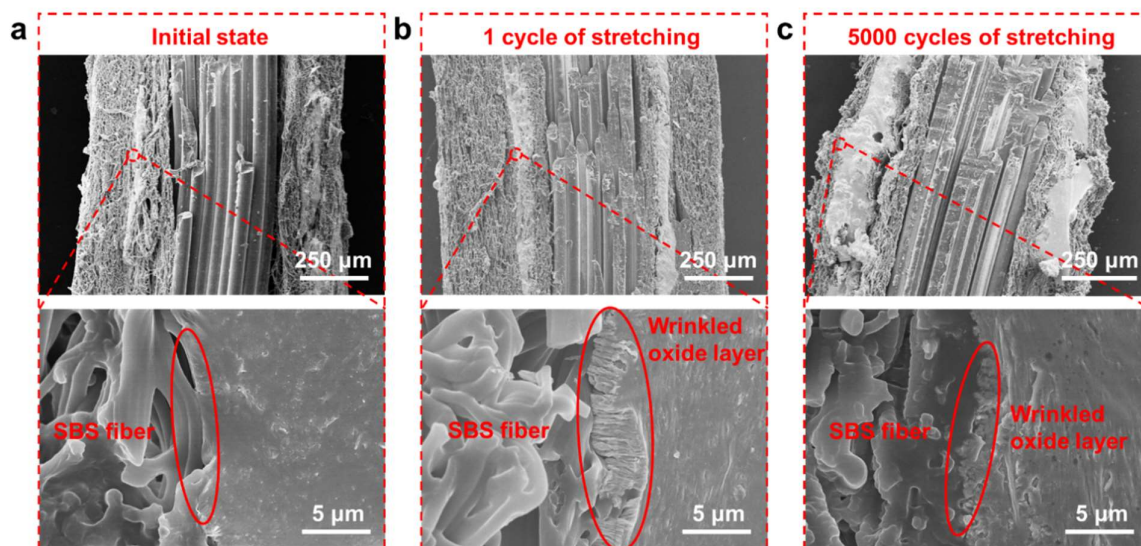


Fig. R3-1. **a** Longitudinal cross-section SEM image of SLMAS yarn in the initial state. **b** Longitudinal cross-section SEM image of SLMAS yarn after 1 stretching cycle (500% strain). **c** Longitudinal cross-section SEM image of SLMAS yarn after 5000 stretching cycles (500% strain).

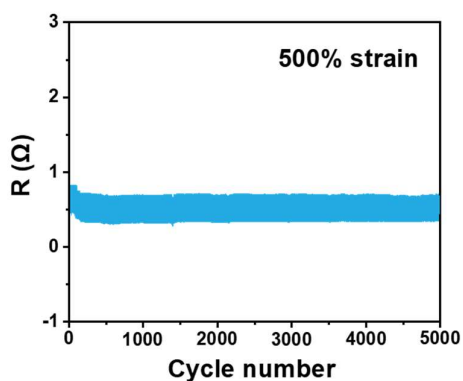


Fig. R3-2. Resistance changes of the SLMAS yarns during the stretching-releasing cycling test (over 77.5 h).

1. Lee, S. et al. Connecting the dots: sintering of liquid metal particles for soft and stretchable conductors. *Chem. Rev.* **125**, 3551–3585 (2025).
2. Yu, R. et al. Dynamic liquid metal-microfiber interlocking enables highly conductive and strain-insensitive metastructured fibers for wearable electronics. *Adv. Mater.* **37**, 2415268 (2025).
3. Wang, M. et al. Stencil printing of liquid metal upon electrospun nanofibers enables high-performance flexible electronics. *ACS Nano* **15**, 19364–19376 (2021).
4. Wang, Q. et al. Stretchable and permeable liquid metal micromeshes featuring strain-insensitive resistance

through in situ structural transformations. *Adv. Mater.* **37**, 2417799 (2025).

5. Ma, Z. et al. Permeable superelastic liquid-metal fibre mat enables biocompatible and monolithic stretchable electronics. *Nat. Mater.* **20**, 859-868 (2021).
6. Cao, J. et al. Ultra-robust stretchable electrode for e-skin: In situ assembly using a nanofiber scaffold and liquid metal to mimic water-to-net interaction. *InfoMat.* **4**, e12302 (2022).

At last, we wish to thank the Editor and the Reviewers again for the very constructive comments and suggestions to improve the quality of our manuscript. Thank you very much!