Progress of MXene-Based Fibers on Wearable Materials: Fabrication to the Functional Demonstration

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Abstract. With the ongoing development of more flexible, functional, user-integrated wearable electronics, MXene materials have attracted interest in their use as next-generation fiber-based systems because of their outstanding electrical conductivity, durability, and adjustable surface characteristics. The incorporation of MXenes in fibrous architecture will be an area of strategic use to address the limitations of traditional conductive fillers, providing much compatibility with textile-form factors in the case of wearable sensors and energy storage fabrics. In this review, a systematic summary of the latest achievements in the production and structural engineering of MXene-based fiber was given, and the methods of fiber production, i.e., electrospinning, wet spinning, and direct ink writing, were especially highlighted. It also investigates the morphological-performance related linkages of these fibers in the realization of high-sensitivity pressure sensors, flexible supercapacitors, and thermoelectric devices. The structure of the functional interfaces and the cooperative mechanisms of mechanical-electrical coupling are critically analyzed in order to clarify structure-function relationships based on the physicochemical characteristics. Moreover, the review also captures the current issues, such as the oxidative stability and infiltration between the interfaces and between polymer resins and manufacturing solutions at scale. Last, but not least, we comment on what seem to be upcoming opportunities in multifunctional smart textiles, i.e., integrated sensing-energy systems, diagnostics based on AI, and earth-friendly manufacturing pathways. Through mapping the state-of-the-art knowledge, the purpose of the review is to expedite the realization and application of MXene-based fibers in any prospective intelligent wearable systems.

Keywords: Ti3CxTx-nanosheets; functional fibers; electrical properties.

1. Introduction

Wearable electronics have also become an essential area of technology that ranges across different fields of use in health monitoring, environmental monitoring, and human-computer interaction among various applications.[1] Such gadgets ensure a smooth process of collecting and using personal data, providing new forms of user-special interaction, real-time control, and self-service. The wearable is continuously transforming even ordinary life situations into becoming adaptive, responsive, and personal in nature via the provision of flexible, effective, and individualized technological interfaces. Tang et al. conducted a systematic review of the design of SCCFs, their fabrication processes, and uses in the areas of possibility to show excellent integration capability in smart textiles and strain sensors. Their paper made an important point that despite the exceptional mechanical compliance and electrical conductivity of these fibers, the long-term stability of performance, especially at repeated deformation and washing events, is a major technical chokepoint that precludes practically feasible wearable applications.[2] Nevertheless, one of the basic problems of developing technology for such devices is the difficulty of transferring sophisticated electronic operations to a flexible, deformable, protective format of user comfort without the loss of performance characteristics. Enabling multifunctionality, e.g., energy storage, signal processing, and sensing, with comfort-hampering mechanical compliance is perhaps a major bottleneck in wearable technology development.[3] Most current wearable systems continue to use hard, heavy, or mechanically fragile components, which, in many circumstances, degrade due to cyclic mechanical loading or cyclic fatigue. This gap between performance and design has spurred much of the development of smart textiles, a new breed of high-performance materials, and is, in essence, the process of transforming conventional comfort materials into multifunctional textiles with structural electronic functionality. Smart textiles are designed to maintain useful properties that are typically characteristic of everyday textiles, including washability, stretchability, and breathability, and add features of the electronic world: conductivity, sensing, or energy harvesting. The integration of conductive materials with the fabric substrate is the key to attaining reproducible functionality of wearables. [4] There are different pros and cons to each category. As an example, carbon-based materials are flexible and have adjustable conductivity; however, due to very high interfacial resistances and lower charge transfer capabilities, they tend to thin gate dielectrics that have low dielectric constants, which are a target for researchers. Metallic fillers have the highest inherent conductivity and are resilient to deformation, mechanically. Conductive polymers are more processable and flexible, but generally do not last long in long-term use. Such shortcomings have spurred the need to develop new materials that are conductive and provide excellent electrical properties, good mechanical durability, and are easily incorporated in fiber systems.

Most recently, MXenes have been identified as one of the most promising candidates in that aspect, providing a combination of high electrical conductivity, mechanical flexibility, hydrophilicity, and the ability to surface functionalize. MXenes are two-dimensional (2D) transition metal carbides, nitrides, or carbonitrates whose structure can have varied forms, and which possess exceptional physicochemical qualities.[5] Maximum conductivity and toughness have been reported in ultracompact MXene fibers produced by thermal drawing of aligned Ti3C2Tx nanosheets by Zhou et al.[6] who remark that the stability of the interface to repeated mechanical strains and washing persists to merit investigation. Their morphology as few-layer nanosheets with a big lateral size and accessible interlayer distance renders a high surface-to-volume ratio that allows for both efficient electron conduction and interaction with polymer and natural fiber matrices. In addition, the plentiful surface terminations (F, OH, O) of MXene flakes provide great chemical reactivity and chemical tuneability, which is not available in other 2D materials like graphene. [7] They have architecture that can be easily exfoliated and form films, and hydrophilic surfaces that can easily be mixed with different textile-forming processes, presenting a potential option to scale up the production of a solution-cast or dip-coated sample to that of an electrospun film. With these positive properties, MXenes are increasingly used to make composite fibers, yarns, and fabrics towards next-generation wearable electronics.[8] Luo et al. have previously fabricated MXene/natural rubber composite fiber via high scale wet-spinning demonstrating the strain dependent electrical conductivity and actually knit into fabrics to achieve a wearable sensing device, but the resulting strain-based electrical conductivity, repetitive washing durability, and potential multifunctional device integration has been observed as a challenge (less relevant to our experiments); still, the current task aims to overcome this concept.[9] Having been discovered in 2011, MXenes have attracted fast popularity in energy storage, hydrogen evolution, EMI shielding, and bioelectronics, which are essential columns of wearable device functionality. As an example, MXenes can be deposited on a variety of substrates- including woven fabrics, polymer films, and nonwovens- to build systems that can monitor health, detect motion, and thermoelectric energy harvesting. Nevertheless, their high rate of development has been associated with severe unsolved problems in obtaining areas of environmental stability, scale-up production, and interfacial robustness, which are essential precedents to actual use of practical application in wearable environments.

The review encompasses the development of the MXene-based target fibers related to the device synthesis and properties, preparation methods, and wearable devices in sensor and electricity-storing goods. With regard to these advances, we attempt to overview the physical properties of MXene-based fibers and electrospinning, wet spinning, and 3D printing techniques used to produce them. Moreover, other application methods of this kind of fiber are also discussed to build wearable supercapacitors, pressure sensors, and energy-harvesting textiles. Finally, we provide the conclusion in terms of issues faced by researchers as well as areas of future development in the scalability, performance, and integration of MXenes-based fibers as a wearable electronic building block. Overall, the recent research on eventually integrating it will undoubtedly facilitate the development of MXene-based multifunctional fibers, and the smart textiles produced by the fibers will certainly bring the potentially disruptive applications of personal health care, environmental perception, energy storage, etc.

2. Structure and Physicochemical Properties of MXenes

2.1 Precursor Engineering and Delamination Techniques

MXene structural tailoring starts with the rational design of its parent MAX phases (commonly Ti3AlC2) with the layered transition metal carbides and nitrides as the precursors. The A-layer (usually Al) is then etched selectively either using chemical etching with hydrofluoric acid (HF) or in situ produced fluoride-based etchants such as LiF /HCl.[10] This reaction gives rise to layered MXene sheets with functional groups of functionalities such as = O, =O, and -F Not only do these functional groups stabilize the flakes in water dispersions, but they also drastically affect their electrochemical activity, rheology, and interactions on surfaces. Recent advances have focused on new etching pathways, which would reduce issues of safety and environmental impact that HF-based chemistry has to date. These are the molten salt etching and the electrochemical exfoliation, which allow narrower control of the terminations of the surfaces as well as the minimization of the dangerous byproducts.[11] These developments have also provided entry into fluoride-free production, increasing the compatibility of processing with the green one. After etching, the form of delamination is a vital point in the generation of processable 2D MXene nanosheets. Values of important physical properties (lateral flake size, thickness, and stability of colloidal dispersion in polar or non-polar solvent) are directly related to the amount of delamination. The engineering of fiber materials. In view of the fiber material engineering, the fabrication of few-layer or monolayer MXenes is especially beneficial. The structures have large surface-to-volume ratios and adjustable aspect ratios and are therefore suitable for solution-processable methods like wet spinning, inkjet printing, or spray coating. Furthermore, thoughtful variation of delamination conditions also makes it possible to control edge defect level and maintain in-plane conductivity, thus making it possible to rationally design MXene-based fiber systems with improved electrochemical, mechanical, and sensing properties.[12] Ostermann et al. described a pulsed electrochemical exfoliation approach that used $NaBF_4$/HCl electrolytes and pulse cathodic potential to exfoliate Ti_3C_2Tx MXene into few-layer flakes with lateral conductivity but without the wrapping hazards of HF; they did note, however, that producing flakes with consistent thickness and scaling of processes to reasonable come-ups are problems yet to be solved.[13] These types of structure-property relationships highlight the key importance of precursor engineering and exfoliation routes to the path to the large-scale manufacture of MXene integrated smart fibers.

2.2 Fiber Formation Techniques: Morphology–Performance Correlation

Transforming two-dimensional (2D) MXene nanosheets into one-dimensional (1D) or quasi-1D fibrous structures is the essential step forward in their application within wearable electronics.[6] The fabrication method is vital to the morphology of the fiber and its physical strength, as well as its functions. Out of these techniques, the technique of wet spinning shines as it is a scalable technique and can be used with aqueous MXene solutions. Depending on the exact settings of parameters, including jet velocity, coagulation bath compositions, and tension after drawing, highly aligned fibers with straight conductive pathways can be manufactured. The electrospinning technique may also be used as another general method with the addition of MXenes to polymer matrices, e.g., polyvinyl alcohol (PVA) or polyacrylonitrile (PAN).[14] It allows submicron fibres with precisely controlled porosity and hierarchical surface textures, of great value in sensors and interfacial energy devices, to be made. Zhang et al. described the creation of additive-free MXene liquid crystals to provide fiberization by the wet-spinning of highly aligned fibres based on the nematic ordering and shear-induced flake orientation. The resulting fibres were highly conductive and had perfect internal alignment, but the authors pointed out that pushing this to diameters 100 times smaller (submicron scale), with tunable porosity useful in multifunctional textile applications, represents a major step forward, which our study seeks to bridge.[15] Precise geometric architecture control can be achieved through DIW-based three-dimensional (3D) printing of MXene inks, whereas biscrolling can exploit the 3D structure through 3D interactions of novel supercoiled yarns with excellent stretchability and high mechanical resilience. The key information about the structure aids in the discussion of the relationship between structure and functionality as it relates to the orientation of MXene flakes on the fiber matrix. In this way, it still represents the critical approach to enhancing the multifunctional capabilities of MXene-based wearable textiles to adjust the morphological anisotropy. [16]

2.3 Biomaterial Integration: Natural Polymer–MXene Hybrids

Biomimetic applications of MXenes with natural biopolymers present a path to synthesise environmentally friendly, biocompatible, and near-ideal performance composite structures based on fibres. Together with MXenes, silk fibroin provides a mechanical scaffold as well as a hydrogen-bonding network and facilitates homogeneous dispersion and improved toughness.[17] The resulting silk-MXene hybrids gain enhanced strain resistance, cytocompatibility, and humidity-dependent conductivity and would be very well-suited to implantable or dermal bioelectronics. On the same note, nanocellulose, not only in the form of cellulose nanofibers (CNFs) and cellulose nanocrystals (CNCs), also offers high mechanical strength, easily modifiable surface chemistry, and exceptional breathability, which creates a green matrix. Xu et al. developed MXene/nanocellulose composite aerogels, fabricated via bidirectional freezing to produce biomimetic porous textures with outstanding conductivity and elasticity; nevertheless, they found that yarn-format fibre spinning from these aerogels with controlled porosity and scalability remains an open challenge.[18] The synergetic effects of Young modulus, conductivity, and stretchability are predicted by the effects of electrostatic and hydrogen-bonding occurrences of nanocellulose with MXenes. [19] In addition, the presence of these natural matrices prevents colloidal instability and oxidative degradation of MXene colloids and makes it possible to use aqueous, low-temperature processing paths. This minimises energy input and production of toxic byproducts immensely. In combination, natural polymer-MXene composites can be considered promising bio-integrated sensors, triboelectric nanogenerators, and smart fibres triggered by humidity.

2.4 Post-Treatment and Structural Reinforcement Techniques

Divalent ions (e.g., Ca2+, Mg2+) or polyelectrolytes (e.g., PDDA) are commonly used chemicals to crosslink the sheets of MXene and enhance the mechanical properties (e.g., strength) and ionic conductivity under aqueous and humid conditions.[20] Further modulus and electronic conductivity are also achieved by processes of structural densification, which include vacuum-assisted filtration and thermal compaction. Insertion of nanometric interlayers between layers can prevent van der Waals collapse without a loss of charge mobility by treating them in a layer-by-layer (LbL) scheme, wherein each layer is contacted sequentially. In addition, mild oxidation or heteroatom doping (e.g., N, S) reactions can be achieved by surface treatments to form active sites that can be employed in electrochemistry or sensing applications (e.g., photonic/microwave irradiation). Such problems can be prevented by mechanical reinforcement of the core by a process known as 'core shell' or by coaxial spinning or by gradient fibre design, and more dramatically by mechanical failure due to cyclic stress.[21] Furthermore, interfacial adhesion is enhanced by micro- and nano-patterning of surfaces (e.g., laser ablation, plasma etching) as well as enlarging surface area to form functional integration. All these post-treatment methodologies have increased the usefulness and dependability of MXene-fibre systems in various wearable use cases.

3. Electrical and Mechanical Performance of MXene-Based Fibers

3.1 Hierarchical Structure–Conductivity Coupling

The greater specific area of sheets and intrinsic layered structure allows the fibres of MXene to find their advantage in high electrical conductivity. Perfect layering and face-to-face stacking of these two-dimensional flakes yield continuous charge localization channels, essentially inhibiting the associated interfacial resistance and resulting in conductivities significantly exceeding 104 S/m, which have become commonplace upon lithography-based two-dimensional corralling between a set of electrodes with ultrathin atomic layer deposition (ALD) films.[6] The process is well explained in Figure 1, where the dynamic sol-gel spinning process with the help of calcium ions can orderly create Ti_3C_2Teln MXene nanosheets in a fibre body that continuously transports the electrons due to layer-by-layer alignment and face-on-face stacks.[22] As soon as the ideal dry-state network has been created, the factor that will determine the fate of wearable electronics will be reliability under operational conditions. Physisorbed water layers make a layer-by-layer proton transporter, rearranging the electronic (sigma e) to ionic (sigma i) conductance ratio and sometimes deteriorating total sigma by more than 15% at 90 % RH.[23] Retention of the performance is thus a fine balance between interflake spacing, terminations on the flake surface (-OH, -F), and encapsulation layers of stretchable elastomers or PVA matrix water-impervious barriers. The atomistic simulations show that tunneling barriers of <0.3 eV are reduced by hydrogen bonding in donor-acceptor pairs of adjacent -OH groups when the distance is <1 nm, and van der Waals forces prevail in charge-hopping in that range of 1-2 nm. Together, the design principles of a hierarchy that are described in this section build the electronic baseline on which mechanical durability and ecological long-term stability will be judged.

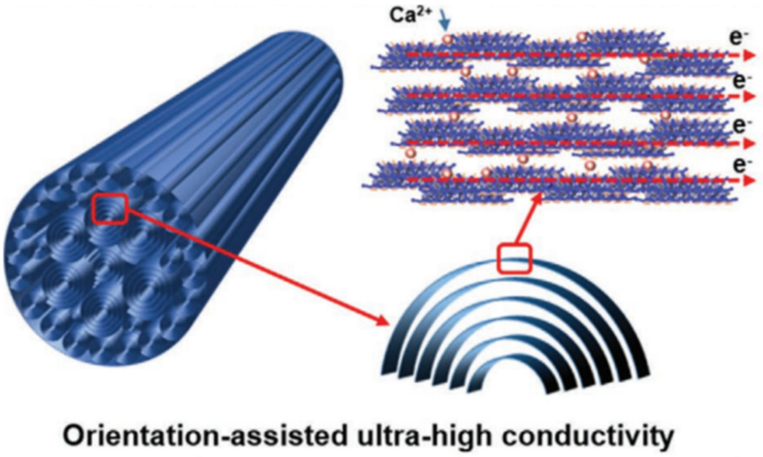

Figure 1. Orientation-assisted assembly enables ultrahigh conductivity.[22]

3.2 Mechanical Robustness: Strength, Toughness, and Flexibility

The interaction between the mechanical compliance of the surrounding matrix and interlayer bonding is a synergetic process that determines the mechanical integrity of fibres in which MXene is used as a base. Although extremely clean, MXene sheets are naturally conductive in nature; however, they are highly likely to fracture brittlely because of the presence of crystalline covalent bonds in-plane and the relatively weak interlayer forces, which arise due to the van der Waals forces. Of interest is the ability to dramatically enhance toughness and flexibility by embedding these flakes in ductile polymeric or biopolymeric matrices (e.g., silk fibroin or polyurethane) to exploit non-covalent interaction (e.g., hydrogen bonding, electrostatic attraction) to bond hard inorganic flakes to a continuous soft phase. Such a design approach has led to composites with strain-at-break exceeding 30 % in addition to electrical conductivity of around 10^3–10^4 S m^{-1}.[24] A demonstration of such a strategy, along with the microstructural outcome, may be observed in Figure 2, in which MXene-silk fibroin composites were formed through the wet-spinning behavior, and their cross-sectional morphology could be predicted.[25] Yu et al. give one such example, where MXene was combined with silk fibroin by wet spinning and hierarchical interfacial engineering, resulting in high stretchability (> 30%), mechanical toughness, and electrical properties simultaneously. Although such short-term measures sound impressive, making such composites transferable into practical, wearable devices demands a careful assessment of the long-term capabilities of fatigue and environmental stability, an aspect yet to be investigated in the context of current publications. [26] In addition to matrix choice, the performance entirely within the mechanical field can also be fine-tuned by regulating the aspect ratio of MXene flakes, in-plane orientation, and also the chemistry termination of said surfaces. Geometries such as very long flakes with a high aspect ratio maximise the ability to transfer stress through the conductive network, and surface terminations that maximise interfacial adhesion maximise a load-bearing capacity. To complement the effects of pre-treatments such as interfacial bonding, post-processing such as thermal annealing and ionic crosslinking (e.g., crosslinking via Ca^{2+}-mediated bridging) enhances cohesion between the interface area, further reducing the likelihood of a crack initiation and propagation against cyclic loading. These structural reinforcements are not optional in systems of wearable materials that are subjected to repetitive tensile or bending deformation and cycles of laundering and other mechanical loads. The durability considerations provide a vital transition into the next argument of environmental stability and longevity operation, where building a combination of mechanical and environmental design intervention in MXene-based fiber systems is necessary.

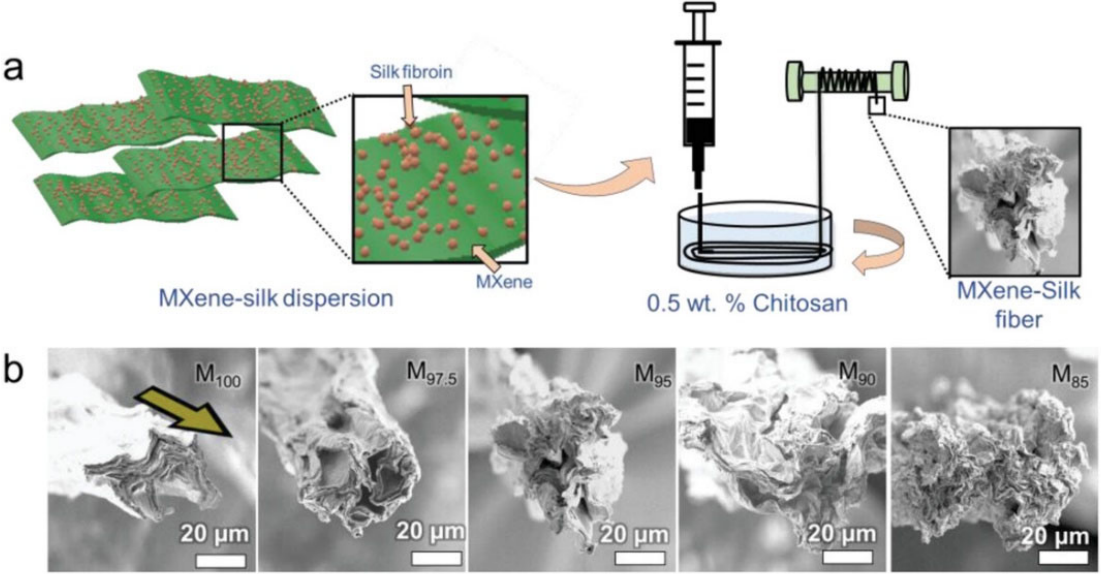

Figure 2. Process of making the MXene-silk fibroin composite fibers and structure. a) Wet-spinning process scheme, where both the coagulation of Dispersion of MXene and silk and the coagulation of chitosan are presented. b) Different samples SEM cross-section images of various possibilities of different MXense values, changes in fiber structure, and tight packing can be observed. [25]

3.3 Strain–Conductivity Coupling and Electromechanical Stability

The vibrancy of strain-sensing is founded on the piezoresistive characteristics of the MXene-based fibre. The structural tension of the stressing (stretch or bend) destroys the conduction network percolating between them, and the sensitivity to the mechanical change in resistance can be engineered reliably using a microstructural design combining predefined microcrack arrays, serpentine topologies, or helical coils.[27] Though such motifs are beneficial gauged with respect to the gauge factor, long-term electromechanical fidelity after repeated deformations is also of prime concern. Recently, Taymaz et al. incorporated wet-spun MXene fibres into carbon-fibre-reinforced polymer (CFRP) laminates, showing stable resistance measurements under repeated tensile testing and low-velocity impact, making the case that MXene conductors support structural-health monitoring. An example of such behaviour is shown in Figure 3, which shows normalised signal profiles of parallel MXene-based fibre sensors under cyclic mechanical loading, showing consistent electromechanical response across the multiple directions of loading. [30]However, this research did not investigate failure mechanisms of the MXene-polymer interface, especially the ones that are caused by out-of-plane shearing or other elastomeric coatings, a fact that has restricted our insights into long-term durability.[28] However, that experiment did not investigate failure mechanisms at the MXene-polymer interphase, namely those caused by out-of-plane shear or extra elastomeric coverings over the MXene, an oversight that has hindered our knowledge of long-term stability. [28] Later observations have shown that over time, fatigue-induced delamination or cracking at the interface between heterogeneous surface materials may continuously reduce signal amplitude, adjust the baseline, and thus reduce sensor precision. Stress mitigation tactics are dedicated to dispelling interfacial stress and repairing conductive ways. Adding soft thermoplastic polyurethane (TPU) sections or elastic polymer over coatings has also become useful in accommodating local stress concentration and maintaining network integrity at >10 bending or tensile cycles.[29] Electrical monitoring in situ links the regain of conductivity to the reversible reformation of hydrogen-bonded junctions and to elastic recoil of the encapsulating matrix. MXene fibre sensors have gauge factors up to ~5 (serpentine patterns, e < 5%) and edge to 10^3 (microcracked films, e~ 50%) at response times below 50 ms, and can display minimal hysteresis after 5000 cycles, depending on architecture and strain regime. These kinds of performance measures fulfil the demands of human-motion tracking, physiological tracking, and interactive clothing. The other bottleneck is combining the high-gauge-factor sensitivity and environmental robustness, and this will be discussed in the next subsection dealing with multifunctional encapsulation and long-term operation stability.

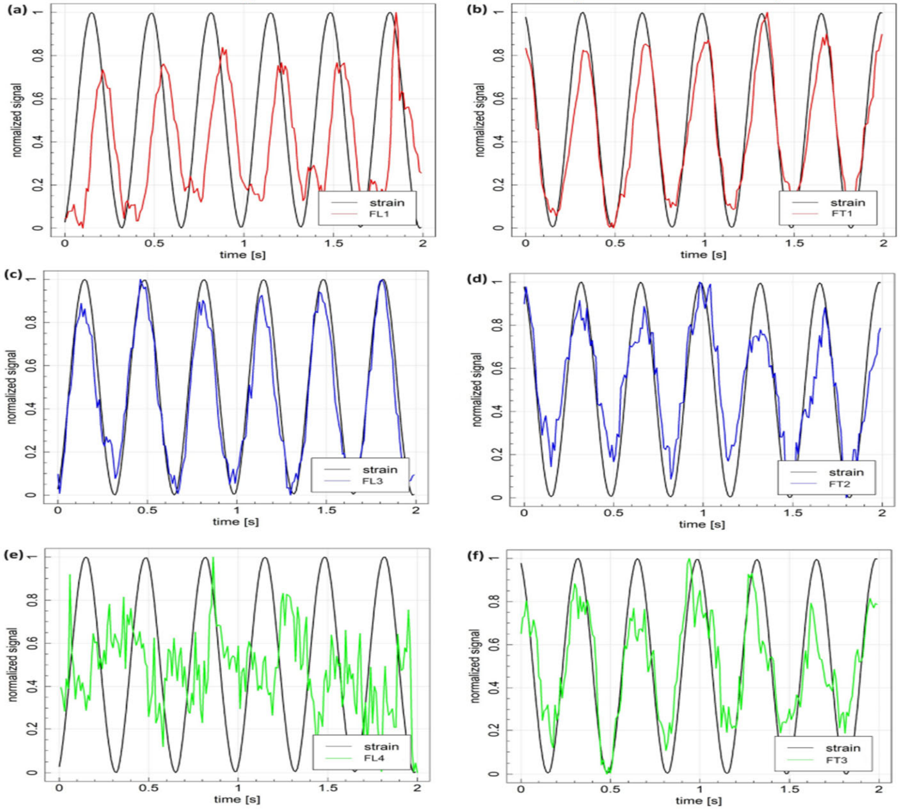

Figure 3. The results of the normalized resistance of the MXene fiber sensors in the case of cyclic deformation are demonstrated in this figure. A, c, e) show the profile in the case when these fibers are aligned with the loading direction, and b, d, f) show the case when these fibers are aligned perpendicularly to the loading direction. In all the configurations, resistance deviations follow a strain cycle-by-cycle application pattern.[28]

3.4 Thermal and Environmental Stability of MXene Fibers

Thermal management and chemical passivation are complementary properties required in order to reliably deploy MXene-based fibres in wearable electronics. Extended oxidising conditions of oxygen, water vapour, or ultraviolet light favour the formation of oxidising defects, thus deteriorating the electrical conductivity as well as the lattice. Inhibition of these pathways has also been achieved by the adoption of multi-layer passivation architectures that include hydrophobic polymer over-jackets, atomic-layer-deposited (ALD) oxide nanofilms, or self-limiting surface oxidation that produces protective oxide-rich skins of TiO_2. [30] In applications when the highest temperatures need to be reached, such as thermoelectric devices and wearable heaters, the anisotropic thermal conductivity of MXene fibres should be maximised through alignment of the flakes along the fibre. It is also possible to use multilayered coatings to improve exposure stress, such as washing, sweating, and mechanical loading. [31] Circuit studies in aged MXene fibre composite show that it can retain more than 90 percent of its original conductivity even after 1000 stretching and washing procedures, and has proven its sustainability in industrial operations. Jeong et al. designed twisted MXene heating wires, produced by a nature-inspired co-twisting of conductive MXene fibres and support yarns, further encapsulated by a polymer matrix, which greatly enhanced oxidation resistance and mechanical strength, allowing stable operation even in humid (99 percent RH) atmospheres with temperatures up to 80 ° C, over 12,000 bends. Figure 6 shows that such twisted MXene heating wires are stable in their performance over environmental and operational stresses, with demonstration of reliability in electrothermal behaviour under cyclic loading, humidity, and thermal ageing conditions.[31] Though their research was not done systematically enough to quantify the effect of flake alignment or the incorporation of phase-change fillers, directional heat transfer, or thermal ageing over time, these effects will be further researched in our experiments.[32]

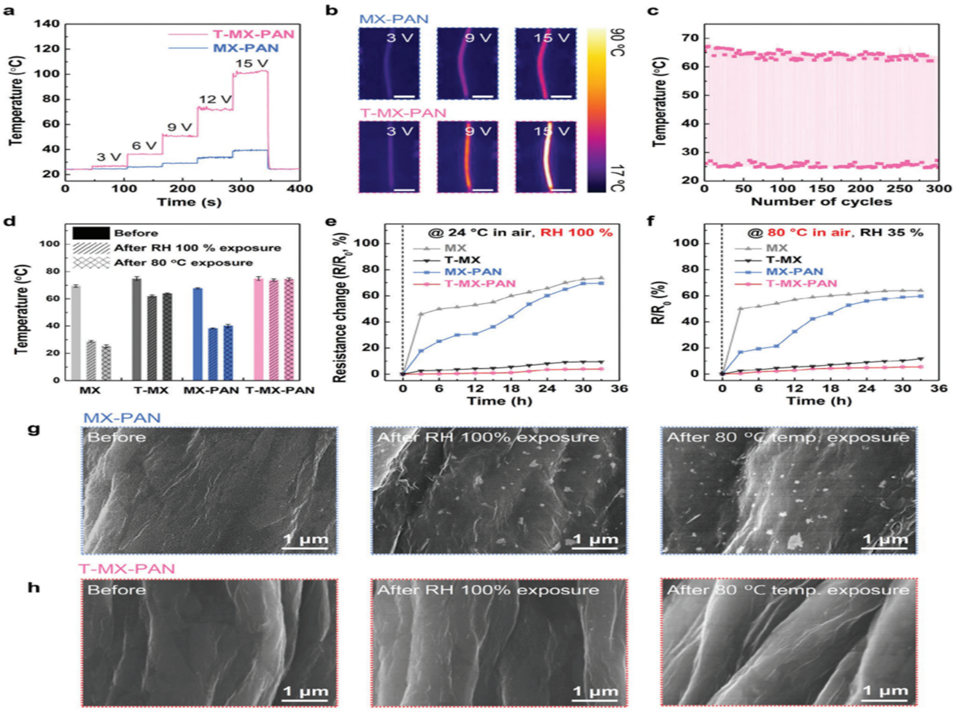

Figure 4. Electrothermal and environmentally stressed behavior of T-MX-PAN heating fibers. (a, b) Temperature versus time and (c) IR thermal camera imaging at various voltages. Long-term stability of more than 300 repeated heating cycles. Effects of heat and humidity aging on varied fiber formulations (d), changes in relative resistance during environmental aging (e f), as well as SEM images of surface morphology before and after long-term exposure to high temperatures in a high-humidity environment (g and h).[31]

4. Applications of MXene-Based Fibers

4.1 Smart Wearable Sensing Systems: From Strain to Biosignals

High-conductivity, compliant, tunable surface chemistry makes MXene-based fibres quite popular in next-generation wearable sensing system modalities. As strain sensors embedded in the material, these fibres provide piezoresistive or capacitive measurement of small levels of mechanical deformation. As an example, a Ti_3C_2Tx-based MXene textile with porous elastomeric containers features high gauge linearity, fast response characteristics, and cycling stability, as well as being suitable for implementing in the monitoring of body movements, joint bending, or breathing in real-time. [31] According to Xu and colleagues, adding CNT and Ti_3C_2Tx to PDMS using a composite film manufacturing process allowed the sensors to be capable of more than 1,000 repetitive mechanical cycles, long-term stability over a range of temperatures (-20°C up to 80°C), and ultrasonic washability. Yet, their work did not touch on multimodal response capacities and on embedding biofunctional sensing elements, something our research intends to follow through with synergistic coupling with biochemical detection systems.[33] At the biosensing scales, MXene fibres also present chemically active surfaces capable of immobilising biomolecules and detecting glucose, lactate, or cortisol in sweat.[34] Conductive polymers or carbon nanotubes can be used to make hybrid MXene sensors more biocompatible and mechanically compliant, and can add signal transmission. These attributes cause them to become potential candidate for health-monitoring processes and early disease diagnostics. Also, MXene fibres can be sensitised to environmental factors like humidity and temperature based on the hydrophilic functional groups and their thermosensitive natures, allowing assessment of microclimate states within wearable materials. Moreover, e-textiles that are based on MXene are used in the human-machine interface (HMI), which provides more haptic feedback, as well as gesture recognition. Future breakthroughs would consist of multimodal sensing arrays, wireless signal collection, and inclusion of AI in data analysis of autonomous health systems.

4.2 Fiber-Based Energy Storage and Harvesting Architectures

The applications of MXene fibres in the production of flexible energy storage systems. They have a high areal capacitance and energy density on account of their intrinsic metallic conductivity and redox-active surfaces. Wet-spinning or biscrolling has formed a fibrous architecture, which keeps conductivity when strained and under bend, a key factor in wearable electronics.[35] MXene fibres tend to be combined with pseudocapacitive materials such as polyaniline, MoS_2, or conducting polymers in supercapacitors in order to increase the energy density and cycle life. When lithium-ion is being intercalated and transported in the fibre-based batteries, interlayer spacing and a high number of defect loci on the MXene anode enhance the lithium-ion migration throughout the interlayer events and hence boost the performance of the battery. In addition, thermoelectric MXene fibers use the same principle of the Seebeck effect to turn thermal differences into electricity. In combination with carbon nanotubes or elastomeric matrices, these fibres show sag skin-contactible stretch and effective transduction with thermal energy to electrical energy. Beyond this, co-integrating energy harvesting and energy storage on a common fiber platform will make self-powered wearable systems a reality.

4.3 EMI Shielding and Photothermal Regulation for Electronic Textiles

The spread of wearable electronics has led to the need for sophisticated materials in electromagnetic interference (EMI) shielding. MXene-based textiles have demonstrated effective EMI attenuation (through reflection and absorption) as a result of the properties of 2D conductive layers and controllable dielectric properties. The conductive assemblies made of fibrous MXene have tunable shielding effectiveness by manipulating fibre orientation, porosity, and topography. Hierarchical engineering of porous surfaces on MXene-coated textiles allowed generating EMI shielding efficiencies as high as 42 dB (in the X-band) and rapid photothermal response (204300c under sunlight), as confirmed by Liu et al. Nevertheless, the nature of the influence of controlled fiber orientation and porosity in facilitating GHz-range shielding performance to more than 50 dB was not systematically studied, and this was the path our research traversed through aligned-assembly techniques. Indicatively, MXene-polymer composite fibres are aligned, and thus, the shielding effectiveness is well above 50 dB at GHz regimes, applicable to any economic standards of electronic protection. At the same time, MXenes show excellent photothermal conversion with infrared and visible light owing to combined broadband absorption and localized plasmon resonance. Wearable textiles utilise this capability to thermoregulate by acting passively and providing self-warming and dynamic comfort over a range of temperatures. The two functionalities of EMI shielding and photothermal modulation serve to underline the capabilities of MXene fibers in multifunctional smart wearables.

5. Conclusion

MXene-derived fibers are a promising interplay and fusion of 2D materials and precision textile-based benefits, which provide an all-encompassing compendium, useful in the sector of versatile applications in the area of flexible electronics, energy storage, biosensing, and human-machine interfacing. They make possible multifunctional and adaptive systems, owing to their high electrical conductivity, programmable mechanical behavior, and excitability, as well as functionalization of their surfaces. Nonetheless, in spite of great efforts, there are several challenges that still inhibit their presentations as a mass deployment of smart textiles in the real world. At the material level, they still remain compromised in the long run by intrinsic instability, especially in the form of oxidation in ambient or humid conditions. The use of conventional synthesis methods that use risk-hazardous etchants poses safety concerns as well as problems of inconsistency batch to batch and inability to scale. On the structural and fabrication scale, the inability to have controlled alignment of flakes, uneven dispersion, and reproducible fiber production hinders the integration of MXenes on a textile manufacturing scale. From the device's point of view, the interface between hydrophilic MXenes and hydrophobic polymer matrices has been identified as a potential problem in terms of efficiency of interfacial adhesion, mechanical integrity, and establishment of effective percolation networks. Another area, application-related requirements such as skin compatibility, washability, and long-term comfort, has been decently covered, and as such, these products cannot be easily translated into user-centric wearable systems. In the future, MXene-based fibers have to go beyond component-level optimization and should be designed to become system-level intelligent. Such a transition will not only entail materials innovations, but also healthy interfacing with wireless communications MACs, energy-harvesting systems, and data-processing devices. Multidisciplinary work will be required to exploit the full potential of materials science, electronic engineering, textile technology, and computational modeling as intersecting disciplines to enable fully integrated, AI-supported, and (functionally) autonomous textile platforms. Finally, the emergence of scalable fabrication processes, widespread performance testing guidelines, and human-centered design models will make a decisive contribution and help to overcome the gap between demonstrations in the laboratory and real commercial practice. By cooperating in innovation to address such multiscale bottlenecks, MXene-based fibers have the potential to form the heart of technologies in the future generation of intelligent, adaptive, sustainable e-textiles.

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