textiles

MDPI

Review

Temperature-Dependent Shape-Memory Textiles: Physical Principles and Applications

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Abstract: Textiles have been pivotal to economies and social relationships throughout history. In today's world, there is an unprecedented demand for smart materials. The advent of smart textile fabrics, crafted from high-quality, high-performance fibers, has enabled the incorporation of specific functions into clothing and apparel brands. Notably, the rise of smart fabrics is evident in astronaut suits designed to regulate temperature and control muscle vibrations. Moreover, the scope of these products has expanded beyond everyday wear, encompassing fields such as medicine and healthcare, ecology/environmental protection, and military and aerospace. This review explores the recent advancements and challenges associated with intelligent fabrics, particularly temperature-dependent shape-memory metamaterials. The potential for innovative smart textile materials to enhance traditional fabrics' overall functionality and utility is immense, especially in domains such as medical devices, fashion, entertainment, and defense. Crucially, ensuring user comfort is a primary consideration in these applications for promoting the widespread adoption of wearable devices. Developing smart textile devices necessitates a multidisciplinary approach that combines circuit design expertise, knowledge of smart materials, proficiency in microelectronics, and a deep understanding of chemistry and textile production. The synergy across these diverse fields is vital to unlocking the full potential of smart fabrics and enabling their broad implementation. By embracing this comprehensive approach, we can pave the way for groundbreaking advances in smart textile technology, driving innovation and progress in the field.

Keywords: smart fabrics; textiles; applications

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1. Introduction

Different authors have extensively studied shape-memory materials (SMMs) [1–8]. They are called intelligent or smart materials due to their ability to respond dynamically to external stimuli. These external stimuli can be temperature, pressure, humidity, or electricity. If the material is responsive to different input stimuli and if this response is repeatable, it can be considered a "very smart" material [9,10]. Figure 1 shows a schematic representation of different shape-memory alloys used for various purposes such as automotive applications (sensors and actuators), aerospace applications (hydraulic lines, actuators, structural connectors, and vibration dampers, among others), robotic applications (microactuators or artificial muscles), and biomedical applications (high corrosion resistance, biocompatibility, and non-magnetic functions, among others).

Shape-memory materials (SMMs) can recall their original shape after undergoing deformation, making them highly responsive to stimuli. Specifically, these materials exhibit significant structural changes beyond a specific transition temperature when considering the temperature. This phenomenon is referred to as the thermally induced shape-memory effect. In the case of SMMs, heating them triggers a restoration of their original structure

once they have been permanently deformed. The shape-memory effect can be stimulated by various physical factors such as environmental conditions, mechanical forces, magnetic fields, and thermal changes.

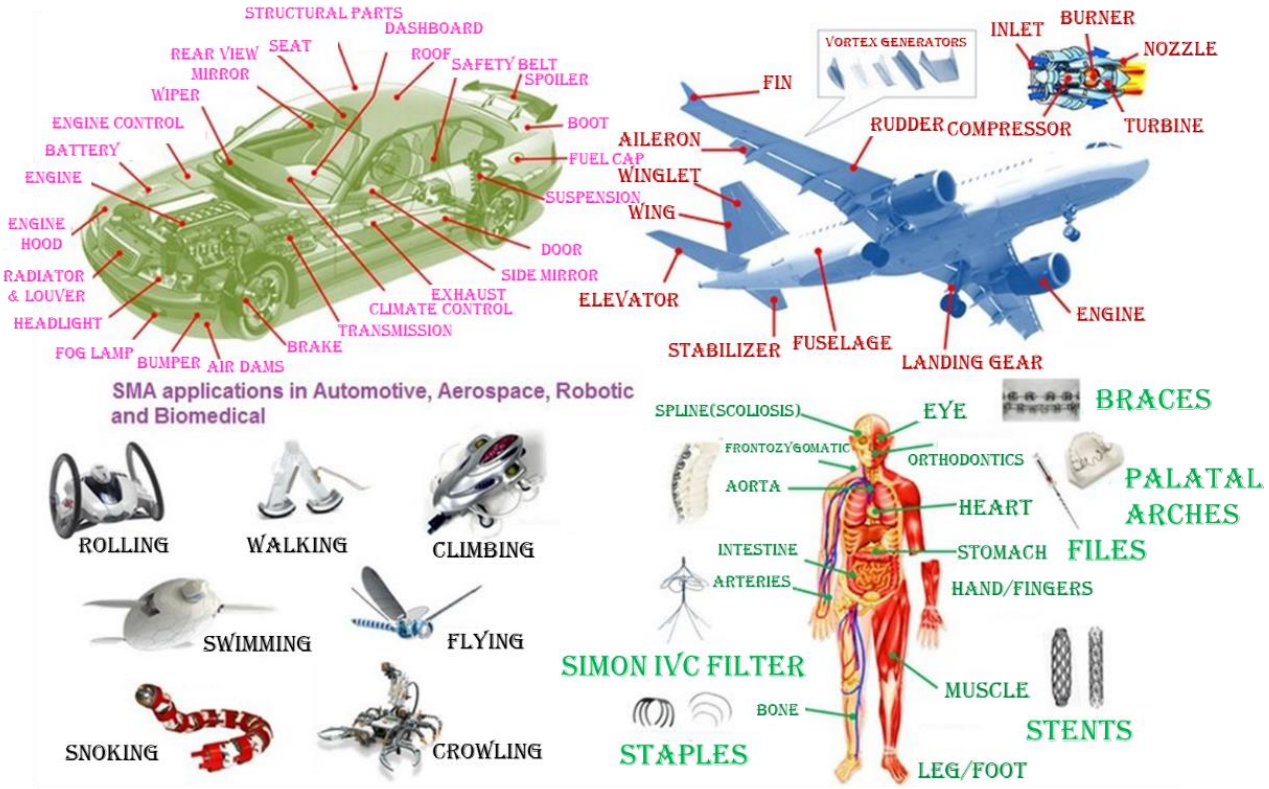

Figure 1. Some examples of smart-material alloys. The figure was taken with the kind permission of reference [11]. In addition, the letter sizes were modified, aiming to better visualize the content.

Consequently, SMMs can be tailored to achieve desired characteristics, including predefined shapes, positions, strains, stiffness levels, natural frequencies, damping properties, frictional behaviors, and other static and dynamic material traits. This unique behavior of shape-memory materials opens up exciting possibilities for their application in a wide range of fields. By harnessing their stimuli-responsive nature, engineers and researchers can develop innovative solutions that leverage the inherent capabilities of shape-memory materials to create adaptive structures and functional devices [9–12].

Usually, shape-memory materials are developed for the biomedical and engineering industries [10,12]. However, some studies can be found regarding their application in the textile industry. An example is the t-shirt created by the Corpo Nove fashion house in Florence. According to the developers, "even if the fabric is screwed up into a ball, pleated, and creased, a blast from a hairdryer pops it back to its former shape". The fibers contain nitinol interspersed with nylon. The cost (USD 3750) and the only color available (metallic gray) appeared to satisfy customers [13]. Another example is a membrane called Diaplex, which is discussed in [14]. This product has two-layer lamination with 10–20,000 mm of waterproofing and 10–30,000 g of moisture permeability. Its other excellent properties such as its elasticity (200%), texture, durability, wind resistance, thermal insulation, and water repellency were highlighted. Its activation point (which is freely settable) was 0 °C. At lower temperatures, it has high thermal insulation, while at higher temperatures, it has a higher vapor permeability.

Figure 2 shows some shape-memory polymers, gels, and ceramics. All of these smart materials follow the same physical principle as the one applied to the shape-memory alloys.

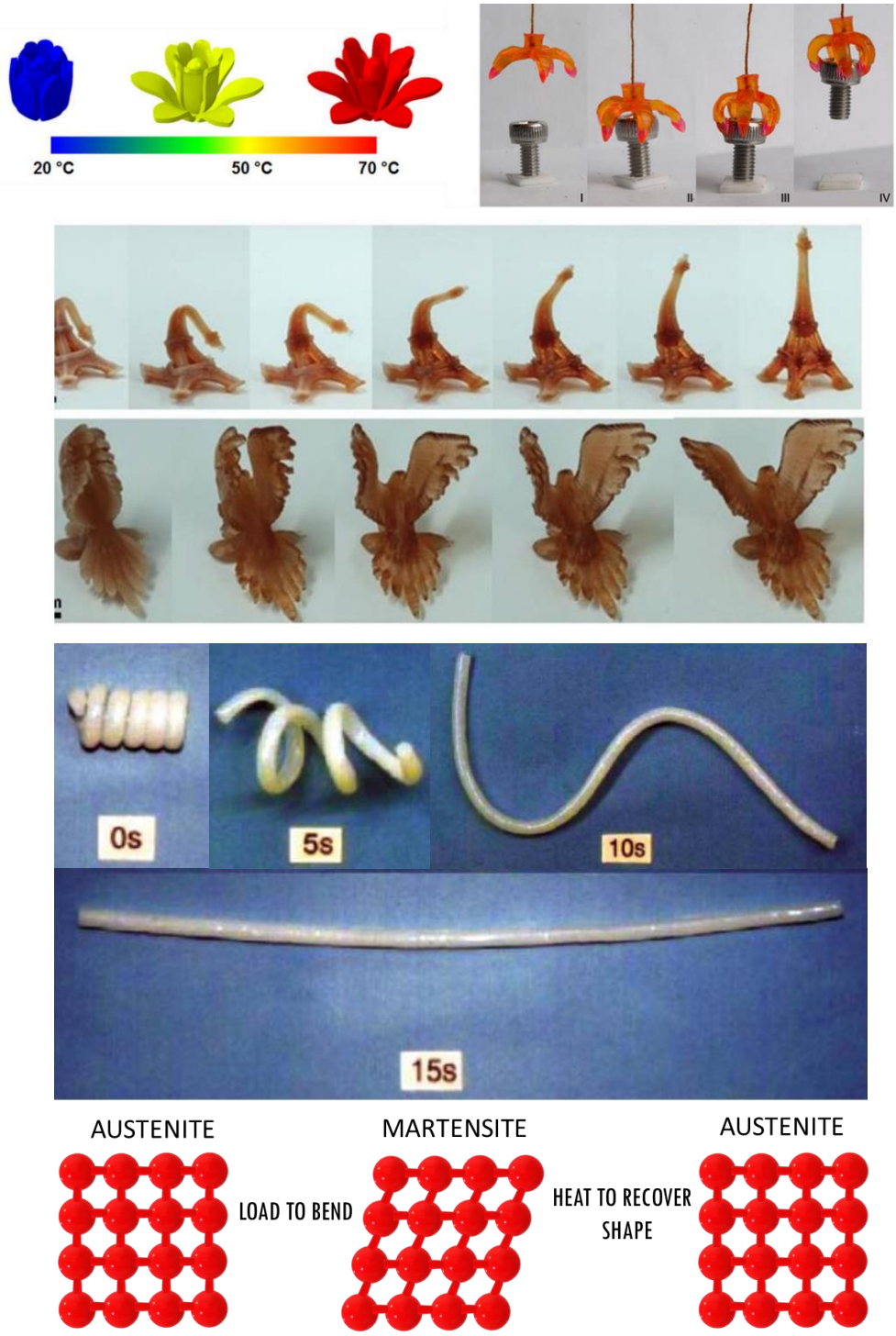

Figure 2. Some examples of smart-material polymers and gels. The figure was taken from the internet [15] and with the kind permission of [16]. The austenite transformation to martensite was based on reference [17]. The figures represent changes in the shape format by some external stimulus, usually temperature at given time.

Despite its importance, its primary use for the textile industry is to enhance performance and functionality, which increases the cost of the final product and limits the number of customers interested. However, as with any other "new product", the price can initially be inaccessible for most customers, but it tends to normalize or at least be more accessible to the users.

The same fiber and fabric fabrication techniques can be used to manufacture shape-memory polymer textiles for biomedical applications. In addition, spinning methods, including electrospinning, wet spinning, melt spinning, weaving, weft knitting, sewing, and embroidery, allow for the production of smart-textile fabrics [18,19].

2. Brief History

The concept of the memory effect in shape-memory materials can be traced back to 1932, when Ölander first observed it in an Au47.5Cd alloy [20]. The author noted a rubber-like behavior associated with the aging of martensite. According to Ölander, if the material was deformed in the martensite state, it would recover its original shape upon heating, indicating a reverse martensitic transformation. However, it was observed that the material did not exhibit this effect upon cooling, failing to return to its initial state.

In 1950, the observation of martensites with twinned lamellar structures in different alloys shed light on their distinct behavior during cooling. This resulted in less localized work against the parent phase and a semi-coherent interface [21]. Subsequently, in 1951, Chang and Read provided a crystallographic explanation for the rubber-like behavior of martensite in AuCd [22]. They applied an external shearing force to banded martensite from a single AuCd crystal, causing the twin layers to align in the same direction or the opposite direction based on the applied shear. Upon heating, the deformation was found to revert, which marked the origin of the shape-memory effect. Figure 3 provides a schematic representation of the martensitic transformation under different conditions. These early discoveries laid the foundation for understanding and further exploring the fascinating properties of shape-memory materials, paving the way for advancements in the field.

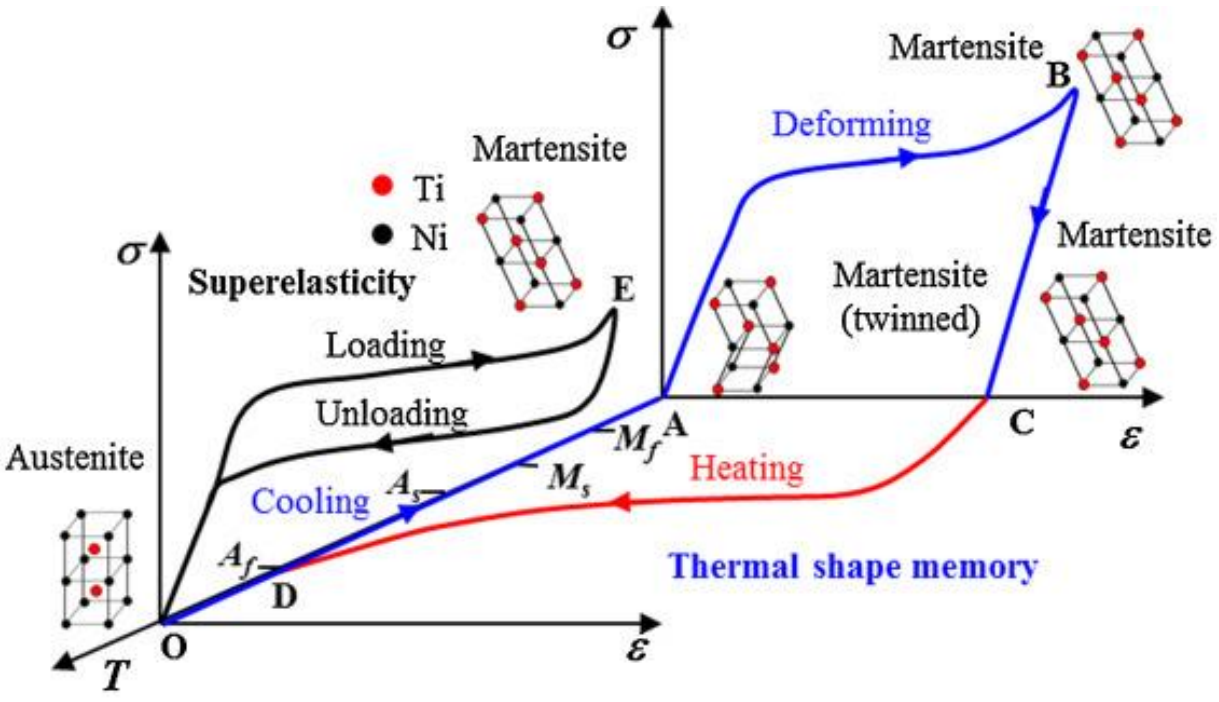

Figure 3. Martensitic representation under different conditions. The image was obtained with the kind permission of [23].

The same crystallographic behavior was observed in 1953 by InTl [24], and in 1954, the shape-memory effect was observed in CuZn [25]. In 1957, the shape-memory effect was observed by Chen [26] in CuAlNi, while in 1958, the first shape-memory effect heat engine was created when an AuCd crystal lifted a suspended weight by changing the temperature [27]. Finally, in 1961, Muldawer and Feder [28] patented an AuAgCd alloy with a shape-memory effect on an electrical switch for the first time. In the late 1950s,

studies regarding NiTi were conducted. Due to its unique behavior, new crystallographic processes were elaborated, and the Naval Ordnance Laboratory (NOL), after rigorous and persistent studies, elaborated an engineering NiTi alloy called NITINOL (nickel plus titanium plus NOL). The NOL group, headed by Buehler, and the team coined the term shape memory. Much development and science have occurred since then. More details about the origin of the shape-memory effect can be found in [24].

3. Physical Principles

Understanding the behavior of shape-memory textiles is essential for comprehending the temperature-dependent shape changes in polymeric materials [28]. Unlike shape-memory alloys (SMAs), shape-memory polymers (SMPs) significantly transition from a rigid polymer state to a highly flexible one. This transformation can be repeated countless times without polymer degradation as the material passes through its transition temperature. The "memory" of the original shape is derived from the stored mechanical energy and the reconfiguration that occurs during the cooling stages of the polymer.

It is important to note that a single polymer chain alone cannot exhibit a shape-memory effect as it is not an inherent property of the chain itself. Instead, the shape-memory effect arises from combining the overall polymer structure, its morphology, and the applied processing techniques. At a macroscopic level, a thermally induced shape-memory effect is attributed to interconnected networks of polymer chains which define the material's permanent shape. These networks exhibit a thermal transition, such as a glass transition or a crystallization point, within which the shape-memory effect is triggered. The temporary shape can be stabilized through these transition regions, which are known as switching segments. The ability to deform from the permanent form to the temporary shape and recover the permanent body can be attributed to the entropy elasticity at the molecular scale [4,28,29]. Figure 4 provides a schematic representation of the shape-memory effect in polymers. By understanding the underlying mechanisms and properties of shape-memory textiles, researchers and engineers can further develop and harness the unique capabilities of shape-memory polymers for various applications in fields such as biomedical devices, robotics, and smart textiles.

The transition can occur considering any of the following transitions: T_m or T_g. Melting points (T_m) are preferred because their transition is sharper than glass transitions (as can be visualized in Figure 5A), and so the temperature at which the shape recovery takes place is better defined. Thus, a reasonable way to produce polymers with shape-memory properties is through the preparation of networks containing crystallizable polymer chains. The crystallinity can be due to crystalline polymer chains or side-chain crystallization. If T_g is considered the transition temperature, some consideration must be taken regarding the physical behavior of the polymer in the glassy and transition states. In the glassy state, segmental movement does not exist. Only local motions can occur, and they do not contribute to the backbone's movement and, consequently, to changes in physical behavior. If enough thermal energy is given to the backbone, the reptation movement significantly dissipates the energy as heat [2,28]. Upon specific thermal activation, when enough molecular mobility is considered, there is an increase in the free volume among the polymeric chains in a short time interval, leading to an abrupt decay of the modulus (approximately three to four orders of magnitude). Different conformational states can be achieved without significant disentanglement for the same energy state in the elastomeric plateau. Except for polymers with nematic isotropic transitions [30], most of the polymers will be presented as disoriented amorphous chains, where the energy distribution is similar (entropically favored). In the elastic state, when an external force is applied, the molecules will stretch in the direction of the applied force. The entanglement of the chains prevents a significant movement; consequently, the sample returns to its original state when the stress is released. This kind of memory effect is promoted by recovering the polymer chains in their original state. All chains tend to return to their original length but are sometimes restricted by the viscous component and "new" entanglements [31–33].

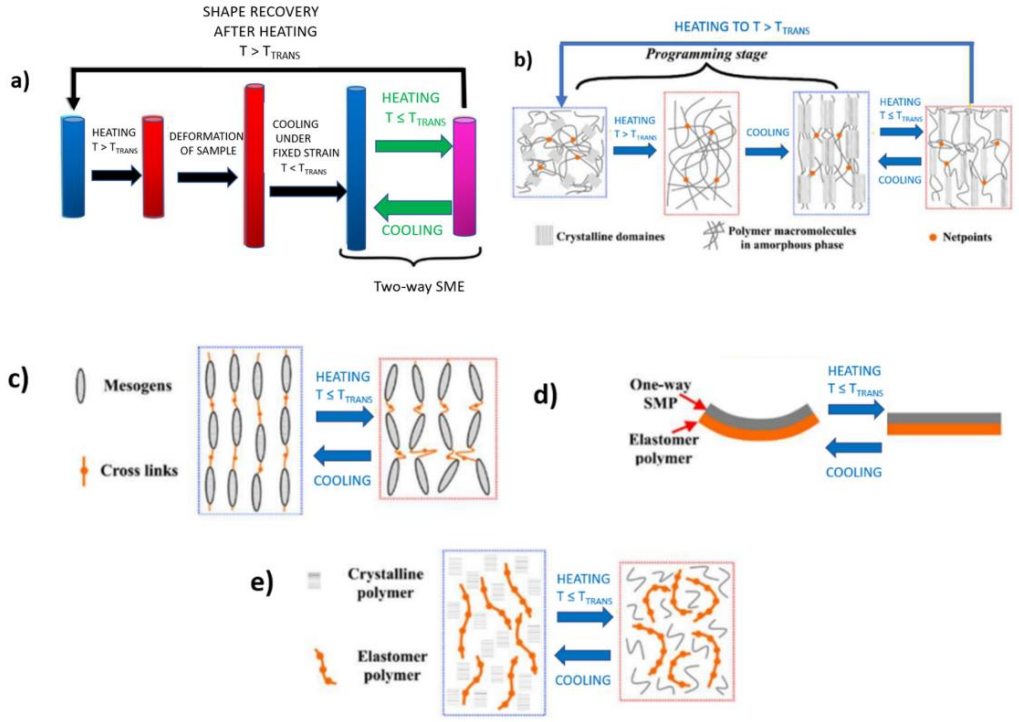

Figure 4. Two-way shape-memory effect in SMPs at the macroscopic level (**a**) and at the structural level for: (**b**) semi-crystalline polymers, (**c**) liquid crystalline elastomers (LCEs), (**d**) multi-layered polymer composites, and (**e**) interpenetrating polymers. The legend was maintained to be the same as it was in the original study, and the image was taken under the common creative license term [28]. In addition, the picture and the letter size were modified, aiming to better visualize the content.

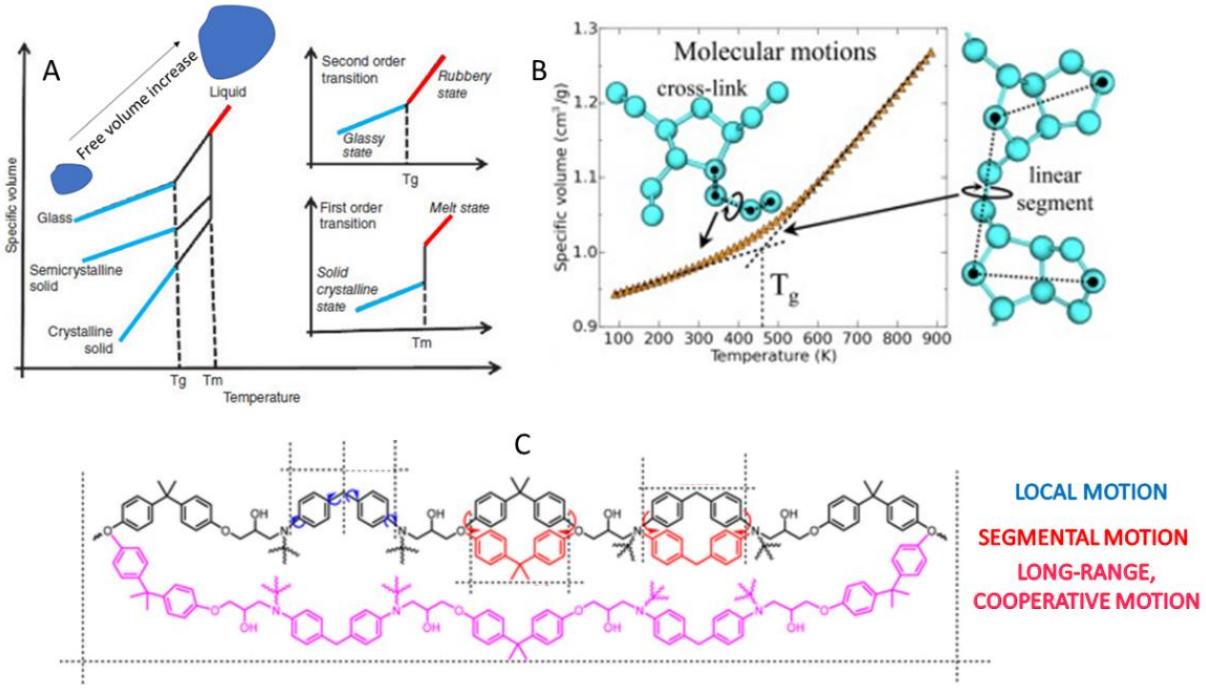

Figure 5. (**A**) Specific volume vs. temperature representing T_g and T_m. (**B**) Difference in the molecular motions before and after the glass transition temperature. (**C**) Example of local, segmental, and long-range motion for an epoxy resin. Figure 5A was based on reference [31]. Figure 5B,C were based on [34,35] and were used with the kind permission of the publisher. Figure 33c was slightly altered for better visualization.

The recovery effect is well-known in the rheology of polymers, as demonstrated in Figure 6. According to the figure, as stress is applied to an undeformed polymer, the polymer chains tend to align in the direction of the applied stress. If stress is removed and the polymer is in the elastic regime, the "memory" generated returns the initial configuration. In molecular terms, when stressed, the molecules gain specific stored energy, allowing the chains to return to their initial state. However, in most cases, the viscous component impedes the return in its totality, i.e., some small portions of different backbones "touch each other", which increases the local viscosity and, consequently, requires more energy than the given stress would require to return to the original state. For polymers, this contact is also known as the micro-Brownian motion, where an interdiffusion among the molecules occurs. In addition, distinct conformational states can be available as the molecules can be presented in different configurational states for the same energy level [36–38]. This "lack" of energy does not occur in shape-memory polymers because their programmable memory allows the chains to return to the original position without any significant "entanglement" effect that dissipates some energy portion. Another exciting feature is that the memory effect for SMPs appears to "memorize" some path for the amorphous chains while for non-SMPs, the polymeric chains can attain distinct configurational states for the same energy level, and for SMPs, only a limited number of configurational states are possible. This would be why the material deforms and returns to the same original condition.

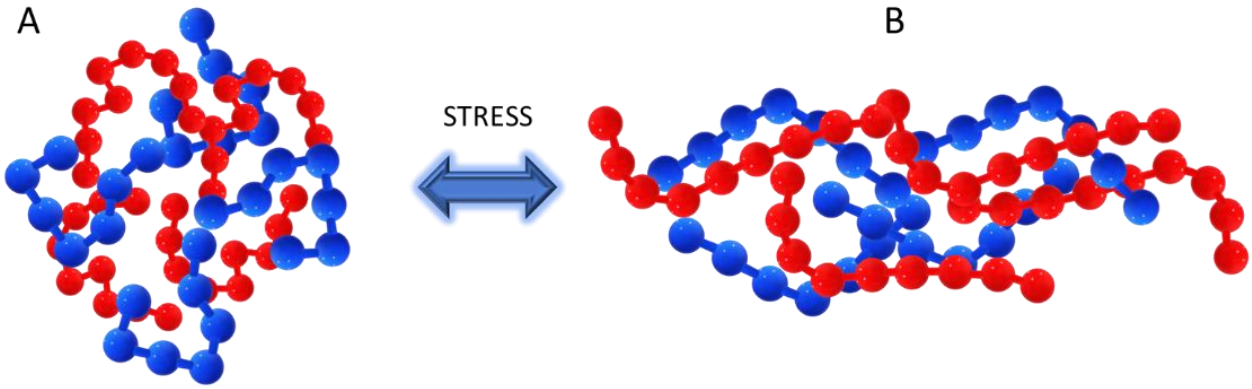

Figure 6. The molecular motion under stress. Different colors were used to facilitate the visualization.(**A**) represents the molecular chains without stress while (**B**) represents the molecules stretched to the strain direction.

The working mechanism of shape-memory polymers relies on the specific type of polymer employed, and these can be categorized as either thermoplastic or thermoset polymers. Physical crosslinking occurs in the amorphous region of thermoplastic polymers, and a similar mechanism occurs in semicrystalline block copolymers. On the other hand, in thermoset polymers, the crosslinking is chemical, analogous to what is observed in semicrystalline rubbers.

4. Manufacturing Processes and Treatments

The manufacturing processes for shape-memory textiles build upon traditional textile production methods. Shape-memory textiles can be created using shape-memory fibers [39]. The fundamental principle involves modifying the shape-memory properties of the polymer by adjusting the composition of the soft and hard components in the polymer's main backbone. Polyurethane (PU) is extensively utilized in this context due to its versatile properties, which are achieved by incorporating various monomers in different ratios [40–42]. Most of these manufacturing methods employ spinning techniques, where a polymer solution is extruded through a spinneret under the influence of external forces, forming stretched fibers that solidify through drying or solidification processes [43]. These methods

include melt-spinning, electrospinning, wet spinning, ring spinning, and friction spinning. Although the techniques may vary, the underlying principle remains the same: the polymer solution or melt is transformed into yarn, which is subsequently used to produce textile fabrics or nonwoven materials [44–50].

Weaving, weft knitting, sewing, and embroidery are techniques that produce textile fabrics for the integration of thin wires into the textile fabric. Dyer has produced dynamic shape-memory textiles by inserting small-diameter wire shape-memory alloys [51]. In this case, the integration occurs at the yarn level. Different studies have been reported in the literature using NiTi wires on PU filaments [52], shape-memory alloys for protective clothing [53], and SMA wires into knitted fabrics to enable new design aesthetics for apparel [54].

Some finishing treatments and coatings include shape-memory polyurethane solutions with high strength retention and zero formaldehyde content. The combination of this solution with liquid ammonia and dimethyloldihydroxylethyleneurea was also successfully studied [55]. Fabrics coated with shape-memory polymers can respond to temperatures that are often warmer than ambient conditions, including laundering and raised body temperatures during exercise, thus helping to better remove creases and wrinkles, with no detrimental losses to their strength and durability. Other applications of SMP-treated fabrics include windproof, waterproof, and breathable fabrics. If combined with shape-memory alloys, other products such as trousers, leggings, jumpers, curtains, and blinds can be obtained [31,56,57].

Some additive manufacturing processes for futuristic technologies are mainly based on 4D printing [58]. When a 3D printing structure is modified into another system by an external stimulus, it generates a 4D printing material. Both techniques are similar, but 4D printing technology allows the production of more adaptable infrastructure in the future, as in the medical field. Pieri [59] and Nadgorny et al. [60] demonstrated several polymers and nanocomposites with distinct 3D responsive characteristics using the materials' fundamental properties, chemistries, and physics. Azam et al. [61] showed self-folding capsules fabricated with a biodegradable PCL using lithography to produce precision geometries such as shapes, sizes, and porosities. Two-dimensional templates were created using the lithography of SU-8, a biocompatible, epoxy-based polymer, as well as hinges made from PCL. Heat activated the PCL hinges to fold the capsule itself. They encapsulated beads, chemical dyes, mammalian cells, and bacteria, demonstrating their diversity for uses such as drug delivery, "micro-Petri dishes", or even pseudo-vesicles or lysosomes. Malachowski et al. [62] created heat-responsive drug-eluting devices comprised of a multi-fingered gripper. The gripper successfully grabbed tissues and could be loaded with drugs and dyes. The group then demonstrated the enhanced release of doxorubicin compared to a control patch and released dye in a pig's stomach. the experimental success suggested to the authors that their technology could be used for sustained-release drug delivery. Another biomedical aspect that has been demonstrated is use in medical devices. A stent was developed and shown as a proof of concept by Bodaghi et al. [63] using a polyjet printer and a UV-crosslinked liquid photopolymer that expanded upon heat exposure. Ge et al. [64] created a stent using high-resolution micro-stereolithography and photo-curable methyl methacrylate. Both authors used models to predict the stents' behaviors. Four-dimensional-printed SMPs have also been used to create cell scaffolds. Senatov et al. [65] printed a PLA/HA scaffold, studied the effect of programming temperature on stresses formed during compression deformation, and demonstrated MSC survival on a 3D printed scaffold. However, the shape-memory effect was not utilized during the cell study. Hendrikson et al. [66] explained that 4D-printed SMP devices could be applied to clinical scaffolds as long as the cells were attached and viable after recovering the sample.

5. Shape-Memory Textiles

SMPs are the most commonly used materials for textiles and clothing compared to shape-memory alloys. This is due to the ability to mold these related materials to enable properties suitable for thermally insulating fabrics, breathable materials, shoes, and finishing to avoid creases and shrinkage. The manufacturing processes include finishing, coating, laminating, blending, and others.

Some polymers suitable for textile applications are presented in Table 1.

Table 1. Polymers used for textiles. The data in the table were obtained from [31].

Polymers	Physical Interactions	
	Transient Shape	**Original Shape**
Polynonbornene entanglement	Glassy state	Chain
Polyurethane	Glassy state	Microcrystal
Polyethylene/nylon-6 graft copolymer	Microcrystal	Crosslinking
Styrene-1,4-butadiene block copolymer	Microcrystal/glassy state of poly(1,4-butadiene)	Microcrystal/glassy state of polystyrene
Ethylene oxide-ethylene terephthalate block copolymer	Microcrystal of PEO	Microcrystal of PET
Poly (methylene-1,3-cyclopentane) polyethylene block copolymer	Glassy state/microcrystal of PMCP	Microcrystal of PE

The potential use of shape-memory polymers for textiles is attributed to their (i) functional properties, (ii) property change due to phase transformation, and (iii) suitability for outdoor, casual, and sportswear.

(i) Functional properties: It is well-known that some physical properties are significantly altered when a polymer passes through T_g. The volume expansivity, for example, has a constant slope below T_g and another constant (and higher) slope above T_g. This occurs due to the fast increase in the main backbone in a short time interval, increasing the free volume among the chains and, consequently, expanding this volume. Water vapor permeability is a more specific application for textiles where moisture is required at higher temperatures and avoided at lower temperatures. This characteristic is excellent for sportswear, where the clothing detects a higher body temperature and the coating responds accordingly, enabling the clothing to become more comfortable. If the temperature drops, the heat is maintained inside by "closing" the pores or approximating the fibers. The polymer must have the characteristics required for such a purpose. For example, if the humidity level is the triggering element, its potential use in hygiene products such as diapers, training pants, and incontinence products is visualized.

(ii) Property changes due to phase transformation: Significant changes in some properties, such as elastic modulus and hardness, are directly related to crystal structure changes at specific temperatures. Sutures are one application that exploits these changes in temporary and permanent shapes. It is known that keyhole surgery is complicated, and if a smart shape-memory suture that ties itself into a perfect knot is applied, many drawbacks are eliminated. MenemoScience developed a self-knotting suture where a slight body temperature increase was able to be detected. Moreover, the suture could seal complex wounds where access was limited. Following this principle, other applications are expected, such as its use in army uniforms, camping materials, artificial leathers, temperature sensors, and artificial blood vessels, among others.

(iii) Outdoor, casual, and sportswear: The change in physical properties when a material goes through a transition temperature makes SMPs' potential use in garments a valid application, mainly for when such a textile creases. The original state would be recovered by washing the textile at higher temperatures. In contrast, the original

wrinkles would be retrieved by immersing the fabric in water. Following this principle, multilayer fabrics for adaptable protective clothing or leisurewear features could be developed. This would guarantee protection from wind and weather, dissipate perspiration, and enable excellent stretch and recovery properties. In addition, the fibers could respond to external stimuli in a predetermined manner, making them valuable for sportswear.

Pearson et al. [67] conducted a comprehensive study on polyurethane composites with alumina, aramid, and poly(p-phenylene-2,6-benzobisoxazole), focusing on thermal, thermomechanical, and dynamic mechanical analyses. The results revealed a significant reduction of 37% in the linear expansion coefficient and an impressive increase in the storage modulus (97%) and thermal stability when incorporating 1 wt% of poly(p-phenylene-2,6-benzobisoxazole) into the composite. Niue et al. [68] investigated the use of Zylon fibers for structural reinforcement in high-field magnet coils exposed to visible light. Remarkably, their findings demonstrated no loss of mechanical strength even after 8 years of exposure to UV radiation. Peng et al. [69] developed a Zylon/epoxy composite and evaluated its fatigue behavior under quasi-static tensile and tensile fatigue loads. The fatigue curves exhibited distinct stages, which conventional distribution models successfully described.

The stability and mechanical properties of shape-memory polymers (SMPs) are crucial in their practical applications. The shape programming process involves several steps, including shape deformation, shape fixing, and the release of external stress. Another significant step is the deformation of the material under external stress accompanied by heat, wherein the polymer is maintained at the desired temporary shape even at elevated temperatures. Subsequently, the temperature is lowered while maintaining the external stress, obtaining the temporary unaltered shape once the external stress is removed. SMPs have found wide-ranging applications in areas such as 4D printing, aerospace engineering, biomedical devices, flexible electronics, shape-memory alloys, and soft robotics. They can respond to various external stimuli, including microwaves, chemicals, electricity, magnetism, light radiation, and water [70].

6. Today's Applications for Different Uses

Shape-shifting sutures were presented in a previous study [71]. These shape-memory sutures knotted themselves when exposed to heat. This material allowed for the sealing of hard-to-reach wounds. Figure 7 represents part of the study by the authors where the self-tightening capability and knot security were verified by differences in pressure.

A new shape-memory material for smart textiles and medical textiles was developed by Cera et al. [72]. The fabric used keratin, a fibrous protein in hair, nails, and shells, extracted from Agora wool left over from textile manufacturing. The material was a bioinspired and hierarchically structured shape-memory material. Shape-memory polymeric materials lack long-range molecular order, enabling more controlled and efficient actuation mechanisms. According to the authors, "Here, we develop a hierarchically structured keratin-based system with long-range molecular order and shape-memory properties in response to hydration. We explore the metastable reconfiguration of the keratin secondary structure, the transition from α-helix to β-sheet, as an actuation mechanism to design a high-strength shape-memory material biocompatible and processable through fiber spinning and three-dimensional (3D) printing. We extract keratin protofibrils from animal hair and subject them to shear stress to induce their self-organization into a nematic phase, which recapitulates the native hierarchical organization of the protein." This self-assembly process could be tuned to create materials with the desired anisotropic structuring and responsiveness. The combination of bottom-up assembly and top-down manufacturing would allow for the scalable fabrication of strong and hierarchically structured shape-memory fibers and 3D-printed scaffolds with potential applications in bioengineering and smart textiles. Figure 8 represents the study completed by the authors.

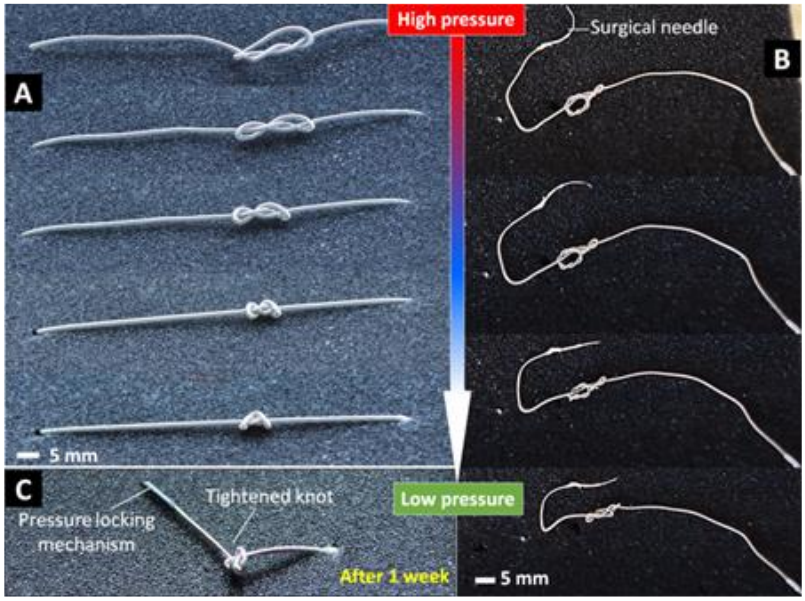

Figure 7. Self-tightening capability and knot security of the S2 suture knot. (**A**) A prototype (OD1.49 × L070 mm) was pressurized to 100% elongation and tied in a loose knot with both ends fixed. The knot tightened when the input pressure was reduced. (**B**) Similar to A but with the prototype OD0.8 × L100 mm, both ends were set free. (**C**) Stability of the tightened knots after 1 week. The images were reused under a Creative Commons Attribution4.0 international license [71]. The legends are identical to those used in the original study.

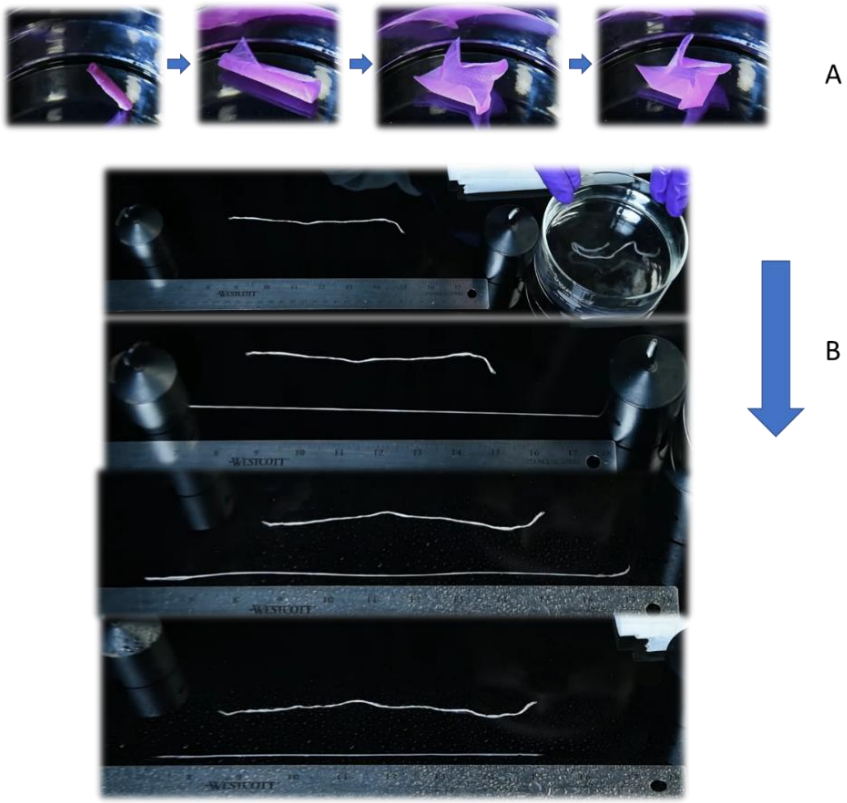

Figure 8. The sequential images were obtained from [73]. (**A**) A material made from recycled wool that acquired a distinct form when in contact with water, and (**B**) a filament made from stretched keratin protein that, when sprayed with water, returned to its curled format. The filament above is a reference for comparison purposes.

Amaterrace [14] offers many textile products, including highly waterproof and breathable, lightweight, high-density fabrics. Diaplex, from Mitsubishi Corporation Fashion Co., Ltd.). (Tokyo, Japan is an intelligent texture in which transition temperatures can be controlled to monitor thermal insulation and vapor permeability. Figure 9 represents the principle of the flexible barrier mechanism.

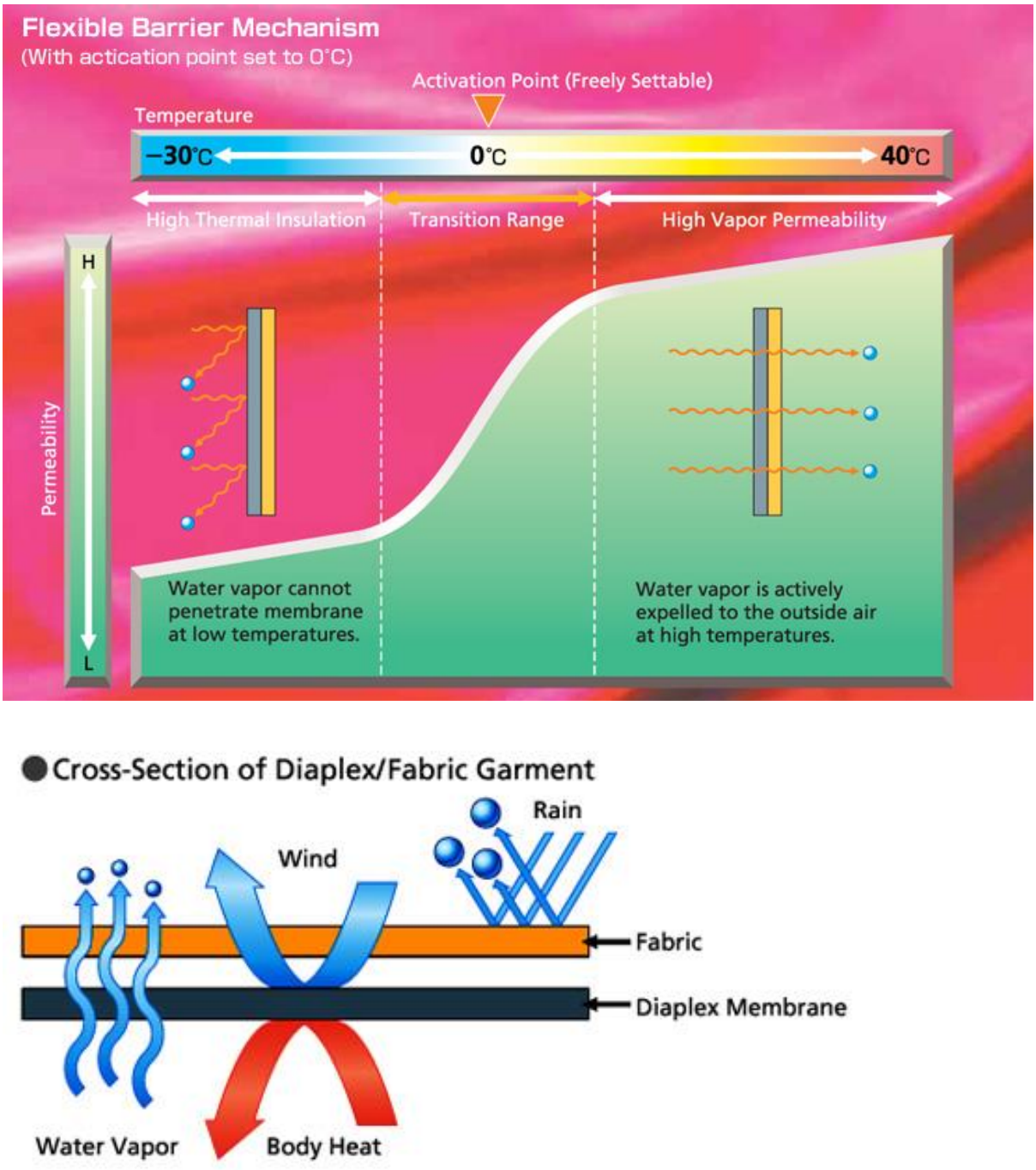

Figure 9. Images obtained from [14] showing the flexible barrier mechanism and a cross-section of Diaplex's fabric.

Other examples can be found in Table 2.

Table 2. Thermally responsive textiles and their respective strategies and functions. The data were obtained from [31].

Thermally Responsive Textiles	Strategies and Functions
Shape-memory finishing	Dynamic aesthetic textiles Finishing for wrinkle-free properties Finishing for crease retention Finishing for anti-shrinkage properties
Shape-memory fiber	Wet-spinning methods Melt-spinning methods Profiled fibers Electroactive SMP fibers
Shape-memory fabrics	Spun SMP fibers Low-pressure apparel Biological safety textiles Dynamic aesthetic fabrics Temperature and moisture management fabrics
Two-way fabrics	Two-way SMP textiles
Breathable fabrics	Traditional breathable fabrics Breathable fabrics with improved WVP
Damping fabrics	Damping properties of SMPs Damping properties of SMP fibers
Phase-change materials	Solid–solid PCMs Chemical crosslinking PCMs Thermoplastic PCMs SMP fibers with phase-change effects
SMP nanofibers	SMP nanofiber coated fabric SMP nonwoven nanofiber
Shape-memory foams	SMP foam pillows SMP foam mattresses SMP insoles
Thermochromic textiles	Liquid crystal type Molecular rearrangement type

SMPs are used for a variety of products with distinct geometries and characteristics.

1. General and regenerative medicine: A medical stent is the flagship for SMPs' biomedical use, with enormous material use per year—more than 600,000 coronary stents are implanted annually in the United States [74]. New developments in biomedical textiles for cardiovascular and endovascular applications are extremely innovative, with complex and fully customizable geometries. These biomedical textiles are already being used for heart valve replacements, aortic arch reinforcement, stent graft covering, carotid artery repair fabrics, tissue grafts, PAD (peripheral artery disease) treatments, hypertension treatments, angioplasty balloon/reinforcement, distal/embolic protection, coronary bypass grafts, cardiovascular patches, vascular prostheses, branch vessel filtration, and sewing rings for heart valves. Its main advantages include lower invasiveness, a lower profile, controlled density and porosity, flexibility, shape transformations, high tensile strength, biocompatibility, its inherent capabilities for promoting the healing of cardiovascular tissue, radial reinforcement, and expansion. These textiles can be formed via knitting, braiding, or weaving medical-grade fibers [75]. Regarding regenerative medicine, SMPs are used for wound healing and tissue regeneration [76]. Polyurethanes are an excellent choice due to their thermomechanical, chemical, and shape-memory properties after implantation, and they provide a reliable platform for controlled responses [77,78].

2. Drug delivery: Incorporating microcapsules into textiles has been studied over the years. Studies have shown that textiles that incorporate microcapsules containing active principles with antimicrobial, cosmetic, or even drug characteristics, will enable them to be released from the microcapsules and penetrate the skin upon contact, unraveling many exciting applications. The main advantages include protection from weather conditions, breathability, flexibility, comfort, and the expression of our personality [79,80]. The main issue is how to design vernacularizing systems for precise incorporation into the fabrics. For example, chemical affinity significantly affects release behavior. Therefore, using textiles with two functionalities broadens the range of applications, including diseases via skin-textile contact, which creates advantages over the administration of the active substance.

In general, the materials for smart medical textiles are divided into (i) smart dyes (including chromism, photochromism, and thermochromism) and (ii) nanofibers (using nanotechnology in medical textiles and the posterior fabrication of fabrics). Other applications for smart textiles for medical treatments are active textile dressings for wound healing, smart textiles for infection control management, drug-releasing textiles, designing ultra-personalized embodied smart textile services for wellbeing, and light-emitting fabrics for photodynamic therapy. Textile-based sensors for health monitoring are also a focus of study, helping customers to sleep (textiles with integrated sleep-monitoring sensors) and monitoring pregnancy conditions (textile-integrated electronics for ambulatory pregnancy monitoring) [81]. In the case of the smart fabric bellyband, the primary use is to monitor uterine activity and assess fetal wellbeing by using a wearable battery-less, wireless sensor on a high-mobility and comfortable bellyband.

Narayana et al. [82] developed stress-memory polymeric filaments for compression therapy, considering changes at the filament level. Chen et al. [83] synthesized shape-memory polyurethane using isonicotinamide (BINA) as a moisture absorption agent. A fast recovery speed was observed when it was immersed in a specific relative humidity for a short time period. Chen and co-authors [84] developed electrically actuated ankle-foot orthoses (AFOs) with shape-memory textile composites. The authors used acrylic copolymers with embedded electrochemical fabrics, which were triggered under uniform heat. According to the authors, the programmable property could be repeated at least 20 times, with stable shape fixity and recovery.

The main drawbacks of SMPs over their counterparts are their low recovery stress, their lower recovery speed and response time, and the possibility of a longer, more achievable lifecycle [85]. The main advantages of shape-memory fabrics over commercial products are their high mechanical performances, high power-to-weight ratios, large deformations, large actuation forces, high damping capacities, high-frequency responses, high-wear resistance capabilities, high corrosion and chemical resistance capabilities, low operation voltages, high specific strengths, excellent compactness, and excellent lightness. On the other hand, their main disadvantages include their low energy efficiency, complex thermomechanical behaviors, expensive materials, temperature-dependent effects, poor fatigue properties, and low operational speeds [86].

7. Future Research

Several prospects and gaps can be identified for future research on shape-memory polymers (SMPs). While the shape-memory effects have been demonstrated in the literature, achieving precise control over shape-recovery behaviors, particularly concerning the intermediate shape during recovery, remains challenging. Most studies have focused on the initial and final stages of the shape-memory process, leaving the intermediate shape less explored. To address this, developing multiple SMPs with a single transition phase can enable more precise control. Additionally, research on nonreversible and athermal chemical reactions holds promise for exploring new shape-memory phenomena. One recommended direction for future research is the synthesis and reinforcement of two-way SMPs which have the potential to recover stress levels comparable to those of shape-memory alloys.

However, it should be noted that the mechanical strength of these materials is often not as high as that of conventional composites, and efforts must be made to address this limitation.

With the rapid advancements in products, technology, and science, it is expected that SMPs with improved functionality and portability will emerge. Furthermore, using controllable and deformable SMPs can pave the way for a new generation of soft stimuli-responsive materials, offering innovative solutions to scientific challenges. In summary, future research endeavors should focus on achieving precise control over shape recovery behaviors, exploring new shape-memory phenomena through nonreversible and athermal chemical reactions, developing two-way SMPs with enhanced mechanical strength, and advancing the functionality and portability of SMPs to address scientific challenges effectively.

8. Conclusions

Shape-memory polymers (SMPs) hold immense potential for utilization in the textile industry. One of the key advantages of SMPs is their ability to respond uniquely to different stimuli, allowing them to maintain their properties under varying and changeable circumstances. However, significant efforts are still required to maximize their performance and minimize their costs, ensuring competitiveness in the market. In addition, a critical challenge is the limited number of extensively studied products that can be applied without causing failure. Therefore, future developments are necessary to explore the potential of SMPs under different and simultaneous stimuli. Considerable efforts are being dedicated to using modern polymer chemistry and biomaterial science methods to develop smart materials with tailored properties, particularly for medical applications. These advancements can potentially assist surgeons in performing minimally invasive procedures and contribute to patients' recoveries and healthcare cost reductions. Furthermore, SMPs can find applications in various industries by enabling the restoration of their original shapes through the application of appropriate external stimuli. Moreover, it is anticipated that future research will focus on investigating different stimuli beyond heat.

In conclusion, SMPs offer significant advantages for the textile industry, and further research and development efforts are required to enhance their performance and reduce costs. The medical field benefits from tailored SMPs that assist in minimally invasive procedures and aid in patient recovery. Additionally, SMPs hold potential for diverse industrial applications where they can return to their original shape in response to specific external stimuli. The exploration of alternative types of stimuli will further broaden the scope of SMP applications.

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