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Shape memory textiles – technological background and possible applications

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ABSTRACT

While shape memory alloys (SMAs) and shape memory polymers (SMPs) can already be found in diverse applications, shape memory textiles are less often used. Nevertheless, they are regularly investigated. Typical ways to produce shape memory textiles (SMTs) are introducing shape memory wires, printing shape memory polymers on them ("4D printing"), or using textile materials such as poly(lactic acid) (PLA) which show shape memory properties on their own. This review gives a brief overview of these technological possibilities and possible applications of shape memory textiles.

1 Introduction

The shape memory effect describes the situation that a material can be deformed and recover its original shape due to an external stimulus, e.g. by heat, light or chemical modifications of their environments [1]. Typical applications of shape memory polymers (SMPs), shape memory alloys (SMAs) or shape memory ceramics (SMCs) can be found in biomedicine [2-4], spacecraft [5], soft robotics [6,7] or also smart textiles [8,9].

Shape memory materials can be found in diverse shapes, from bulk to thin films to fibers or foams [10-12]. Another special possibility to use shape memory materials is 3D printing [13]. In this context, shape memory polymers are often used to enable easier printing and folding the desired structure afterwards [14]. This technique as well as printing objects with alternating shapes, triggered by different stimuli, is often called "4D printing", with time as the fourth dimension [15-17].

While 3D printing on textile fabrics belongs to the emerging research topics of our time [18-22], combinations of 4D printing with textile fabrics are nevertheless scarce. Similarly, shape memory textiles in general are not investigated very often. Fig. 1 shows the numbers of hits in the Web of Science for both topics. While the wordings “4D printing” or “4D textiles” seem to become more often used, there is no such trend visible for the technical term of shape memory textiles.

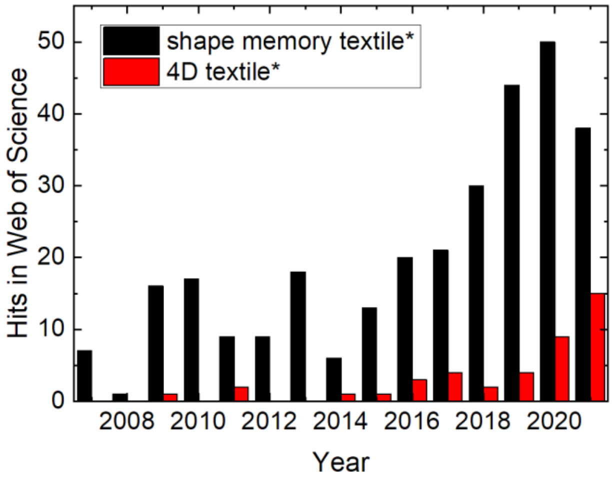

Fig. 1 Hits in the Web of Science for chosen search phrases. Data taken on November 21, 2021.

Here we give an overview of shape memory textiles, produced either by using SMPs for the fabric construction, integrating shape memory materials or using 3D printing or other coating method to apply a shape memory layer.

2 Shape memory textiles produced by shape memory fibers

Several polymers show shape memory properties alternating soft and hard parts in the polymer chain, such as poly(lactic acid) which is often used in 3D printing by the fused deposition modeling (FDM) technique [23-25], polyurethanes (PUs) [26-28] and others. This offers the possibility to produce polymer fibers with shape memory properties by different spinning methods, often by melt-spinning [29] or also by electrospinning [30,31], which can be processed further into a yarn and finally into a textile fabric or directly into a nonwoven.

This is why the production of shape memory fibers belongs to the often reported techniques to prepare shape memory textiles. Meng *et al.*, e.g., used wet spinning to prepare shape memory polyurethane fibers with poly(caprolactone) segments [32]. The switching temperature of these fibers was 36 °C, i.e. quite near the temperature of the body interior, enabling interesting applications in smart clothes. They found a high recovery ratio of more than 95 % under cycling thermal drawing and recovery. The group also compared wet and melt spinning of this material and found the latter to result in higher tenacity, breaking strain and shape memory effect in comparison with wet-spun shape memory fibers [33]. Besides, they reported on the influence of different heat treatments of melt-spun shape memory fibers at different temperatures, leading to differently improved mechanical and SME properties [34].

Kumar *et al.* also used polyurethane as shape memory polymer and produced filaments by melt spinning [35]. They found a glass transition temperature of approx. 30 °C, i.e. closer to the body surface temperature. By combining this filament with nylon, they prepared a yarn which was circularly knitted to produce smart compression stockings. The pressure exerted by these stockings onto a patient’s leg increased with increasing activation temperature, enabling such materials as smart wound care products or the like, e.g. by applying dynamic pressure by a programmed heating stimulus [36,37].

Jin and Hu produced a core-spun yarn by ring-spinning and friction spinning with wet-spun shape memory core fibers and a cotton roving as the covering material [38]. These yarns were woven into twill fabrics with pure cotton warp yarn and the shape memory core yarn in the weft. The switching temperature was identified as 58 °C. Interestingly, they found shape memory effects even in the warp direction of the fabric under cyclic loading and recovery and a higher SME in the ring-spun yarns than in the friction-spun ones.

Wet-spinning was also used by Ji *et al.* to produce SME fibers from polyurethanes with different hard-segment contents and compared them with thin films of the same materials [39]. They reported less shape fixity of the fibers, but higher shape recovery in comparison with the thin films.

Sáenz-Pérez *et al.*, on the other hand, used melt spinning to prepare different PU fibers with shape memory effect and producing plain knitted structures from them [40]. They found very high shape recovery ratios of mostly more than 99.9 % with glass transition temperatures around 37-38 °C for the self-prepared fibers and around 52 °C for a commercial material tested in comparison.

Similarly, Walczak *et al.* prepared melt-blown fibers from poly(L-lactide) (PLLA) blended with atactic poly(hydroxybutyrate) (a-PHB) [41]. They obtained a high shape recovery for a nonwoven prepared from this material and concluded that blending of PLLA with a-PHB significantly reduced the glass transition temperature from 65 °C to 38 °C, making the new polymer blend highly interesting for self-fixing and self-adjusting implants, graft anchors, or other biomedical purposes.

Such biomedical applications necessitate biocompatibility. Preparing polyurethane fibers by wet spinning, Meng *et al.* concentrated on the evaluation of the cytotoxicity, hemolysis, sensitization, and dermal irritation and found none of these potential problems to occur, making such shape memory fabrics indeed highly interesting for biomedicine [42].

Besides pure polyurethanes and PLA or PLLA, there are also more complex polymers and blends used as shape memory fibers. Meng *et al.* combined PU with multiwall carbon nanotubes (MWCNTs) to produce melt-spun fibers [43]. While spinning became more complicated with increasing MWCNT content, lower concentrations resulted in homogenous distribution and alignment and correspondingly high tenacity and initial modulus as well as increased recovery ratio and recovery force. On the other hand, Deng *et al.* prepared polyurethane SMFs which they coated with a sheet of carbon nanotubes (CNTs) to prepare a shape-memory supercapacitor in combination with a gel electrolyte [44].

Another polymer investigated as a possible shape memory fabric is poly(trimethylene terephthalate) (PTT), a semi-crystalline thermoplastic polymer [45]. Zhao *et al.* suggested this material for fashion design. Interestingly, recovery at different temperatures between 20 °C and 60 °C resulted in similar crease recovery ratios in spite of the glass transition temperature being between 40 °C and 60 °C, which the authors attributed to the low crystallinity of the PTT filament. On the other hand, a high crease recovery rate could be reached by simulated ironing and hand stroking, as it is easiest used for crinkled clothes.

Lu *et al.* suggested covalently crosslinked poly(acrylamide) (PAAm) and ionically crosslinked carrageenan, forming a hydrogel with high elongation up to a factor of 20 [46]. By stretch-drying these stretched hydrogels, fibers were formed with shape memory properties similar to their wet state.

Quite an unexpected shape memory effect was found by Zhu *et al.* in cellulose/chitosan multifilament fibers [47]. The fibers were spun from a new solvent from LiOH, KOH and urea aqueous solution and showed a two-switch shape memory behavior under stimulation with water and acid due to changing the self-aggregation force between both partners in the blend.

Besides different materials, different spinning methods should also be mentioned. While wet and melt spinning produce fibers with diameters in the micrometer range, electrospinning can be used to prepare nanofibers or complete nanofibrous mats. In crosslinked poly(ε-caprolactone) (PCL) nanofiber mats, contraction was found upon heating and relaxation upon cooling again, as depicted in Fig. 2 [48]. Cyclic thermomechanical tests showed reversible actuations around 22 % for a strain of 300 % and a pore size variation of 11 % upon varying the temperature between 10 °C and 60 °C. This relatively low variation on the microscale was attributed to the necessarily much larger changes on the macroscale.

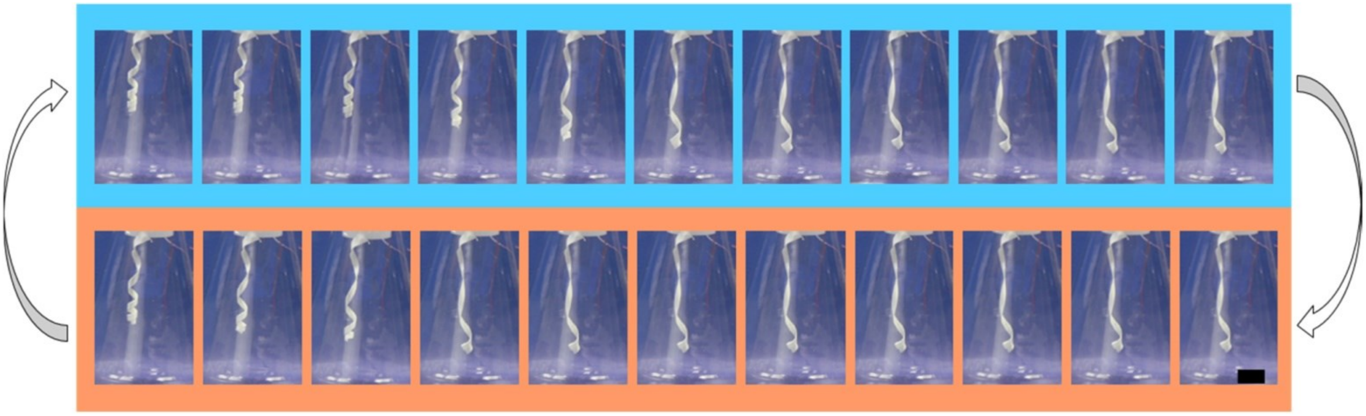

Fig. 2 Video images of sequential heating (orange) and cooling phases (blue) for a twisted specimen investigated in the range of 60 °C-10 °C. The scale bar shows 2 cm. From [48], originally published under a CC-BY license.

In crosslinked electrospun Nafion® nanofiber mats with a small additional amount of poly(ethylene oxide) (PEO), Zhang *et al.* found even a shape memory effect with multiple shapes at different temperatures due to a broad transition temperature range from 60 °C to 170 °C [49]. Combining PEO and PU, Feng *et al.* used coaxial electrospinning with crystalline PEO in the core and elastic PU in the shell to produce nanofibers with good shape recovery and temperature-dependent control of micro-pore structure and the

Besides the shape memory effect itself, another interesting property for several possible applications is the water vapor permeability, which was investigated by Zhuo *et al.* and found to decrease with an increase of the relative humidity and to increase with an increase in temperature [51].

As this short overview shows, there are diverse materials and spinning processes which allow producing shape memory fibers, yarns or nonwovens with varying shape memory properties for different applications. Nevertheless, spinning shape memory fibers from polymeric materials is not suitable for all situations. The next section thus describes examples of shape memory alloys integrate in textile fabrics in the form of wires or filaments.

3 Shape memory textiles with integrated shape memory alloy wires

Most production techniques for textile fabrics, such as weaving or weft knitting, as well as sewing and embroidery enable integrating thin wires or adding them to a textile fabric. By this method, e.g., fabrics from natural fibers, high-tenacity yarns etc. can obtain shape memory properties, although the base material does not show this effect [52].

The most basic integration of SMAs is on the yarn level. Chan Vili reported about integrating NiTi wires with diameters 0.2 mm and 0.3 mm as well as PU filaments of 0.15-0.35 mm into wrap spun yarns with different twists and other varying parameters [53]. She suggested using such yarns in diverse fabrics, applied for design purposes, for smart room partitions or smart curtains. Wang *et al.* [54] as well as Congalton [55] investigated the possibility to integrate SMA springs into thermal protective clothing, enabling modification of the air gap between the fabric layers. Similarly, Huang *et al.* suggested an integrated SMA wire into woven fabrics used as sleeves to shorten them upon heating up and elongating again when the environment becomes cooler [56], while SMA wires were integrated into knitted fabrics to enable new design aesthetics [57]. Special Origami techniques were used by Cabral *et al.* to design dynamic light filters, based on SMA wires integrated in woven fabrics [58], and Liu *et al.* applied Miura-origami designs to prepare samples for compressive loading [59].

Salej Lah *et al.* investigated in detail the mechanical and shape memory properties of a Nitinol (Ni-Ti alloy) wire and demonstrated the influence of embedding it into a smart textile fabric [60]. Fig. 3 shows the different crystal phases of the Nitinol wire, triggered by heating and cooling, loading and unloading, as well as the corresponding effects on a textile fabric in which these wires are embedded.

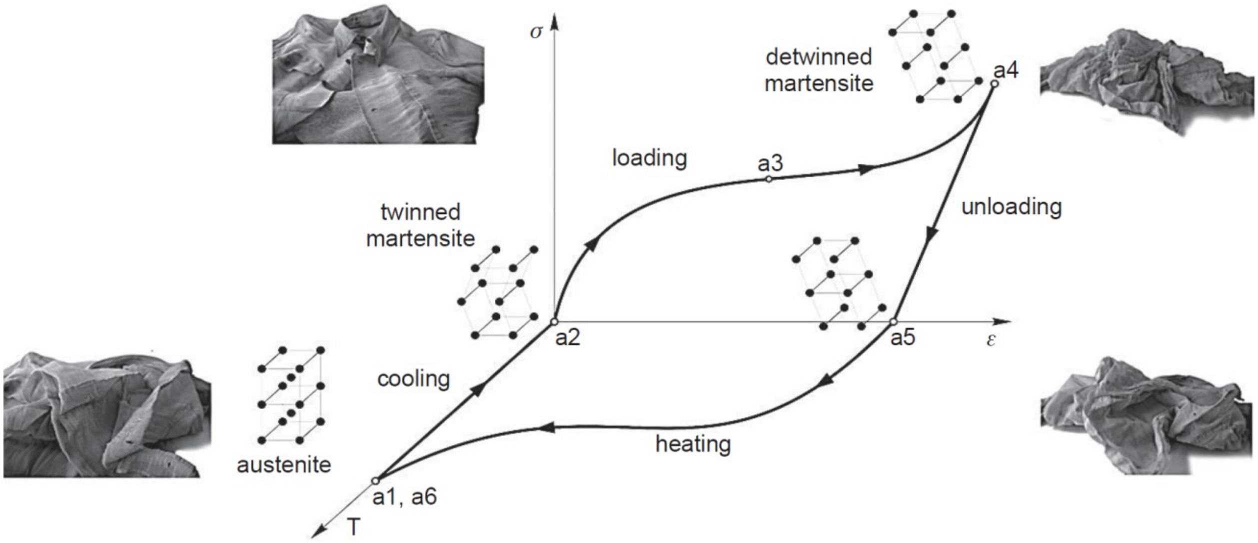

Fig. 2 Shape memory effect: example of shape changing of smart textile fabric with Nitinol filaments as function of stress (σ), temperature (T) and deformation (ε). From [60], originally published under a CC-BY license.

Besides design applications, the aforementioned crinkle recovery belongs to the often reported reasons to include SMA wires in textile fabrics. Weinberg *et al.* showed that integration of a NiTi microfilament (diameter below 10 µm) into knitted textile fabrics led to superelastic recovery, and they suggested using such fabrics in addition for actuating and energy absorption [61]. To enable actuating by moving parts of smart fabrics over large distances, Helps *et al.* suggested embedding an SMA wire in a coiled guiding tube attached to the smart textile to overcome the problem of relatively small changes of the wire length upon heating [62].

Vasile *et al.*, on the other hand, concentrated on the wrinkle recovery of woven fabrics with integrated SMA wires [63]. They mentioned the problem of SMA wire slippage inside the woven fabrics, depending on the combined yarns and the weaving parameters. Similarly, Vasile *et al.* investigated wrinkle recovery of flax fabrics in dry and wet conditions, comparing pure flax woven fabrics with hybrid fabrics including hybrid flax/SMA yarns and found significantly increase wrinkle recovery in the latter, which could be improved by optimizing the hybrid yarn structure [64,65].

Only few theoretical examinations of SMA/fabric hybrid textiles can be found in the literature. Holschuh and Newman developed a two-spring model to simulate the behavior of such hybrid textile in dependence from different design and material variables [66]. They found clear differences between spandex and neoprene fabrics on the one hand, showing linear response up to an elongation of 200 %, and polyester elastic as well as a tri-laminate Lycra on the other hand, showing nonlinear responses for these strains. Their main aim was modeling compression garments, which was enabled by a broad range of possible mechanical performances, depending on the design parameters.

Besides the integration of SMA wires into yarns or directly into textile fabrics, it is also possible to add SMPs to a textile fabric by coating or 3D printing. The next section shows examples of this approach.

4 Shape memory textiles prepared by 4D printing or coating on fabrics

While the so-called 4D printing belongs to the strongly investigated topics in the moment, 4D printing on textile fabrics is still scarce, possibly due to the often insufficient adhesion between both partners.

Nevertheless, some attempts are reported in the literature, often making use of the interplay between relatively stiff imprinted polymers with shape memory effect and the soft, elastic fabric.

Leist *et al.*, e.g., used the shape memory polymer PLA to print on nylon fabrics to train the composites thermo-mechanically into temporary forms and restore the original shape by heating them [67]. Khan and Hassan showed the process of preparing 4D textiles with a self-folding box as an example [68].

Zhang *et al.*, on the other hand, interpreted the term "4D textiles" in another way [69]. They used 3D printing with PLA to mimic textile structures, here circular braided preforms, partly embedded in a silicone elastomer matrix, and found high recovery of nearly 100 % in radial direction as well as circumferentially. This could be used to produce an "open" tube by cutting it along the longitudinal direction, flatten it and then use it as a gripper.

Combining 3D printing with embedded fibers in a single-step process, Wang *et al.* used a double nozzle conversion printer in which a carbon continuous fiber was impregnated by polyamide (PA) 6.6 in the nozzle before printing [70]. The final sample, however, consisted of one pure PA layer and another one with embedded carbon fibers, working similar to a common bi-metal sheet under the influence of heating the environment. This example shows that 4D printed textiles can also be prepared without using materials with shape memory properties.

A broad overview of the concepts of 4D textiles, often working with these multi-layer structures, was given by Schmelzeisen *et al.* [71] as well as Koch *et al.* [72], while Stapleton *et al.* concentrated on finite-element modeling textiles with a printed polymeric grid on top, in which the textile fabrics were stretched during printing and which thus deformed after taking them off the printing bed into the final state [73].

The other aforementioned possibility to prepare shape memory fabrics is given by coating them with a shape memory polymer, such as polyurethane. Liem *et al.* combined PU with dimethyloldihydroxy-ethyleneurea (DMDHEU) as a fiber coating on cotton fabrics in order to reduce residual stress in the weft fibers [74]. The effect was attributed to balancing swelling due to moisture absorption by crosslinking between fibrils due to DMDHEU. Similarly, Liu *et al.* used this material combination for a wrinkle-recovery coating [75].

A more plastic effect was aimed at by Jahid *et al.* who coated cotton fabrics with different PUs and found the finished fabric changing its permeability with temperature and humidity, in this way combining thermal insulation and water vapor transmission, depending on the environment [76]. The idea of this smart textile is illustrated in Fig. 3. A similar study was performed earlier by Mondal and Hu with a polyurethane coating [77] and recently on polyester with the same coating material [78].

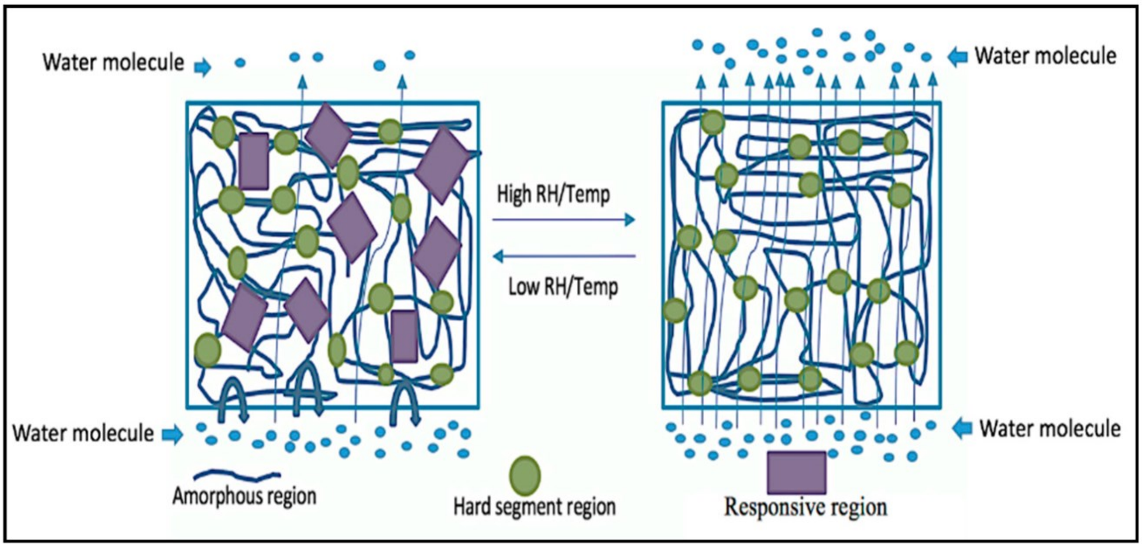

Fig. 3 Molecular design of responsive polyurethane. From [76], originally published under a CC-BY license.

5 Main applications of shape memory textiles

Applications of shape memory textiles can be found in various areas. They can be used as actuators, making them highly interesting for soft robotics, where electric actuators can partly be replaced by shape memory materials driven by other stimuli [6,7,62].

Similarly, applications in smart clothes are of high interest, where the possibility to change the dimensions or orientations of parts of the fabrics enables applying different pressure on the human body, useful from sports to wound care, opening or closing areas to modify air and water vapor permeability, or just producing clothes with high crinkle recovery [8,9,32,35-37,60,76].

On the other hand, biomedical applications should be mentioned, where, e.g., stents can benefit from the possibility to be inserted into the body in a smaller shape and be extended at the desired position [3,4,42].

Finally, shape memory textiles offer a broad range of new possibilities in textile and clothing design [45,53,57].

6 Conclusions

Shape memory textiles can be produced from fibers with shape memory properties, by integrating shape memory allow wires or adding shape memory polymers by 3D printing or coating. In spite of the increasing number of studies on 4D printing in general, however, only a small number of publications reports on these possibilities to make textile fabrics smarter, offer a new freedom of design to them, or just make them more wrinkle-free by adding a shape memory effect.

However, there are still problems to overcome in order to reach all desired functionalities, such as too small dimensional changes, switching in only one direction due to an external stimulus, or insufficient fixture of an SMA wire in a textile fabric.

On the other hand, there are many more stimuli to be explored. Most of the shape memory materials used as fibers, as integrated wires or coatings recover due to thermal stimuli; only very few studies show recovery due to chemical stimuli (e.g. by a modified pH value) or upon illumination, showing the broad range of possible further investigations on shape memory textiles triggered by other stimuli.

While this review gives an overview of the already investigated possibilities to prepare and apply shape memory textiles, it also aims at motivating new investigations in this highly interesting field of research.

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