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Analysis of Hybrid Woven Fabrics with Shape Memory Alloys Wires Embedded

Abstract
Until recently, Shape Memory Alloys (SMAs) were predominantly developed for applications in the biomedical and engineering industry, and only a limited number of applications in textiles are known. Fabrics made of natural fibres (e.g. cotton, flax and their mixtures) present many advantages, such as wearing comfort, but they are subject to creasing. The aim of this study was to investigate the possibility of compensating for this disadvantage by using SMAs to create aesthetic low crease flax/cotton fabrics. Body Temperature SMAs (BT SMA) that regain their (straight) form when they are subject to human body temperature were used for this purpose. Clothing and bed sheeting are potential applications of these hybrid structures, which become wrinkle-free when they are exposed to the heat of the body, a hair dryer or that generated by an electrical current. The materials selected to achieve this purpose were the following: (1) textile yarns (e.g. single cotton or flax/cotton yarns, two-fold flax yarns and two types of loop fancy yarns) and (2) BT SMA wires of 300 µm diameter. A power weaving loom and a hand-weaving shuttle loom were used to embed the SMA wires, and four types of hybrid fabrics were produced. The thickness, wrinkle recovery, dimensional stability as well as the cohesion of the SMA wires in the woven fabric were tested. All the tests were performed before and after a washing cycle for both the hybrid and reference fabrics. An increase in thickness was noticed after washing, and the recovery time after crushing varied according to the type of fabric. The slippage of SMA wires from the fabrics was noticed for all the samples, which was dependent on the type of yarns used, their linear density and the weaving process.

Key words: *hybrid woven fabrics, shape memory, washing test.*

Introduction

Shape Memory Materials (SMMs) have unusual properties (like the shape memory effect, superelasticity, recoverable strain, high damping capacity, etc.) that make them suitable as major components of smart composites. They can sense physical changes in their environment, such as thermal, mechanical, magnetic or electric. These properties are essentially linked to a solid phase transformation during which a „mother phase" (austenite) leads, in a reversible crystallographic way, to a phase called martensite, thus explaining the name: „martensitic transformation" [1, 2]. SMMs exist in the form of polymers, alloys or ceramic materials. Although a variety of metal alloys possess this property, there is only a limited number of them that are commercially important, such as the NiTi-alloy, known as NiTinol. NiTinol exists in different forms: as a bar, rod, wire, shaped wire, sheet, ribbon wire, etc [1]. Due to their biocompatibility, NiTi-alloys are mostly

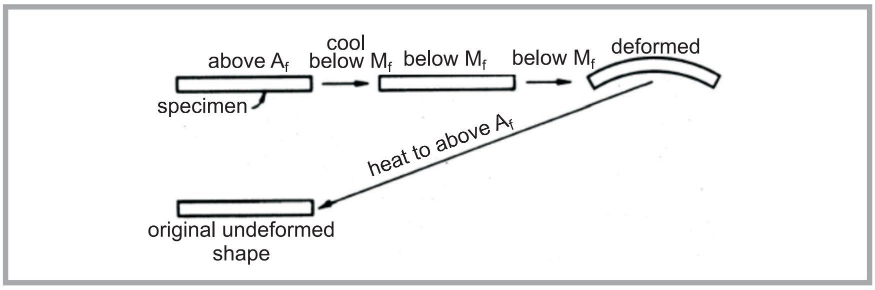

Figure 1. *Principle of single memory effect [2, 7].*

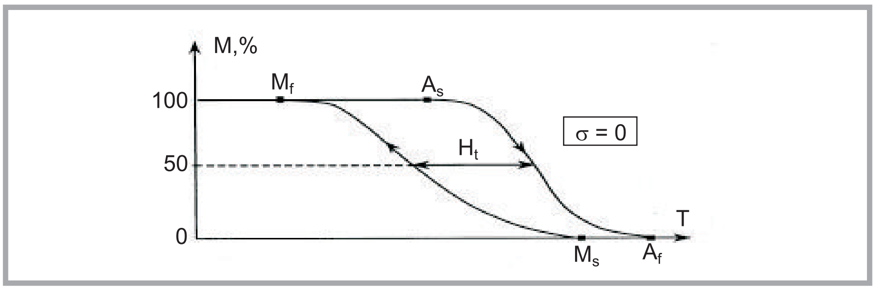

Figure 2. *Martensitic transformation cycle [2, 7].*

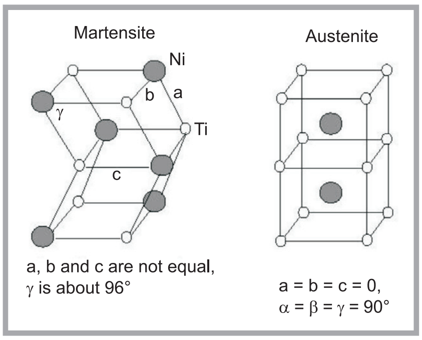

***Figure 3.** Crystalline lattice in the in-martensite and austenite phases [9].*

developed and used for biomedical applications, but NiTinol in the form of fine wires is also suitable for processing on textile machines. However, due to their stiffness and difficult processability in some textile processes (like twisting and knitting), the application of thin SMA wires in textiles is still in the investigation phase, and only a limited number of applications are known [3 - 6].

The hybrid structures developed for this research make use of NiTinol wires with a one-way shape memory effect. A metallic alloy presents a one-way shape memory effect if, after being deformed (typically by a few percent) in a permanent state at low temperature, it recovers its original state after being heated above the transition domain (***Figure 1***). This phenomenon, which consists of a reversible martensitic transformation, appears between two temperatures, called "low" and "high"; however, these do not prejudge their level towards the ambient temperature. The cycle of martensitic transformation which presents a hysteresis is defined by critical temperatures: Mf, As, Ms & Af (***Figure 2***). Below the Mf temperature, the alloy is completely in a martensite phase, and above the Af temperature it is in an austenite state. During a martenstic transformation, the crystalline structure varies from a centre-faced cubic lattice to a centred cubic lattice (***Figure 3***) [9].

Embedding of SMA wires in textile structures

Recent advances in shape memory alloys (SMAs) have inspired researchers to create intelligent textiles as self-regulating shape-changing structures responding to environmental variation, contributing to a new field in the scientific frontier of smart materials [10, 11]. One method used for embedding SMA wires into a textile structure is stitching, as used by Leenders [12] to produce her "moving textiles". Many papers report about knitted NiTi stents [13 - 18] or structures [5]. Another method of embedding SMA wires is via a weaving process, using a hand-weaving loom, as in most of the cases reported in literature. The weaving of metal wires, such as stainless steel ones, on industrial machines is common in the industry, but very few trials of weaving SMA wires have been reported. Boussu et al. [19] conducted preliminary studies concerning the weaving of a SMA fabric using 100% NiTi thin wire of 0.15 mm diameter. Unfortunately, practical details of the fabrication are not disclosed. Zhang et al. [20] first intended to utilise a hand-weaving machine to produce a 100% NiTinol mesh for composites, but they failed because it was quite difficult to keep the quality of the weft, such as tension, equal pitch, etc. Therefore, they developed an apparatus to align the wires and maintain proper geometry and restraints in the warp and weft. Chan Vili [21] manufactured woven samples with alternating textile and SMA wires using a Harris eight-harness table loom. The tensioning of the warp could easily be adjusted, which was found to be an important factor when applying a wire formation. It was essential to achieve a balanced tension to reduce complications during the production of an adequate woven textile.

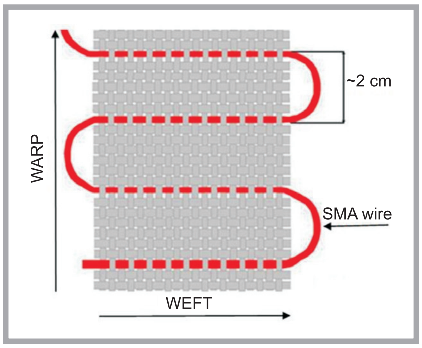

***Figure 4.** Schematic representation of a hybrid fabric with SMA embedded.*

Fabrics made of natural fibres present many advantages, such as wearing comfort, but they are subject to creasing. The aim of this research was to embed SMA wires into 100% natural fibre fabrics in order to compensate for this disadvantage. A hand-weaving loom and industrial weaving loom (a discontinuous process)

***Table 1.** Structural parameters of the parent fancy yarns and contribution of individual components.*

Type of fancy yarn	Component yarns	Linear density, tex	Core yarns, g/km	Effect yarns, g/km	Binding yarns, g/km	Contribution, %		
						Core yarns	Effect yarns	Binding yarns
Loop yarns, 186 tex	Effect yarns (#4)	20	40	80	20	21.5	67.75	10.75
	Binding yarn (#1)	20						
	Core yarn (#2)	20						
Stretch loop yarns, 155 tex	Effect yarns (#2)	31	32.6	62	5.2	21.03	75.62	3.35
	Binding yarn (#1)	5.2						
	Core yarns (#2)	16.3						

***Table 2.** Plan of the experiments.*

Type of weft yarns	Hybrid fabrics				Reference fabrics			
	H1	H2	H3	H4	R1	R2	R3	R4
Stretch loop yarn, 155 tex	X				X			
Cotton single yarn, 20 tex	X	X	X		X	X	X	
Flax /cotton single yarn, 30 tex		X				X		
Loop yarn, 186 tex			X				X	
Flax two-fold yarn, 336 tex				X				X
BT SMA wire 300 µm	X	X	X	X				

***Table 3.** Description of the fabrics.*

Fabric ID	Fabric mass, g/m2	Thickness, mm	Warp density, ends/cm	Weft density, picks/cm
H1	332	1.14	32	12
H2	217	0.58	32	24
H3	330	1.06	32	12
H4	502	1.70	10	5
R1	245	1.11	32	12
R2	174	0.50	32	24
R3	249	1.07	32	12
R4	602	1.75	10	5

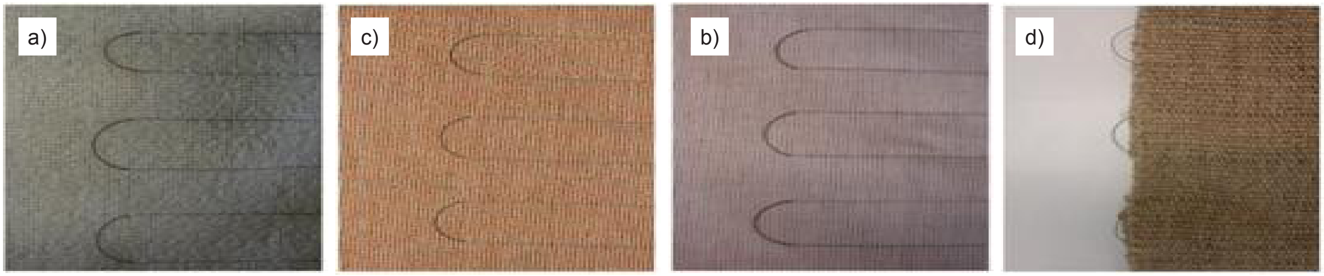

***Figure 5.** Hybrid fabrics samples; a) H1, b) H2, c) H3, d) H4.*

were used to embed SMA wires in the weft direction. Body Temperature SMA wires (BT SMA) were used in these studies, which recover their (straight) form when they are subject to human body heat or another heat source like a hair dryer or electrical current. Some possible applications of such fabrics include wrinkle-free clothing, bed sheeting, camping tents, etc.

Materials and methods

Materials selection

The tendency of fabrics based on natural fibres, like cotton, flax and their blends, to crease and form wrinkles is well known. The idea was to use SMA wires embedded in textile structures and create highly aesthetic, low crease flax and cotton fabrics. The following materials were used in order to achieve this purpose: (1) Body Temperature Shape Memory Alloy (BT SMA) wires of 300 µm diameter and (2) textile yarns (e.g. single cotton yarns, two types of flax yarns and two qualities of loop yarn). The parameters of the textile yarns were:

- Single cotton yarns, 20 tex
- Single flax/cotton yarns (50/50), 30 tex
- Two-fold flax yarns, 336 tex
- Loop cotton yarns, 186 tex, consisting of 2 core yarns, a binding yarn and 4 effect yarns
- Stretch loop yarns (155 tex, twist 500 t/m, stretch 315%) with the following composition:
  - Two open-end cotton yarns, each 31 tex, as effect yarns
  - NYLASTAN®, 52 dtex (composed of Lycra® 20 dtex (15%) + PA 44 dtex), as binding yarn
  - NylastanII®, 163 dtex (composed of Lycra 22 dtex (5%) + 2×PA 78 dtex), as core yarn

During the production of the fancy yarns, the effect yarns are overfed in order to form the effects (loops in our case), which (together with the high number of effect yarns used) explains their highest contribution, as shown in ***Table 1***.

The parameters of the BT SMA wires were as follows: chemical composition, 55.5 Ni-Ti in %, density, 6.45 g/cm^3, melting point, 1300 °C, elongation at failure, 12% min, and the maximum strain recovery, 8%. The transition temperatures at 200 MPa corresponding to the start and finish of the austenite state (As and Af) and the martensite state (Ms, Mf) were As = 47 °C, Af = 53 °C, Ms = -2 °C, and Mf = -10 °C.

The weaving process

In our study, four hybrid fabrics (coded as H1-H4) with SMA wires embedded in the weft direction were produced, as well as their related reference fabrics (coded as R1-R4). Six out of the eight fabrics (R1-R3 and H1-H3) were woven on an air-jet weaving loom, and two fabrics (H4 and R4) were woven on a sampling shuttle loom. SMA wire was inserted into the hybrid fabric according to the pattern displayed in ***Figure 4*** after weaving about 2 cm of fabric with (textile) weft yarns, an SMA wire was inserted, without being cut at the edges. In the case of the air-jet weaving loom, the weaving process was interrupted and the SMA wire inserted manually. The process was repeated each time a wire was inserted.

A plan of the experiments used for the production of the fabrics is shown in ***Table 2***. The mass of the fabrics produced varied between 174 g/m^2 and 602 g/m^2 and their thickness between 0.5 mm and 1.75 mm, as shown in ***Table 3***. Generally, the reference fabrics possess a lower mass per square meter with the exception of sample R4, which is due to the higher linear density of wefts made of coarse flax yarn than that of SMA wire. The weft density given in ***Table 3*** refers to the zones between two SMA wires, while the approximate density of the SMA wires was about 6 picks/10 cm for all the hybrid fabrics. The weft insertion pattern of samples H1-H3 and R1-R3 was 1/1: one cotton yarn of 20 tex/one weft yarn, as displayed in ***Table 2***. All the fabrics were woven with plain weave as it was considered that fabrics with this structure have a higher tendency of forming wrinkles than corresponding modified weaves like twill or satin. Cotton yarns of 20 tex (H1-H3, R1-R3) and coarse flax yarns (H4, R4) were used in the warp direction. No problems were encountered during the insertion process, although the SMA wires were coarser and less flexible than the textile yarns. However, due to the very smooth surface of the SMA wires, it was observed that the SMA wire had a tendency to be easily moved and pulled out of the fabric, therefore a cohesion test was performed. The hybrid fabrics produced are shown in ***Figure 5***.

Results and discussions

The thickness, dimensional stability, wrinkle recovery and resistance to slippage were tested before and after the washing process for both the hybrid and reference fabrics.

The washing process

The fabrics were subjected to one laundry cycle using a washing machine [22]. The washing temperature was 40 ºC, and 38.5 g of detergent, 10 g of softener and 1.5 g of a bleaching agent were used.

***Table 4.** Average results of the wrinkling test.*

Fabric ID	R1	H1	R2	H2	R3	H3	R4	H4
Mark	2	1.5	1.5	1.5	1.5	1	2	2

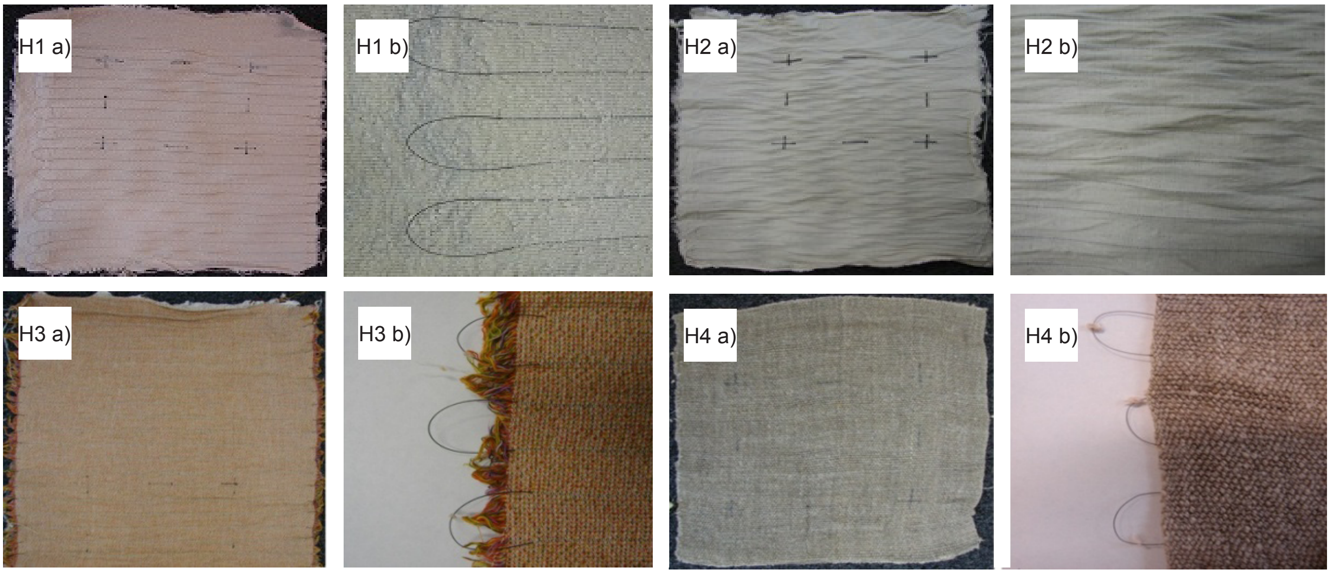

***Figure 6.** Hybrid fabrics after washing, samples: H1, H2, H3,H4; photos a) normal view, photos b) magnified view.*

There was a change in the dimensions of all the reference fabrics treated. The existence of SMA wires embedded into the hybrid fabrics did not significantly influence dimensional change during the washing process. The SMA wires were slightly more visible after the washing process than before it, especially at the edges of the fabrics since the textile materials contracted after the washing process and the SMA wire did not shrink. This is more evident in the case of hybrid fabrics H1 and H2, whose aspect altered after washing. On the other hand, the existence of SMA wire in the structure of hybrid fabrics H3 and H4 can be barely noticed, even after washing. The effect of washing on the fabrics tested is shown in ***Figure 6***, where the normal views are presented on the photos a). whereas the magnified views on photos b).

Thickness of the fabrics

The thickness of the fabrics was measured (before and after washing) [23] using a "Digimatic indicator" called MITUTOYO, which can measure fabrics with thicknesses in the range of 0.01 - 30 mm. The thickness of both the reference and hybrid fabrics increased after washing; the variation in thickness in % in the washing process is shown in ***Figure 7***. A higher variation in thickness occurred for sample H2, which was mostly due to the shrinkage of the textile yarns and the moving/repositioning of the SMA wires in the structure. The increase in thickness after washing is less evident for samples H4 and R4, both made of thick flax yarns, which can be explained by the fact that the shrinkage was smaller than for the other samples (see also ***Figure 8***).

Dimensional stability of the fabrics

All the fabrics were marked both in the warp and weft direction before and after the washing (laundering) process. The shrinkage of all the fabrics (up to 20%) after washing was noticed, as shown in ***Figure 8***. It can also be observed that the shrinkage in % is higher in the warp direction than in the weft for both the reference and hybrid fabrics. Differences between the contraction in the weft and that in the warp direction are higher for the hybrid fabrics when compared with the reference fabrics as the SMA wires inserted in the weft direction prevent fabric shrinkage in this direction.

Wrinkle recovery of the hybrid fabrics

The fabrics were crushed in the weft direction, and wrinkle recovery tests were carried out [24]. The crushed samples were compared with the standards and given the appropriate classification in a scale from 1 - 5, where 1 means a strong wrinkle and 5 the absence of the crease. From the results given in ***Table 4***, it can be noticed that hybrid fabrics H1 and H3 present higher wrinkling than the reference samples, while samples H2 and H4 have the same creasing value as the reference samples. In a martensite state (Ms-Mf) SMA wires are flexible and can be

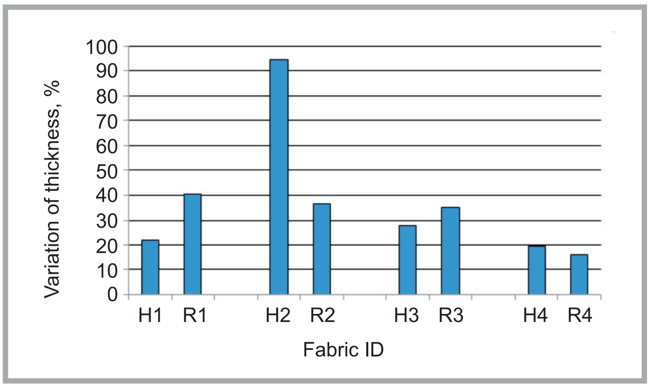

***Figure 7.** Influence of washing process on the thickness of the fabrics.*

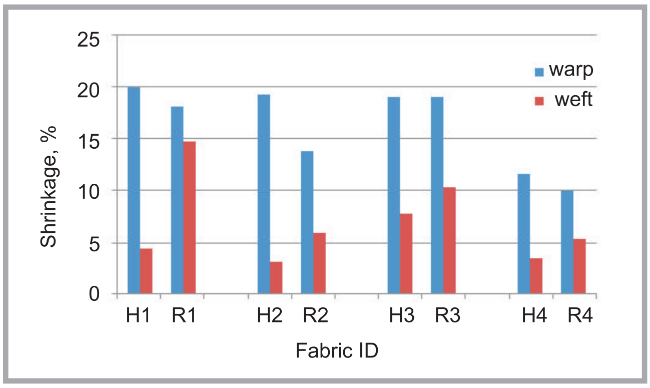

***Figure 8.** Influence of washing on the dimensional stability.*

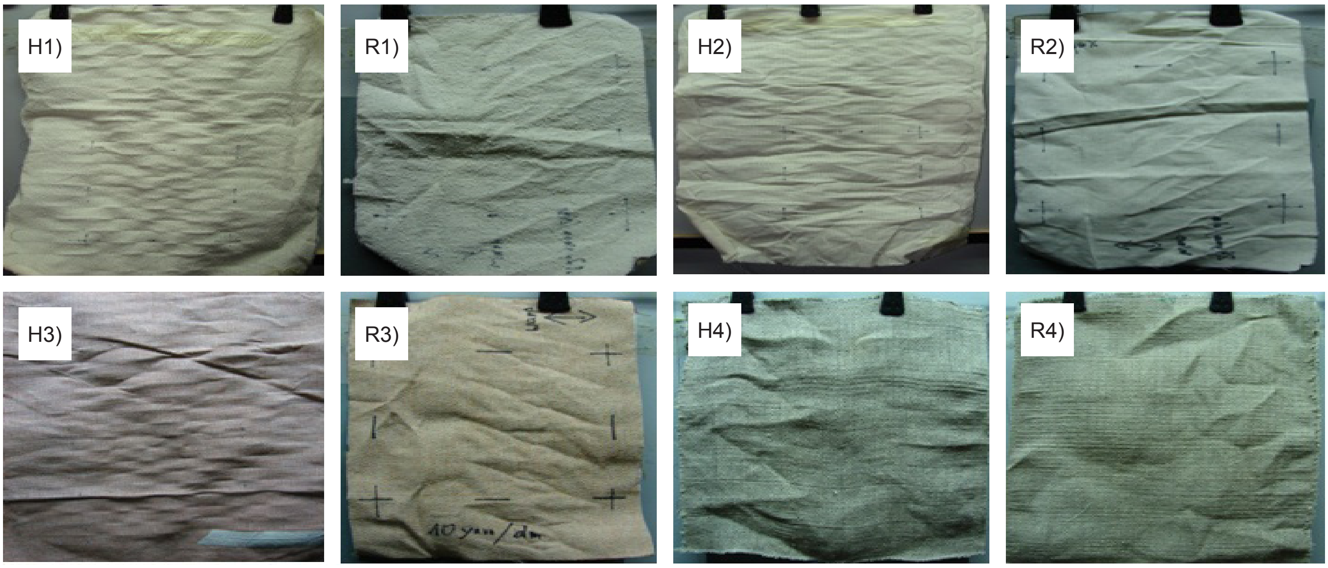

***Figure 9.** Crushed hybrid fabrics samples: H1, H2, H3, H4 and reference samples R1, R2, R3, R4.*

***Figure 10.** Wrinkle recovery for sample H4 after time period; a) t = 0 s, b) t = 8 s, c) t = 23 s.*

deformed to any shape. When the wires are subjected to temperatures above As (47 °C in our case), phase transformation from a martensite to an austenite phase begins. Above Af (53 °C in our case) the wires are in an austenite state and have completely recovered their initial shape (straight, in our case). The heat source can be a hairdryer, an electrical current, body temperature, etc. In this case, a hairdryer was used as a source of heat. The approximate time of recovery of the hybrid fabrics was recorded and is given in ***Table 5***. Under the influence of heating, the hybrid fabrics recovered their flat shape within a few seconds and became smooth, whereas in the case of the reference samples heating had no influence.

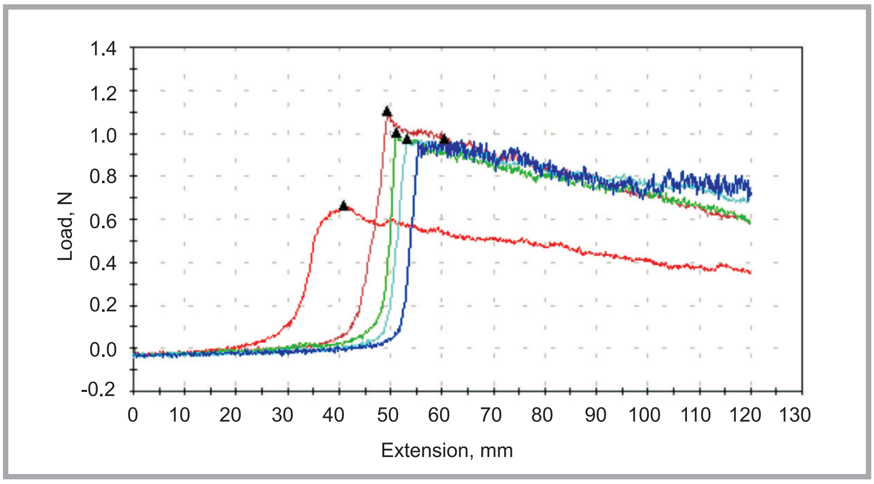

***Figure 11.** Example of a stress-strain curve for sample H1.*

The longest recovery time was observed for sample H4, which was made of coarse flax yarns. Hybrid fabrics H1, H2, H3, made of fine cotton and flax yarns and with a lower weight, (g/m^2) presented almost the same recovery time, around 10 s. ***Figure 9*** show hybrid (a) and reference samples (b) after the wrinkle recovery test. The evolution of the wrinkle recovery of sample H4 is presented in ***Figures 10.a*** to ***10.c***.

Cohesion of the SMA wires in the woven structure

As the slippage of SMA wires from the hybrid fabric was noticed, the cohesion of the SMA wires with the woven structure was assessed using a tensile tester (Instron). The samples were fixed in the upper clamp, the SMA wires were then cut at the edges and fixed in the lower clamp. The tensile tester pulls one SMA wire weft out of the fabric, and the stress-strain curve is recorded (***Figure 11***). Five samples were tested for each hybrid fabric, and average values for the maximum load, its standard deviation STDEV and

Table 5. Wrinkle recovery time of the hybrid fabrics.

Fabric ID	H1	H2	H3	H4
Recovery time, s	~10	~10	~10	~23

Table 6. Resistance to shifting of the hybrid fabrics.

Parameter, unit	Sample			
	H1	H2	H3	H4
Maximum Load, N	0.90	1.14	0.57	0.16
STDEV	0.16	0.08	0.12	0.02
CV,%	17.40	6.70	21.00	16.52

the coefficient of variation CV are displayed in ***Table 6***.

As various types of yarns were used in the weft direction (e.g. fine/ coarse yarns; single/ folded/ fancy yarns; stretch/ non-stretch yarns), as well as different weft densities, different behaviour was noticed due to the various frictions between the SMA wire and textile yarns. The slippage phenomenon was more evident in the case of hand-made fabric (e.g. H4). The low number of picks/cm and the relatively high diameter of the coarse flax yarns (in comparison with the SMA wire) can explain this. Moreover, the structure of these two fabrics is relatively loose due to the relatively low and variable beat-up force on a shuttle sampling loom compared to that on a power loom. Slippage is an unwanted phenomenon as it may cause deterioration of the fabrics during usage as well as injury to subjects coming in contact with the damaged fabric. The possibility of overcoming this drawback will be investigated in the future work.

Conclusions

- Four types of hybrid fabrics with SMA wires embedded in the weft direction were produced using a shuttle sampling loom and power loom.
- Both reference and hybrid fabrics were tested before and after one washing cycle. An increase in thickness was noticed after a washing cycle due to shrinkage of the fabrics, leading to a more bulky structure.
- The recovery time after crushing varied according to the type of fabric. As SMA wires were inserted in the weft direction only, the fabrics were crushed in this direction. To achieve a wrinkle-free fabric (in all directions), another insertion pattern of SMA wires has to be chosen.
- The tendency of SMA wires to be pulled out of the structure was dependent on the type of yarn used and its linear density, weft density and the weaving conditions.
- Attention should be given to choosing an appropriate diameter for the SMA wires and textile yarns, the weave, and pattern of SMA wire insertion to allow adequate recovery and to avoid an anaesthetic non-textile effect. In our case, samples H3 and H4 are a good example, as the presence of SMA wire in the hybrid structure could barely be noticed, even after the washing process. The SMA wires were camouflaged by the loop yarns (in the case of sample H3) and thick flax yarns (sample H4), which was not the case with samples H1 and H2 with fine stretch loop yarns and single flax/ cotton yarns, respectively.
- Further investigations will be conducted to produce hybrid fabrics on an industrial loom with automated insertion of the wire (e.g. via a rapier) to increase the cohesion of SMA wires in the structure and to decrease the time of recovery from creasing.

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