Comparative Analysis of the Mechanical Properties of Hybrid Yarns with Superelastic Shape Memory Alloys (SMA) Wires Embedded

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Abstract
Fabrics made of natural fibers like cotton, flax, and their blends present elevated wearing comfort, but they are unfortunately subject to creasing. Attempts made to improve the wrinkle recovery of flax fabrics by embedding shape memory alloy (SMA) wires in a woven structure highlighted the low cohesion of the smooth wires and the overall "non-textile" aspect of the fabric. This study aimed to overcome these disadvantages by developing hybrid yarns that contain a superelastic SMA wire - Smartflex as a core, covered by textile yarns or fibers. Three types of hybrid yarns were produced, and their structure, aesthetics as well as tensile and bending properties were assessed and compared. The hybrid yarns were embedded in a woven structure, and it was found that they significantly contributed to the increase in the crease recover angle of the flax fabrics.

Key words: *superelastic SMA wires, hybrid yarns, bending, crease recovery.*

Introduction

Shape Memory Alloys (SMA) are a group of metallic materials with outstanding properties such as the shape memory effect (SME), superelasticity, recoverable strain, a high damping capacity, etc. [1 - 3]. The SME occurs due to a temperature and stress dependent shift in the material's crystalline structure between two different phases, the martensite (low temperature phase) and austenite (high temperature phase). The temperature at which the phase transformation occurs is called the transformation temperature. In the austenite phase (***Figure 1.a***), the structure of the material is symmetrical, and when the alloy cools down, it forms the martensite phase and collapses to a structure with a different shape (***Figure 1.b***). If external stress is applied, the alloy will yield and deform to an alternate state (***Figure 1.c***). When the alloy is heated again above the transformation temperature, the austenite phase will be formed and the structure of the material returns to the original "cubic" form, generating force/stress [4].

In addition, SMAs exhibit superelastic behaviour when deformed at a temperature slightly above their transformation temperatures, which means that they can undergo much more intensive bending than a conventional metallic alloy. When a stress is applied to a superelastic SMA wire, and after a rather modest elastic deformation, it will change its crystal structure from an austenite or 'parent' crystal one to a martensite or 'daughter' structure. This 'stress assisted' phase transition allows the material to change shape as a direct response to the stress applied. When the stresses are removed, the material reverts to the original austenite and recovers its original shape [6]. Superelastic applications [7, 8] are isothermal in nature and involve the storage of potential energy ***(Figure 2).*** The sample is strongly deformed at relatively low stresses (a to b) at a temperature above Af. During subsequent unloading, a complete shape recovery occurs (b to c) [9].

Embedding of SMA wires in textile structures

Although a variety of metal alloys possess a SME, only a limited number of them are commercially important, such as the NiTi-alloy, known as NiTinol. NiTinol exists in different forms, such as bar, rod and wire shaped wire, sheet, ribbon wire, etc [1]. Although they are rather stiff, fine NiTinol wires are processable on textile machines. However, the application of thin SMA wires in textiles is still in the investigation phase, and only a limited number of applications are known [10 - 13]. Recent advances in 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 [14, 15]. One method used for embedding SMA wires into a textile structure is stitching [16]. Another method 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 [17 - 20].

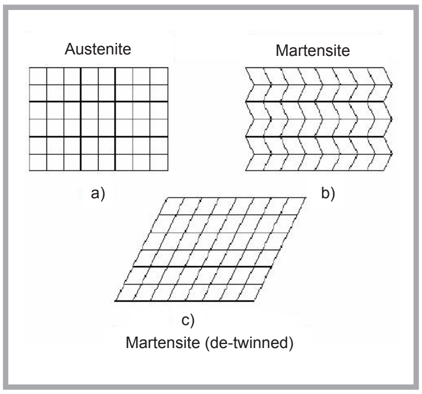


Figure 1. *Crystalline arrangement of SMA in different phases [4].*

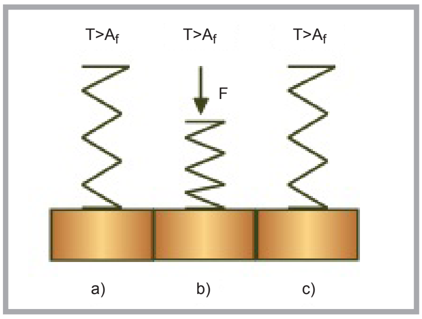


Figure 2. *Storage of potential energy above austenite finish temperature Af.*

Fabric wrinkle recovery

Ideally, a fabric should deform but at the same time recover from deformation rapidly. Wool is known to have very good elastic recovery and therefore has the power of resistance to and recovery from creasing. Flax-containing textile materials, cloth in particular, have elevated consumer properties, but unfortunately they are highly susceptible to creasing, caused by induced elasticity below the glass transition temperature of cellulose. The ability of a fabric to resist creasing or wrinkling and to recover from such deformation is determined by many factors, the most important being the mechanical properties of its fibres (e.g. tensile, bending and torsion properties), the geometrical and constructional parameters of the yarns and fabric, and the presence of finishing agents on the fibres and fabric [21].

Due to their crystalline structure, cellulosic fibres present elevated tensile properties but low elongation, about 3%. [22]. They are therefore highly susceptible to creasing and have a low recovery from it. Unlike most metals, superelastic NiTinol wires can undergo much more significant bending than conventional metallic alloys. For instance, stainless steel can return to its original length if stretched up to 0.3% of its original length, extremely elastic titanium alloys up to 2%, and superelastic Nitinol presents an elongation to failure of 12.5% and a maximum strain recovery of 8%.

Our previous work [20] highlighted the possibility of increasing the wrinkle recovery of flax fabrics upon heating with embedded Body Temperature SMA wires (BT SMA). However, an increased slippage tendency of the SMA wires was noticed as well as the “non-textile” aspect of the fabric. The low adhesion between the naked SMA wires and the other textile yarns, the relatively high diameter of the SMA wires (300 µm) and the unidirectional position of the SMA wires in the fabric were possible reasons for these disadvantages.

Aim of the research

The overall aim of this study was to develop hybrid yarns that overcome the disadvantages mentioned above and increase the wrinkle recovery of flax/cotton fabrics. This paper focuses on the design, production and characterisation of hybrid yarns by integrating a superelastic SMA wire with textile yarns/fibres, thus improving yarn processability, handling and aesthetics. Three types of hybrid yarns composed of a SMA wire core and textile sheath of yarns/fibres were produced, and their tensile and bending properties were evaluated as they influence the wrinkle recovery of fabrics with embedded hybrid yarns. In addition, the bending properties were evaluated after a number of bending cycles and compared with those of the reference SMA wire. Hybrid fabrics were then produced with the developed hybrid yarns embedded, and their influence on the fabrics’ crease recovery was assessed.

Materials and methods

The quality requirements of the hybrid yarns are to preserve the elastic properties of the SMA core, to have appropriate bending properties and preserve them after an amount of bending cycles. In addition, a textile aspect is required (the core has to be covered by the fibres/yarns) as well as appropriate finesses to ensure easy handling on spinning and later on weaving machines.

Experimental design

Hybrid yarns consisting of a SMA straight wire as a core, wrapped with textile yarns or fibres (roving), were produced on a hollow spindle machine. The principle of the hollow spindle process is shown in ***Figure 3 a***: the SMA core yarn is fed to a hollow spindle that carries the binding yarn. Three hybrid yarns of two types were produced:

- (1) two folded yarns (H1 and H2) consisting of a SMA wire twisted together with a single strand (H1) or five strands (H2) and fixed by a binding yarn
- (2) a core/sheath yarn (H3) consisting of a SMA core and PES roving and fixed by a binding yarn.

A superelastic Ni-Ti alloy (Ni 55.8 ± 0.5%) wire “Smartflex”, with a round cross-section and diameter of 200 µm, made by SAES Getters [1], was used as a core. Other characteristics include the following: a density of 6.5 g/cm^3; melting point of 1300 °C; As (austenite temperature), fully annealed, measured by DSC = -10°C ± 8 °C; Af (austenite finish temperature), fully annealed, measured by DSC = +5 °C ± 16 °C. Flax/cotton yarns (H1 and H2) and PES roving (H3) were wrapped around the SMA core, with a PES filament used as binding yarn. The structure of the hybrid yarns is represented in ***Figure 3.b - 3.c***. The type of component yarns used and the architecture of the hybrid yarns produced are given in ***Table 1.***

Production of the hybrid yarns

The hybrid yarns were produced on a fancy yarns spinning machine - Gigliotti & Gualchieri**.** The machine settings used for the production of the hybrid yarns were as follows:

- Hybrid yarn H1: 5000 r.p.m.; Twist Z: 700 twist/m; Winding tension 0.8;
- Hybrid yarn H2: Upper spindle 5000 r.p.m.; Twist Z: 700 twist/m; Winding tension: 1;
- Hybrid yarn H3: Upper spindle 5000 r.p.m.; Twist Z: 400 twist/m; Winding tension: 1; Draft: 20.

Some adjustments were necessary on the machine in order to enable the production of the hybrid yarns. For instance, in order to prevent the unwinding caused by the very smooth surface of the SMA wire, the SMA bobbin was placed horizontally**.** Additionally, an extra PES multifilament of 25 tex was used (as shown in ***Table 1***) to prevent breakage of the PES roving and allow the production of hybrid yarn H3.

Production of the hybrid fabrics

In order to assess the opportunity of using SMA wires to produce wrinkle-free

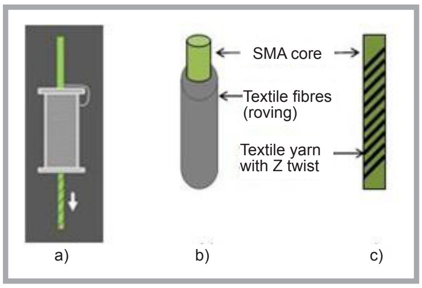


Figure 3. *Structure of the hybrid yarns; a) hollow spindle principle, b) core/sheath (H3), c) folded yarns (H1 and H2).*

Table 1. *Architecture of the hybrid yarns.*

Type yarns	Component yarns	H1	H2	H3
Core	SMA wire, 225 tex	#1	#1	#1
Effect	Cotton/flax yarn (50/50) 25 tex	#1	# 5	-
	PES roving, 2.15 ktex	-	-	#1
	PES multifilament, 25 tex	-	-	#1
Binding	PES multifilament, 25 tex	#1	#1	#1

flax fabrics, the hybrid yarns developed were embedded in 100% flax fabrics with a plain weave. All the fabrics were woven on an *ARM Patronic B60* sampling loom with manual weft insertion. The warp beam consisted of flax yarns 200 tex, and the hybrid yarns used in the warp were fed directly from bobbins. The weaving was possible, although the hybrid yarns had the tendency to unwind from the bobbin. Four types of hybrid fabrics (HF0, HF1, HF2, HF3) were produced by inserting a hybrid yarn (SMA wire, H1, H2, H3) in both the warp and weft directions, with a distance of about 5 cm between consecutive hybrid yarns. In addition, a 100% flax reference fabric (RF) was produced.

Methodology

The hybrid yarns and fabrics developed were conditioned in a standard atmosphere of 65± 2% RH and temperature of 20 ± 2 °C for about 24 hours before being tested, and all the experiments were conducted under standard conditions. The properties of the hybrid yarns and fabrics developed were assessed using the methods described below.

Structure of the hybrid yarns

Photographic images of the hybrid yarns were taken using an Olympus microscope and recorded with use of Cell D Software by Olympus Imaging Software for Life Science Microscopy. Image analysis apparatus Cell D Software was used to study the structure of the hybrid yarns [23].

Linear density of the hybrid yarns

An ITF maillemeter was used to determine the yarn linear density according to ISO 7211/5 (1984).

Tensile properties of the hybrid yarns

A Statimat M tensile tester was used to determine the tensile properties of the hybrid yarns and their components [24]. The settings used were as follows: gauge length 100 mm and test speed 100 mm/min (for SMA, roving, H1-H3); a gauge length of 500 mm and speed of 500 mm/min for the flax/cotton yarn; a gauge length of 250 mm and speed of 250 mm/min for the binding yarn; with a pretension of 0.5 cN/tex in all cases.

Bending fatigue of the hybrid yarns

A novel method [25] was employed to assess the bending property of the hybrid yarns developed. This method is primarily used to assess the resilience of a single filament when subjected to repeated flexing. The cyclic flexing test setup is presented in ***Figure 4***. It employs Favimat apparatus (by Textechno) modified in order to allow the flexing of the one-side-clamped filament. During the test, one end of the filament(s) is clamped, while the other free end is subjected to a perpendicular force. The filament has a free length of 17.5 mm and is flexed x = 2.87 mm from the clamped point. The limits of the displacement are 2.0 - 8.0 mm. The force needed to cause the flexing is measured in both the advancing and receding part of each cycle, thus obtaining a hysteresis force-displacement loop. The filament is flexed up to 300 times at a speed of 100 mm/min. The flexing cycles are limited to 300 due to the memory capacity of the machine. Each test consists of four repetitions, and the test duration for one repetition is about 40 minutes. The resilience is expressed as the ratio between the maximal force of the 300th flexing and the maximum force of the first flexing.

Crease recovery of the hybrid fabrics

A rectangular specimen of prescribed dimensions is folded by means of a suitable device and maintained in this state for a specified short time under a specified load. The creasing load is removed, the specimen allowed to recover for a specified time, and the crease recovery angle formed by the two legs of the crease is then measured. The magnitude of the crease recovery angle is an indication of the ability of a fabric to recover from accidental creasing. [26].

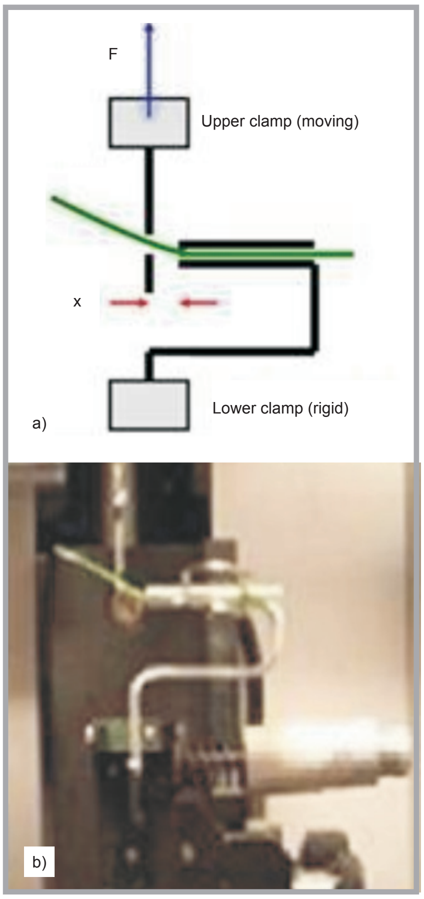


Figure 4. *Cyclic flexing test setup: a - schematic presentation, b - real view.*

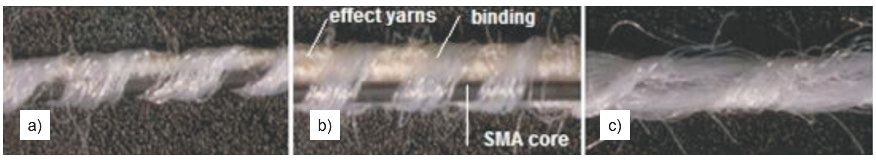
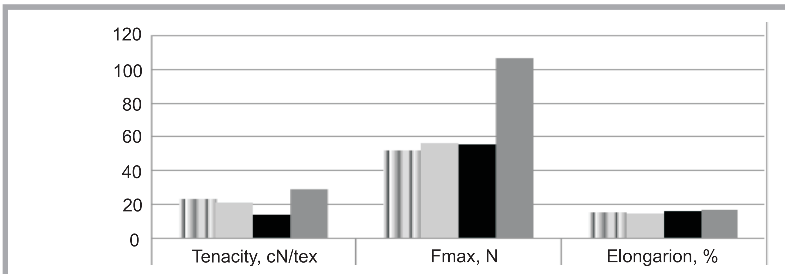


Figure 5. *Structure of the hybrid yarns (magnification 32 ×): a) H1; b) H2; c) H3.*



	Tenacity, cN/tex	Fmax, N	Elongarion, %
SMA Core, 225 tex	23	52	15.3
H1, 272 tex	21	56	14.5
H2, 383 tex	14	55	15.8
H3, 370 tex	28.6	106	16.5

Figure 6. *Mechanical properties of SMA core and hybrid yarns H1-H3.*

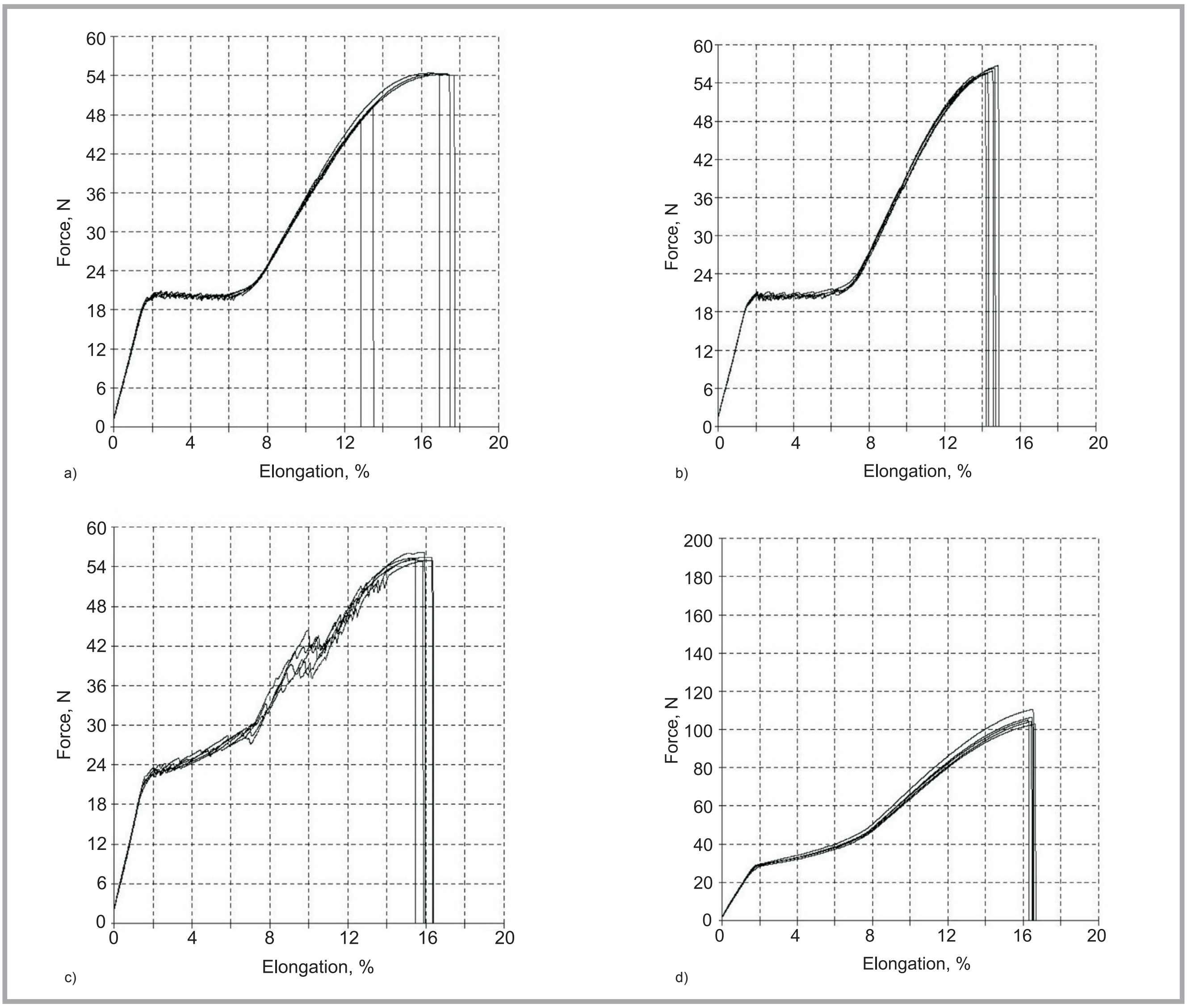


Figure 7. Force-elongation diagrams for: a) SMA core, b) H1, c) H2, d) H3, 100 mm/min.

Results and discussions

Structure of the hybrid yarns

The SMA core was visible in the case of hybrid yarns H1 and H2 (***Figure 5.a, 5.b*** see page 43) as the effect yarns (#1 and #5 respectively) were placed along with the core. The fibre roving had a higher surface covering of the core compared with the twisted yarns, and this uniform covering of the core (***Figure 5.c***) led to a "textile" aspect of hybrid yarn H3.

Table 2. Structural parameters of the parent hybrid yarns and contribution of individual components.

Hybrid yarn ID	Component yarns	Linear density, tex	Component yarns, g/km			Contribution, %		
			Core (SMA wire)	Effect yarn	Binding yarn	Core	Effect	Binding
H1	SMA Core (#1)	225	225	25	25	~82	~9	~9
	Effect yarn (#1)	25						
	Binding yarn (#1)	25						
H2	SMA Core (#1)	225	225	125	25	~59	~33	~8
	Effect yarn (#5)	25						
	Binding yarn (#1)	25						
H3	SMA Core (#1)	225	225	120	25	~61	~32.2	~6.8
	PES roving (#1)	2150, draft 20						
	Guiding filament (#1)	25						
	Binding yarn (#1)	25						

Linear density of the hybrid yarns

The linear density of the hybrid yarns measured was as follows: 225 tex (SMA core), 272 tex (H1), 383 tex (H2) & 370 tex (H3).

Tensile properties of the hybrid yarns

In ***Figure 6*** the tensile properties of the hybrid yarns and the SMA core are compared. It can be seen that the hybrid yarns preserve the elasticity of the SMA core, and hybrid yarn H3 exhibits the highest elongation and tenacity. The structure of H3 with uniformly wrapped fibres around the SMA core and the existence of an extra filament yarn that was used to guide the roving and prevent its breaking may lead to H3 having superior mechanical properties (see also ***Figure 7.d***).

The elongation at failure of the SMA core varied between 13% and 17 %, with

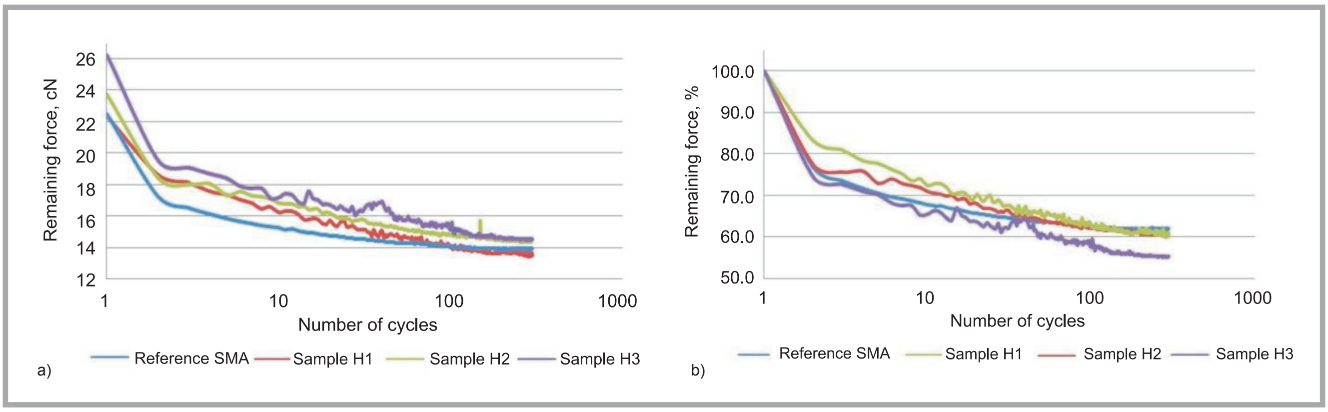


Figure 8. *Remaining force in cN (a) and in % (b) as a function of number of the flexing cycles.*

an average of 15 %, and it presented a maximum strain recovery of about 8% ***(Figure 7.a)***. Hybrid yarn H1 consists of a SMA core, an effect and a binding yarn, therefore its mechanical properties were most similar to those of the reference wire. In ***Figure 7.b*** it can be seen that H1 follows almost the same behaviour and has a similar superelastic plateau to the SMA core. In ***Table 2*** it can also be seen that the SMA core has the highest contribution (82 %) to hybrid yarn H1, with the textile components contributing only 18%.

When comparing the two folded yarns H1 and H2 (***Figure 7.b*** and ***Figure 7.c***), no increase in the Fmax was noticed when increasing the number of effect yarns from a single strand (H1) to five strands (H2). H2 presents a slightly higher elongation at break due to its five effect yarns breaking consecutively, but it also has a lower tenacity than H1**.** The superelastic plateau is also less visible in the case of H2 due to its structure. The work to break for H2 (54.24 N·cm) is higher than for H1 (44.21 N*cm) and even higher than for the SMA core (45.16 N·cm). There is thus no need to increase the number of effect yarns, as it does not significantly increase the tenacity nor the elongation of the yarn.

Bending properties of the hybrid yarns

Higher forces are required to bend the hybrid yarns than for the SMA wire. The hybrid yarns are stiffer than the SMA wire due to the textile materials, leading to increased linear density.

As can be seen in ***Figure 8.a,*** the force needed to flex hybrid yarns H1, H2 and especially H3 is higher than in the case of the reference SMA wire, and the absolute value of the remaining force (cN) after 100 and 300 flexing cycles is still higher for the hybrid yarns. It can also be noticed that H2 and H3 have almost the same resilience after 100 and 300 flexing cycles.

However, when looking at the relative remaining force ***(Figure 8.b),*** it can be seen that the SMA wire and hybrids H1 and H2 exhibit similar resilience after 100 flexing cycles (about 62%), but the resilience of the SMA after 300 flexing cycles is slightly higher (62.1%) compared with 60.3 (H1) and 61% (H2). This is in agreement with data from literature [6], which states in the case of Ni-Ti alloys, there is a decrease of about 55% (from 500 MPa to 275 MPa) in the max. stress after 100 flexing cycles, and a decrease in the max. strain from 8% to 4% after the same number of cycles.

The hybrid sample H3 requires the highest bending force but exhibits the lowest resilience after 100 flexing cycles (57.7%) and 300 flexing cycles (55.4%). This is probably due to the fibrous sheath around the yarns being damaged, and the fibres around the core (H3) are more likely to be displaced more easily than the yarns (H1 and H2).

Crease recovery of the hybrid fabrics

The crease recovery angle in the warp direction was measured using a specimen of 4 cm × 1.5 cm with a hybrid yarn positioned in the middle of the specimen. In ***Figure 9*** the crease recovery angle after 5 s and 5 minute is illustrated for hybrid fabrics HF0, HF1, HF2 and HF3 with an embedded SMA wire, H1, H2 and H3 hybrid yarns. Sample HF1 has the highest recovery angle from creasing (126°), followed by sample HF0 (121°) with an embedded SMA wire. For all the samples, the recovery angle increased between 8.7% (H1) and 11.9% (H2) after 5 min. It can be also seen that the RF present a recovery angle of 40°, while the hybrid fabrics have a recovery angle of 120°, which means that the hybrid yarns significantly improved the recovery from creasing of the flax fabrics.

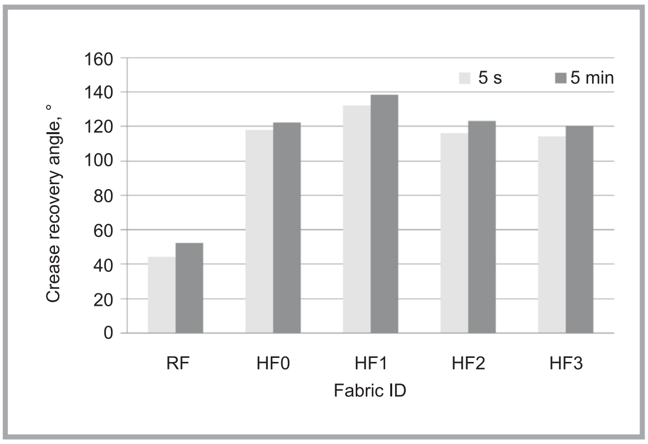


Figure 9. *Crease recovery angle of the fabrics.*

Conclusions

- SMA wires can be successfully combined with textile materials to produce hybrid folded yarns (H1, H2) and core sheath yarns (H3) using a modified spinning set-up based on the hollow spindle principle.

- The hybrid yarns fabricated present different aesthetic features. Hybrid yarn H3 presents the best aesthetic features, in the opinion of the authors, as the core is uniformly covered by the roving, it camouflages the SMA wire core and has, therefore, a textile-like appearance.
- As was expected, the mechanical properties of the hybrid yarns are strongly related to the SMA core's mechanical properties and yarn structure. It was noticed that hybrid yarn H1 with a single effect yarn presents near similar mechanical properties (e.g. force-elongation diagram) as the SMA core. No increase in the tenacity and elongation was noticed when increasing the number of effect yarns from a single strand (H1) to five strands (H2), thus there is no need to increase the number of effect yarns as this will not positively influence the mechanical properties of the yarns nor their price.
- Higher forces are employed to bend the hybrid yarns as they have a larger diameter and are also stiffer than the SMA wire. Hybrid sample H3 requires the highest bending force but exhibits the lowest resilience after both 100 flexing cycles and 300 flexing cycles.
- The application of the hybrid yarns significantly increased the crease recover angle of the flax fabrics, from 40° to about 120°. It is expected that a higher number of hybrid yarns in the woven structure will have a positive impact on the crease recovery angle of the fabrics.
- In the opinion of the authors, hybrid yarn H3 fulfils most of the quality requirements as it presents the best aesthetic features, high elongation and tenacity. It is, however, stiffer than the other hybrid yarns and exhibits lower resilience after 100 and 300 flexing cycles. When the bending properties and crease recovery of the fabrics are the most important features required, the authors would then recommend hybrid yarn H1.

Acknowledgments

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