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Wrinkle Recovery of Flax Fabrics with Embedded Superelastic Shape Memory Alloys Wires

Abstract
The present study explores the possibility of using superelastic Shape Memory Alloy (SMA) wires to improve the wrinkle recovery of flax fabrics that exhibit very poor recovery from creasing. Three types of hybrid yarns (H1- H3) were developed consisting of a SMA wire (Ni-Ti alloy) as the core, with a textile shield around it. Hybrid fabrics (HF1 - HF3) were developed by embedding the hybrid yarns in both the warp and weft directions of a fabric, to bring about all-direction recovery from creasing. The wrinkle recovery angles (WRAs) of the hybrid fabrics were assessed in both dry (RH 65%) and wet (RH 90%) conditions, and they were compared with those of reference flax fabrics (RF) and forth hybrid fabric (HF0) with Ni-Ti SMA wires embedded. The results showed a significant increase in the Wrikle Recover Angle (WRA) for all hybrid fabrics, from about 40 to approximately 120 degrees. Statistically significant differences were noticed between the WRA of hybrid fabrics HF2 and HF3 in dry conditions, as well as a significant variation in the WRA with humidity for hybrid fabric HF2. In addition, the bending properties of the four hybrid fabrics were assessed, but no significant correlation was found between these properties and the WRA of the hybrid fabrics.

Key words: *superelastic SMA wires, hybrid yarns, wrinkle recovery angle.*

Introduction

Factors affecting the crease recovery of fabrics

Nowadays aesthetic aspects have an increasing influence on the overall quality of a garment. Fabric appearance is usually characterised by a number of factors such as strength, pilling, abrasion resistance, shrinkage, drape, colour and wrinkles. Wrinkles are defined as fabric deformation based on its viscoelastic properties. Wrinkles are classified into two categories, namely desirable and undesirable wrinkles occurring during wear [1]. The creasing of textile materials is a complex phenomenon which involves tensile, bending compression and torsional stresses. Bending elasticity plays an important role in the creasing phenomenon of fabrics [2]. The crease recovery of fabrics depends on the time of creasing, the time of recovery and the extent of crease curvature. The deformation-recovery behaviour of most fibres is time-dependent because the fibres are viscoelastic. Materials which resist creasing also resist deformation, and therefore they behave as rigid material. Ideally a fabric should be deformed, but at the same time it should recover rapidly from deformation [2]. It is well known that some fibre types, such as wool have very good elastic recovery power, and therefore they have the power of resistance to and recovery from creasing. The resistance and recovery power of creasing are largely influenced by the type of woven structure in which wool is employed. Cellulosic materials such as cotton, viscose and linen have a very poor resistance to creasing owing to a very high orientation of cellulose present in the fibre [3].

Wrinkle-free fabrics

Some well known modalities used to improve a fabric's wrinkle resistance refer to the adequate selection of the fabric construction, raw materials and/or wrinkle-resistant finishing. Shape Memory Materials SMMs (e.g. polymers and alloys) have also been used lately for the same purpose.

Fabric construction and selection raw materials

Fibre, yarn and fabric characteristics and finishing processes contribute to the development of wrinkles. Factors that affect wrinkle development include fibre type and its bending performance, fibre diameter, yarn twist, weft-warp density, fabric construction and thickness. Improvement in fibre bending performance increases the wrinkle resistance of fabrics. Low and high twist levels of the warp and weft result in a decrease in the wrinkle resistances of fabrics. However, medium twist levels of yarn improve the wrinkle resistance of fabrics [1].

The studies in [2] showed that the crease recovery of well-relaxed fabrics woven from high recovery fibres is independent of the fibre linear density and fabric construction. However, the crease recovery of fabric woven from poor recovery fibres, such as cellulosic fibres, can be improved significantly by choosing a more open fabric construction (e.g. tweed, satin) [4]. By increasing the weft-warp density, the wrinkle resistance of fabrics decreases. Knitted fabrics have a higher wrinkle resistance than woven fabrics, and an increase in fabric thickness results in an increase in the wrinkle resistance of fabrics [1].

Wrinkle-resistant finishing

Many cotton fabrics are treated with chemicals to reduce wrinkling. Wrinkle-free finishing is also known by consumers as 'Easy Care' and 'Wrinkle-resistant' [4]. This finishing uses the following methods of high-temperature processing: impregnating the material, and drying and processing at high heat. Various products are used to produce wrinkle-free cellulosic fabrics [5].

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The chemicals that are most commonly used in the easycare or wrinkle-free finishing of fabrics are dimethyloldihydroxyethyleneurea (DMDHEU), dimethylolethyleneurea (DMEU), melamine-formaldehyde condensation products, citric acid, polycarboxylic acids (e.g. BTCA) and related compounds. They act on the fibres largely by changing their viscoelastic properties. Fabrics finished with these conventional chemicals show better wrinkle recovery ability than untreated fabrics and hence are called 'wrinkle-free' fabrics. However, after repeated washing wrinkles reappear on the fabrics and ironing becomes necessary to achieve the original flat appearance [4]. The wrinkle recovery of cotton fabrics can also be improved by using high molecular weight film-forming polymers, such as polyacrylates, polyurethanes, polyethers, silicones and elastomers [4]. Nevertheless some of these products (e.g. BTCA) are expensive to use and citric acid causes yellowing. Anti-wrinkle finishing is also applied to fabrics for clothing, but it leads to increased fabric costs. Conclusively, the costs can be minimised by selecting fibres, yarn and fabric with high wrinkle resistance characteristics before applying crease resistant finishing. Nevertheless it was found that some finishing processes significantly affect fibre characteristics, and while the wrinkle recovery angle increases by approximately 50%, the breaking strength and tear strength decrease by about 25%, and the pilling performance is reduced by 59% after crease resistant finishing [1 - 3]. A higher initial fabric strength could compensate for the strength reductions [8].

Shape Memory Polymers (SMPs) and Alloys (SMAs)

Stimuli-responsive polymers (SRPs) like thermal-responsive shape memory polymers, moisture-responsive share memory polymers, etc. can be applied in textiles to improve their functionalities in terms of aesthetic appeal, comfort, etc. In recent years, shape memory emulsion with shape memory polymer (SMP) has been reported [4]. Hu en her group [4, 7 - 9] successfully developed shape memory emulsions from the polyurethane polymer family and employed them in the finishing of cotton fabrics to obtain a shape memory effect. The emulsions could be applied to woven cellulose fabrics such as cotton, ramie and linen as well as to wool fabrics by the pad-dry-cure method. Their studies revealed that the shape memory functions could be efficiently achieved through high wrinkle recovery, crease retention and bagging recovery.

One of the advantages of using SMPs is that the treated fabric does not release formaldehyde during finishing, as in the case of using DMDHEU. In addition, SMPU finishing will not significantly affect the mechanical strength and witness index of the fabric, as in the case of employing wrinkle-free finishing based on polycarboxylic acids, typically BTCA (1, 2, 3, 4-butane tetra-carboxylic acid), which is also expensive [10].

Shape Memory Alloys (SMAs)

SMAs show two unique capabilities: the Shape Memory Effect (SME) and superelasticity (SE), which are absent in traditional materials. Both SME and SE largely depend on the solid-solid, diffusion-less phase transformation process (known as martensitic transformation), from a crystallographically more ordered parent phase (austenite) to a crystallographically less ordered product phase (martensite). The phase transformation is typically marked by four transition temperatures, known as Martensite finish (*M*f), Martensite start (*M*s), Austenite finish (*A*f), and Austenite start (*A*s). Phase transformations may take place depending on changing temperature (SME) or changing stress (SE) [11]. The deformation behaviour (superelasticity) of the SMA can be as high as 20× of the elastic strain of steel. The strain related to this phase transformation is fully reversible after removing the stress. Commercial NiTi alloys (NiTinol) show as much as 8% of the superelastic strain [12].

SMAs exist in different forms: a bar, rod, wire, shaped wire, sheet, ribbon wire, etc. Although they are rather stiff, fine SMAs wires are processable on textile machines. Some application fields of smart textiles based on SMA wires include medicine, composite materials, shape changing clothing, etc. [13 - 22].

Shape memory fabrics with improved wrinkle recovery under certain conditions (temperature variation) were developed by embedding Body Temperature SMA wires (BT SMA) in flax fabrics. [21] Nevertheless a non-textile aspect of the fabrics and a slippage tendency of the SMA wires out of the fabric structure were observed, probably due to low adhesion between the naked SMA wires and the textile yarns, a relatively high diameter of the SMA wires (300 μm) and to the employment of the SMA wires only in the weft direction.

Aim of the study

A distinction should be made between shape memory fabrics and wrinkle-free fabrics. Fabrics treated with SMP or embedded Nitinol wires with the shape memory effect (SME) can be called shape memory fabrics. Shape memory fabrics can recover their original shape under certain conditions (temperature variation) due to the SME of the embedded SMPs or SMAs. A wrinkle-free fabric has good elasticity and can therefore recover after the release of forces that cause deformations. A wrinkle-free fabric is not temperature sensitive and cannot recover its original shape as a consequence of temperature variation.

Hence, it was of interest to develop new hybrid fabrics with high wrinkle recovery which are not temperature sensitive. The present study investigates if SMA wires that exhibit superelasticity (SE) are a good alternative to create *wrinkle-free fabrics*. The recovery of the fabrics should be spontaneous, without employing any heating/cooling treatment, and their mechanical properties and esthetics should not be altered.

To ensure a textile-like aspect of the fabrics, three types of hybrid yarns were produced with superelastic SMA wires 'Smartflex' as a core and textile shield. The hybrid yarns were inserted in both the warp and weft directions to allow increased recovery from creasing in all directions. The WRAs of the hybrid fabrics were assessed, both in dry (RH 65%) and wet (RH 90%) conditions and were compared with those of a reference flax fabric as well as of a fabric with Smartflex wire embedded to evaluate the need of using hybrid yarns instead of SMA wires only. The bending properties of the fourth hybrid fabrics were assessed as they were expected to influence the aesthetics of the fabrics, in particular their WRA.

Materials and methods

Materials selection

- SMA wires

'Smartflex' wires [11], superelastic at room temperature, consisting of a Ni-Ti alloy with Ni 55.8 ± 0.5 %, were used as a core. The Ni-Ti alloy has the

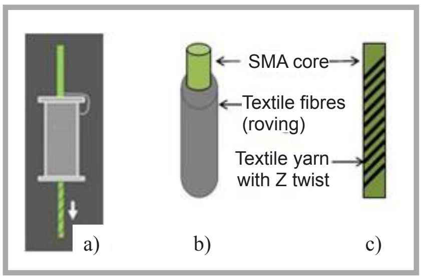

Figure 1. Structure of the hybrid yarns: a) hollow spindle principle, b) core/sheath (H3), c) folded yarns (H1 and H2).

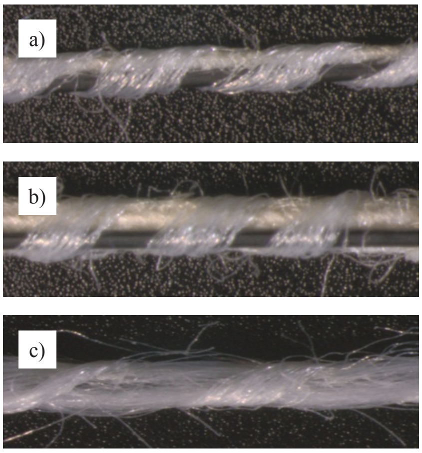

***Figure 2.** Structure of the hybrid yarns (magnification 32 ×); a) H1, b) H2, c) H3.*

***Table 1.** Tensile properties of hybrid yarns.*

Parameters	SMA wire	H1	H2	H3
Linear density, tex	225	272	396	370
Tenacity, cN/tex	23.0	21.0	14.0	28.6
Tenacity, % CV	6.50	0.95	0.93	2.83
Elongation, %	15.3	14.5	15.8	16.5
Elongation, % CV	13.0	1.89	2.04	0.73

following characteristics: a density of 6.5 g/cm^3, a melting point of 1300 °C, T_{As} (austenite temperature) = -10 ± 8 °C and T_{Af} (austenite finish temperature) = +5 ± 16 °C fully annealed, measured by DSC.

The SMA wire was used to produce three types of hybrid yarns, coded as H1- H3.

Hybrid yarns

Hybrid yarns consisting of a SMA straight wire as a core, wrapped with textile yarns or fibre roving were produced on a fancy yarn spinning machine - Gigliotti & Gualchieri. The principle of the hollow spindle process is shown in ***Figure 1.a***: the SMA core yarn is fed to a hollow spindle that carries the binding yarn. The structure of the hybrid yarns is as follows: (1) a folded yarn (H1) consisting of a SMA wire twisted together with #1 effect yarn and fixed by a binding yarn; (2) a folded yarn (H2) consisting of a SMA wire twisted together with # 5 effect yarns and fixed by a binding yarn; (3) a core/sheat yarn consisting of a SMA core and PES roving and fixed by a binding yarn. The properties of the components yarns were presented elsewhere. [22] The structure of the hybrid yarn H3 is represented in ***Figure 1.b*****,** and the structure of hybrid yarns H1 and H2 is shown in ***Figure 1.c***. The structure of the hybrid yarns is represented in ***Figure 2*****,** and the characteristics of hybrid yarns H1-H3 and SMA wire measured are given in ***Table 1.***

Flax yarns

In addition, flax yarns 172 tex were used in both the warp and weft directions to produce fabrics where the hybrid yarns were embedded.

Hybrid fabrics

The SMA wire, flax yarns and hybrid yarns H1 - H3 were used to produce hybrid fabrics. Four hybrid fabrics (coded as HF0, HF1, HF2 and HF3) and a reference fabric (coded as RF) were produced by inserting a SMA wire or a hybrid yarn H1, H2 or H3, respectively, in the flax fabric. The hybrid yarns were embedded in the flax fabric in both the warp and weft directions. The distance between two subsequent hybrid yarns was approximately 5 cm, as displayed in ***Figure 3.*** Flax yarn 172 tex was used in both the warp and weft directions. The fabrics were woven with a plain weave 1/1 as flax woven fabrics with a plain structure are most susceptible to wrinkle formation. An ARM Patronic B60 sampling loom was used, and it was noticed that yarns H1 and HF2 were easier to process. The fibrous sheet around the core of H3 was often displaced during weaving, and this yarn presented snarls that may also cause problems in the further processing of this yarn on an industrial weaving machine.

Methodology

The construction parameters of the four hybrid fabrics and their various aesthetic properties were studied. The hybrid fabrics were conditioned in a standard atmosphere of 65 ± 2% RH and at a temperature of 21 ± 1 ° C for about 24 hours before being tested, and all the experiments were conducted under standard conditions. In addition, the WRA of the fabrics was also assessed for samples conditioned at 90 ± 2% RH and 35 ± 1 °C.

Structure of the hybrid fabrics

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

Number of yarns per centimeter

This represents the number of yarns in a fabric counted over a specified length. The distance over which the yarns have to be counted depends on the fabric density: for less than 10 yarns/cm, one counts over 10 cm of fabric; between 11 and 50 yarns/cm one counts over 5 cm of fabric; for more than 50 yarns/cm one counts over 2 cm of fabric. Counting is repeated 3 to 5 times per direction [24]. Both the number of ends and picks were calculated.

Yarn count and crimp factor

The crimp is defined as the difference between the straightened thread length and the length of the fabric expressed as a percentage versus the length of the fabric [25].

Mass per unit area

5 samples of 100 cm^2 each are cut from the fabric. Each sample is weighed and the mean weight per m^2 is calculated. For a small sample or irregular fabric, one single square or rectangular piece is cut out, measured and weighed [26].

Fabric thickness

The thickness is measured by means of a thickness gauge. The choice of the presser foot and pressure applied are determined in the function of the fabric. The fabric is put under the presser foot, without creases. The presser foot is then lowered in a slow and careful movement, and the thickness is read after 30 seconds. The thickness is measured in 10 places distributed over the sample, and the average is calculated [27].

Fabric flexural rigidity

Bending rigidity is a key component in deciding fabric handle and drape as it is an important contributor to a fabric's formability, buckling behaviour, wrinkle and crease resistance [28]. Flexural rigidity represents the resistance against bending and is one of the parameters that determine the drapability of a fabric. The quantities measured are the bending length and flexural rigidity, which is done by pushing a fabric strip with a bar of a certain weight above it, marked in cm, over the horizontal part of the 'Stiffness tester', so that the fabric bends over the edge. If the edge of the strip coincides with a line that makes a certain angle with the horizontal plane, the overhanging length is measured by reading the bar. The bending length is calculated as half the overhanging length, and the flexural rigidity is calculated as the mass per surface of the fabric multiplied by the bending length raised to the third power [30].

Wrinkle recovery

Wrinkle recovery is the property of a fabric which enables it to recover from folding deformations.

A test specimen of 4×1.5 cm creased and compressed under controlled conditions of time and load is suspended in the test instrument for a controlled recovery period, after which the recovery angle is measured. The WRA is taken as a measure of the elasticity of the fabric and of the wrinkle recovery capacity of the specimen [29].

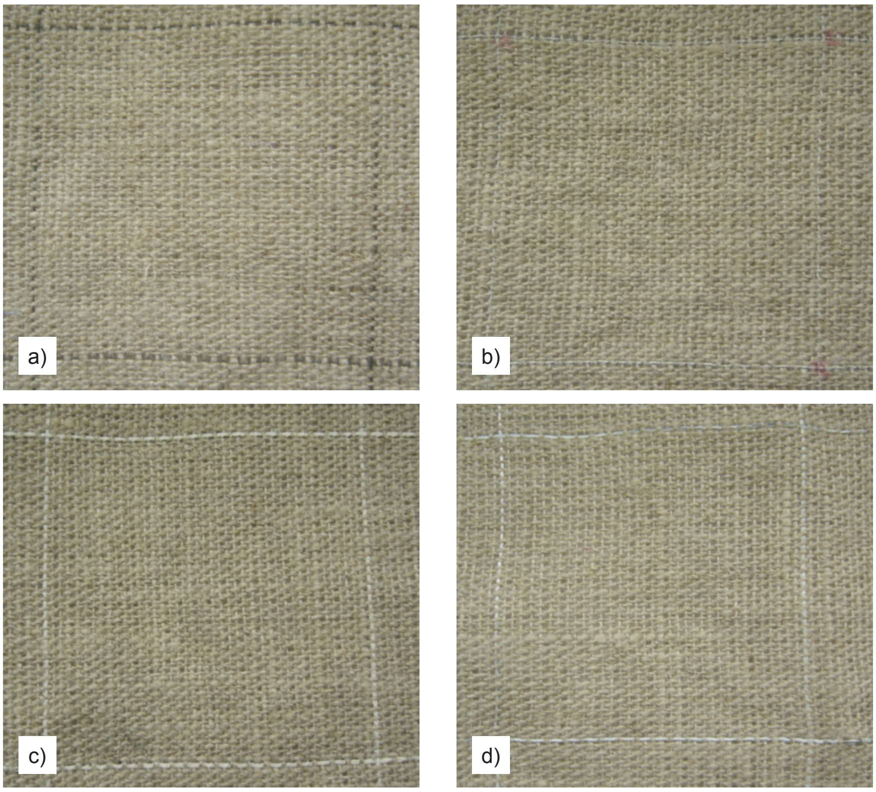

Figure 3. *Structure of the hybrid fabrics; a) HF0, b) HF1, c) HF2, d) HF3.*

Table 2. *Construction parameters of the hybrid fabrics.*

Fabric ID	Thickness, mm	Weight, g/m^2	Weft density, picks/10 cm	Warp density, ends/10 cm
HF0	1.07	374.7	79	127
HF1	1.19	371.3	72	125
HF2	1.09	381.2	76	124
HF3	1.13	369.9	69	124

Results and discussion

Fabric construction

The structure of hybrid fabrics HF0-HF3 is shown in ***Figure 3.a - 3.d.*** Unlike the fabric with embedded SMA wires, all three specimens HF1 - HF3 have a textile-like aspect. Nevertheless sample HF3 feels more rigid and hybrid yarn H3 sometimes forms loops on its surface. This yarn is the thickest and most rigid (see also ***Figure 4***, paragraph **Flexural rigidity of the hybrid fabrics**), therefore less suitable for a plain weave 1/1. In contrast, the finest hybrid yarn H1 is hardly noticeable in the structure of fabric HF1, which feels like the most flexible fabric of all four investigated. The construction parameters of the fabrics are listed in ***Table 2.*** The thickness of the fabric was measured between hybrid wires as well as on the wire itself. The value in ***Table 2*** is an average of 10 individual measurements. The hybrid yarns were more rigid and difficult to bend when compared with the flax yarns, and they formed kinds of snarls on the surface of the fabric, leading to (local) variation in the thickness (CV% between 9 and 19%).

The crimp factor of the flax measured varied between 9 - 12 %. The crimp factor of the hybrid yarns was not possible to evaluate in either warp or weft directions as the superelastic core immediately spring back to a straight form when the yarns were cut and released from the woven structure.

Flexural rigidity of the hybrid fabrics

Generally speaking, the bending properties of a fabric are determined by the yarn-bending behaviour, the weave of the fabric and the finishing treatments applied [4]. The samples were tested with the hybrid yarn lying in the middle of the sample in the warp direction. The flexural rigidity in the weft direction was not measured due to the small size of the samples produced on the sampling loom, with a maximum fabric width of 60 cm. The bending length (cm) and flexural rigidity G in g·cm of the hybrid and reference fabrics are shown in ***Figure 4,*** as well as the bending properties of the corresponding hybrid yarns. The bending length of the fabrics varied between 7.9 mm (HF2) and 10.4 mm (HF0). The force required to bend the hybrid yarns (first bending cycle) was 29.69 cN (HF3), 28.62 cN (HF0), 25.34 cN (HF2) and 24.29 cN (HF1). The testing method for evaluation of bending properties of the hybrid yarns was reported elsewhere [22].

In ***Figure 4*** (see page 60), it can also be noticed that hybrid fabric HF3 has a higher flexural rigidity G than HF1 and HF2. As shown in ***Figure 2,*** the corresponding hybrid yarn HF3 is a core/sheat yarn consisting of a SMA core with PES roving around, fixed by a binding yarn. Its structure is different from that of H1 and H2, which is also reflected in its different bending properties.

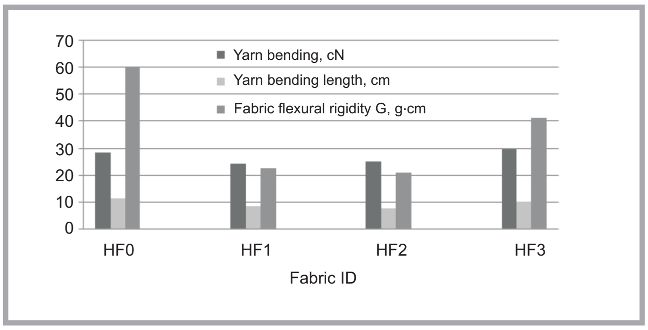

Figure 4. *Bending properties of the hybrid yarns and fabric flexural rigidity.*

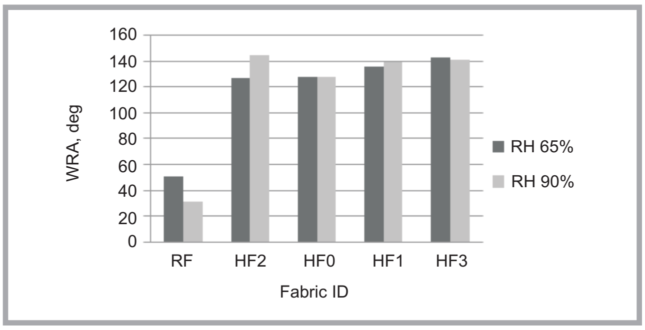

Figure 5. *Influence of humidity on the wrinkle recovery angle WRA of fabrics.*

A one-way ANOVA analysis (significance level alfa = 0.05) was performed to determine if the differences between the hybrid yarns and hybrid fabrics were statistically significant. No significant differences were found between the bending of the hybrid yarns, bending length or flexural rigidity of the four hybrid fabrics, meaning that the different structure of the three hybrid yarns did not lead to different bending properties of the hybrid yarns nor for corresponding fabrics.

Wrinkle recovery

During the measurements, the SMA wire was always positioned in the middle of the sample, in the warp direction. The values from the graphs are average values of 10 measurements. Both reference flax sample RF and hybrid fabrics HF0-HF3 were tested in dry (RH 65%) and wet (RH 90%) conditions. After 5 minutes from removing the weight, the WRA was recorded, and it was noted that most of the fabric recovery took place in the first seconds after removing the weight, due to the superelastic SMA wire, which sprung immediately back and tended to recover its initial, straight shape.

In ***Figure 5*** it can be seen that the embedded hybrid yarns have significantly improved the WRA of all samples, from about 40 degrees to more than 120 degrees. The influence of humidity on WRA can be also deduced from ***Figure 5***, where it can be seen that, unlike the hybrid fabrics, the dry reference sample recovered faster than the wet one. The same behaviour could be noticed for sample HF3, which had a slightly lower (3.5%) WRA in wet conditions. Embedded hybrid yarn H3 consisted of PES fibres around the core, which absorbed less humidity than the #5 cotton yarns, respectively, and #1 cotton yarn in the case of hybrid yarns HF2 and HF1. The WRA of the HF2 was about 14% higher in wet conditions, which was probably due to the structure of this yarn.

A one-way ANOVA test revealed that there are statistically significant differences between the WRA of the hybrid fabrics in dry conditions. A post hoc Tukey test performs a pairwise comparison of the means to see what the significant differences are. The tests showed a significant difference between the WRA of fabric HF2 and HF3. As the four hybrid fabrics differ from each other by the type of hybrid yarn, it means that the structure of yarn H3 led to fabric HF3 having a higher wrinkle recovery. No statistically significant difference was found between the WRA of the fabrics in wet conditions. A paired ANOVA test revealed a significant difference between the WRA in dry and wet conditions for fabric HF2, meaning that humidity has a significant influence on hybrid yarn H2 and thus on the WRA of fabric HF2. Unlike the other hybrid yarns, H2 consists of five cotton component yarns that absorb more humidity than H1 and H3.

No statistically significant (Pearson) correlation was further found between the fabric stiffness, fabric bending length, yarn bending, WRA65% and WRA 90% of the hybrid fabrics, which indicates that the wrinkle recovery of the fabrics is influenced by additional factors.

Conclusions

1. Superelastic SMA wires were employed to create wrinkle-free fabrics. Four hybrid fabrics were woven on a sampling loom by inserting superelastic SMA wires (H0, H1, H2, H3) in the flax fabric. The wires were inserted in both the warp and weft directions, with the distance between two consequent wires being 5 cm.
2. The superelastic SMA wires significantly improved the wrinkle recovery (WRA) of the reference flax fabrics from about WRA 40 degrees up to WRA 120 degrees. Significant differences were noticed between the WRA of hybrid fabrics HF2 and HF3 in dry conditions. There were some variations in the WRA with humidity for all samples, but they were not found to be statistically significant, except for fabric HF2. This was probably due to the fact that embedded yarn H2, consisting of five cotton yarns wrapped around the core, absorbed more humidity than other hybrid yarns.
3. All the hybrid fabrics HF1- HF3 developed had an elevated textile-like aspect when compared with fabric HF0 with an SMA wire embedded. Nevertheless, fabric HF3 was more difficult to weave, feels more rigid and some snarls alter its aesthetics. Both HF2 and HF1 were easy to weave and exhibit elevated aesthetics. There were no significant differences between the WRA of HF2 and HF1, therefore hybrid yarn H1 would be preferred, considering also its lower price and fast production.
4. It is assumed that the embedded hybrid yarns with a SMA core will not decrease the mechanical properties of flax fabrics and may therefore be a valuable alternative to “wrinkle free” finishing. However, the crease retention should also be assessed in addition to the measurement of WRA, which only gives an indication of the elasticity of the hybrid fabric. Such fabrics can be employed in applications where shape recovery after deformation is needed, for example tents, curtains, bags, etc.

Acknowledgments

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