# Investigating Smart Textiles Based on Shape Memory Materials

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Abstract The emergence of high performance fibers and Smart textiles has led to the development of new textiles having sensing, adapting and reacting capabilities. Textile designers are exploring unorthodox areas for inspiration for the production of new and pioneering textiles. This paper investigates Smart aspects of textiles based on shape memory materials particularly for enhancing the aesthetics of woven interior textiles. Shape memory alloy and shape memory polymer have been modified to allow the materials to be incorporated into the woven structure. Through yarn spinning, hybrid blends have been produced; the aesthetic engineering of which has provided new woven textiles that are capable of sensing a temperature change and reacting by changing to a prescribed shape. Examples of applications for these new dynamic textiles will be described and discussed.

Key words shape memory alloy, shape memory polymer, woven, fabric design, interior

Shape memory materials (SMM) are able to sense a change in temperature and react by changing into a prescribed shape [1]. SMM have additional properties, which include pseudoelasticity or recoverable stroke (strain), high damping capacity and adaptive properties, which are due to the ability to reverse the transformation during phase transitions. There are a variety of physical changes that SMM can sense in their environment, including thermal, mechanical, magnetic or electric. These physical factors are able to stimulate the shape memory effect (SME) enabling them to respond and transform to a prescribed shape, position, strain, stiffness, natural frequency, damping, friction and other static and dynamic characteristics of material systems.

SMM can be seen in a variety of materials such as alloys, ceramics, polymers and gels. These have been explored and developed as they demonstrate SME behavior [1-3]. These materials have also been commercially developed as they are a part of some consumer products [4]. As an adaptive material they can convert thermal energy into mechanical work. Until recently, SMM has been predominantly developed for applications for the biomedical and engineering industry [5]. A recent application for shape memory alloy (SMA) was a shirt designed by Corpo Nove, a fashion house in Italy, which shortens its sleeves when the temperature rises and does not require ironing when stimulated [6, 7]. Mitsubishi Heavy Industries have produced their own range of active sports clothing called "Diaplex" by applying a shape memory polymer (SMP) laminate [8]. The SMP laminate is placed between two layers of fabric, creating a membrane, which is simultaneously waterproof, windproof and breathable.

There are a variety of factors which can stimulate SMM, including electric current, solar energy, magnetic energy and heat produced by changes in body temperature. Despite the recognition of the importance of SMM, their use has almost exclusively been applied for industrial products for enhancing their performance and functionality. Their aesthetic attributes have yet to be recognized and this project was set up to explore the area of aesthetics of SMM. The two types of SMM applied to this research are SMA and SMP. The unique shape recovery of the SMM inspired the aesthetic development of the materials. The change of shape wanted to be enhanced within the woven structure, thus the object of the designs were to enhance this movement. The design aspect of the research was the focus, wherein the characteristics of the SMM motivated the designs of this research.

## The Principle of SMA

The deformation mechanism of SMA consists of a crystal lattice structure. The SME of the material is due to the martensitic phase transformation (MPT). There are two stable phases, a low-temperature phase called martensite and a high-temperature phase called austenite. During the martensite phase the SMA can be distorted into its predetermined shape. In addition, the alloy can regain its original shape by the reverse transformation upon heating to a critical temperature called the reverse transformation temperature (A^sub s^) [1]. Figure 1 illustrates an example of the MPT.

The training of the SMA comprises a procedure of repetitive heating and rapid quenching to permit a permanent relationship between the two stable phases. On completion of this procedure, the SMA is capable of 'remembering' to transform into the prescribed shape at the stimulant temperature. SMA additionally can demonstrate super-elasticity (SE), which is a pseudo-elasticity that occurs above A^sub s^. Upon a force or load the alloy can deform and when relieved the material will voluntarily regain its original form at a stable temperature. This phenomenon can take place without assistance of heat. SME and SE have a close association with the martensitic transformation. SME and SE are in general characteristically thermoelastic transformations.

## The Principle of SMP

Rubber can expand several times under stress and return to its original shape and length almost immediately when the stress has been removed and if it has not been deformed beyond its yield point. At room temperature rubber shows an elastic property however, elasticity is lost at temperatures below -196°C. Consequently, the elongated shape is fixed and cannot return to its original shape, provided that the temperature is kept below its glass transition temperature (T^sub g^). The T^sub g^ is defined as a temperature above the performance of elasticity of a polymer, which spontaneously decreases. Rigid polymers can demonstrate rubber-like characteristics, as shown in Figure 2. In this figure the slope of the temperature curve adjusts, as at T^sub g^. During the rubber state, a three-dimensional polymer network remembers the original form and during the glass state inter-chain interactions are firmly positioned in the temporary form.

As with SMP, when heated above the T^sub g^ it can be deformed in shape. If it is then cooled to below its T^sub g^ and retained at the deformed shape, the form is subsequently made permanent. During the rigid state elasticity is low, although it would be able to recover the original shape when heated above its T^sub g^. The SME of the SMP works due to the movement of a molecular chain, which is the result of the Micro-Brownian motion when heated above T^sub g^ [10, 11]. When the SMP is crosslinked or partially crystallized, the rubbery state would be slight due to the restricted molecular movement. However, in this state, deformation of the material can easily occur when an external force is applied while simultaneously the molecular chains move in the direction of the tension. When the deformation of the material is sustained and the temperature of the material is lowered below its T^sub g^, the Micro-

Brownian motion will be fixed and the oriented molecular chain and transformation will simultaneously be fixed, and this can be made permanent if the temperature is kept below T^sub g^. Nevertheless, if the temperature is increased above T^sub g^ the Micro-Brownian movement is activated and the molecular structure is released, enabling the material to recover its original shape.

## Comparisons of SMA and SMP

The SMA was purchased from Dynalloy Inc., in diameters of 0.20 and 0.30 mm, untreated with SME as different shape transformations were required for the experiments within the study. This alloy is composed of 50% nickel and 50% titanium (also known as NiTi) and was chosen as it has the best composition of its kind. This type of SMA exhibits the highest strain of up to 8%, recovers fully, rapidly and is strong. The SMA can be thermally trained to change in a variety of shapes if the shape is held in place during thermal treatment. It requires a temperature of at least 40°C to stimulate the SME.

The SMP was purchased from Diaplex Co. Ltd, in a pellet form. It is a type of polyurethane and consists of hard and soft segments. The SMP pellets were intended to be processed using a range of extruders at the Scottish Borders campus. This had not been tried before and the manufacture of an SMP fiber was one of the unique aims of this research. The material can extend by up to 200%, but it cannot recover its full original form and the rate of recovery is very slow. This type of SMP was suitable for the applications required for the present study as it has a low start transformation temperature of 25°C. In the experiments the SMP was only trained to contract along its length when stimulated. Table 1 summarizes the characteristics of the materials.

## Creating New SMA Textile Yarns to Enhance Textile Aesthetics

To train the SME of the SMA, high temperatures are required for the alloy to "remember" a prescribed shape. A Falcon electric furnace was purchased specifically for the research. The training of the SME was accomplished by heat treatment of a temperature of 650°C in the furnace. A series of heating and quenching is required for the SMA to remember the prescribed shape transformation. Steel rods were used to wrap the SMA into a spiral shape and sustain the shape during thermal treatment. The rods were then securely placed on a custom- made frame to allow the heating and quenching procedure to be less hazardous (Figure 3).

It was necessary that the SMA was heat treated before being developed in yarn production, as the conventional yarns composed in the yam formation would not be able to endure the high temperatures. Thus, it was crucial to consider the thermal treatment before applying the SMA to the woven structure. Depending on the particular design required, it was fundamental that the SMA was heat treated before being further developed into a yarn formation and woven.

To develop the yarn formation, a Gemmil and Dunsmore Fancy Wrap Spinner was employed. A variation of fancy yarns can be produced by changing the settings of the computer on the yarn spinner and by altering the placement of the yarns being fed into the rollers. The initial consideration was to investigate and attain a correct tensioning of the wire. It was found that when the wire spool was positioned on the base of its package, vertically, the wire would spring from the spool (known as flyer pay-off) as it was fed off the creel and caused problems. Consequently an X-frame with a removable bar to hold the wire spool was devised to allow the wire to be taken off the package in a horizontal position (Figure 4). The positioning of the frame was significant, as it was established that positioning it at the back of the machine on the floor, significantly reduced the length of the wire as it was drafted into the machine.

A diversity of yarn formations were developed where conventional yarns were wrapped with the SMA to enhance the aesthetic design and were specifically designed for interior yarns to be woven. The conventional yarns intended to be a part of the yarn formation consisted of a fibrous surface structure that enabled them to interlock with one another when twisted into a yarn formation. These yarns were a range of natural and synthetic fibers with varying tex counts including cotton, viscose, wool, polyester, nylon monofilament, Lycra, polypropylene, Lurex, etc. It was essential that the yarns selected complimented each other or sometimes contrasted to create an effect.

It was established that at lower twist levels the SMA would cause certain obstructions in the production of a yarn formation with adequate dimensional stability. This was owing to the surface quality of the alloy preventing other yarns from adhering to its surface; subsequently the SMA would protrude intermittently outside the yarn structure and not sustain its position as the core. Following an investigation of the varying levels of twist, results were finally achieved which produced a yarn formation with good dimensional stability. To achieve a fibrous surface on the yarn formation as seen in Figures 5-7, overfeeding was required. This was produced by increasing the wraps per minute (WPM) of roller 1, to subsequently be higher than roller 3. This would cause the effect yarns to be fed through roller 1 faster and overfeed, producing a textured surface and creating a 'bulky' yarn formation. If roller 1 was running at the same speed as roller 3, a smooth yarn would be produced. Depending on the speed of the rollers the yarn can be highly or loosely twisted, which can affect the performance such as the handle of the yarn formation. It was additionally essential to consider how the SMA would move within the structure. As a result the majority of the yarn formations produced were twisted at 200 WPM to allow the SMA to move the yarn formation into a coil shape when stimulated.

Throughout the creation of new dynamic yarn formations the movement was the key attribute of the SMM and was thoroughly considered. Yarn formations with an optical effect were inspired by the notion of movement and reflective light and were achieved by applying Lurex yarns. To attain specific characteristics such as depth and texture, conventional yarns with contrasting tex counts were blended collectively, as this created relief textures on the surface of the yarn which were further enhanced within the woven structure. As the yarn formations were intended for interior textiles, smooth and soft tactile qualities were not always necessary.

## Manufacture and Embellishment of SMP-based Yarns

Following the results of preliminary extrusion of an SMP fiber it was decided to attempt to improve the mechanical properties of the SMP such as the tensile strength and the recovery. A series of experimentations involving the SMP being systematically blended with other polymers was conducted. A Bradford Ram extruder was used for these experiments as small quantities could be processed. It was decided to blend the SMP individually with nylon 12 and polypropylene. These polymers were selected as they have a similar T^sub g^ to the SMP, being about 90°C and good tensile strength. A scope of 5-30% of the selected additional polymer was extruded and produced a modified SMP. The additive polymer was accurately weighed in proportion to the required ratio blend and prior to processing was dried in an air circulating oven for 12 h at 80°C. The SMP is highly sensitive to moisture, thus if not adequately dried this would induce complications during the extrusion process. The samples were extruded at a temperature range of 170-220°C, which was increased in increments of 10°C, for each test. The extrudate was being collected using a take-up machine at 20 m/min. During the extrusion process it was observed that particular samples displayed poor flow rate, curling at the die orifice and intermittent breaking of the filament during drawing. In addition, some blends did not extrude or were not homogeneous. It was essential that the polymer blend did not compromise the SME, although the addition of a secondary polymer would enrich the mechanical abilities of the SMP.

The polymer samples were thoroughly tested for tensile strength using a Nene instrument M5. The fibers were elongated until fracture and the results were analyzed and compared. The polypropylene blend produced better results than the nylon 12 blend as the sample displayed better strength and elasticity, as shown in Figures 8 and 9. When these findings were compared with the tensile test results for 100% SMP fiber, however, it was discovered that the SMP still produced the optimum results (Figure 10). Table 2 presents a summary of the tensile test results for the polymer blends and pure SMP. As the results indicate, the SMP demonstrated good strength and elasticity in comparison with the polymer blends. For these reasons it was decided that the 100% SMP fiber would be further developed and the polymer blending was ceased.

Further extrusion also took place using a pilot-plantscale screw extruder and extrusion into a water bath using a bench-top laboratory-scale screw extruder. The latter was used in an attempt to produce a larger diameter extrudate of 0.30-0.50 mm, to improve the strain of the SME. The polymer samples produced were difficult to draw and were also brittle. Subsequently a pilot-plant-scale screw extruder was used, as a large quantity of SMP could be extruded and the extrudate could also be drawn simultaneously. Varying temperatures throughout the extruder were tested until a sufficient range of temperatures were found, ranging from 175-205°C. Monofilaments and multifilament with varying diameters of 0.20-0.40 mm were manufactured and subsequently further developed in yarn production to furnish the polymer with aesthetic qualities.

The embellishment of the SMP fiber was developed in a similar manner to the SMA yarn formations. Again, a range of conventional natural and synthetic yarns with a variety of color, texture, and tex count were spun with the SMP to produce an array of new yarn formations (Figures 12-14). Since the SMP contracts along its length when stimulated, the SMP was positioned as the core of the yarn structure, as this would allow the SME to take effect throughout the length. To take advantage of the ductile characteristic of the SMP, the polymer was also overfed within the yarn formation. This was inspired by the notion of the SME performing on the surface of the yarn in comparison to the whole of the yarn changing shape. In further developments of the yarn formation, spandex was spun with SMP to assist the polymers recovery. The SMP has different characteristic in comparison with SMA as it is a softer and more ductile material.

It was essential to consider the performance of the SMP during the transformation, as it was important that the SMP was not restricted to move within the yarn structure. When stimulated the recovery of the SMP is not 100% and moves at a slower pace in comparison with SMA. With these factors taken into consideration the number of conventional yarns twisted in the composition needed to be a minimum of three strands. To assist the SMP to move within the structure the twist of the yarn was sustained at a level of 250 WPM and some compositions were as low as 175 WPM. The yarn formations still did not necessarily require a smooth surface or a light handle, as again the applications were intended for woven interiors textiles that would not entail regular handle or contact.

The SMP fiber does not require to be thermally treated to train the SME before being developed as a yarn formation. The SME is attained during the extrusion process, thus while elongating from the die orifice the SMP 'remembers' to contract along its length when stimulated. The design of the woven structure was considered in relation to the SMP contracting along its length.

## The Design and Production of Smart Woven Textile Fabrics

The woven samples were manufactured using a Harris eight-harness table loom. The simplicity of this loom allowed the liberty of being experimental and reduced wastage of the limited SMM. The tensioning of the warp could be easily adjusted, which was found to be an important factor when applying a wire yarn formation. It was essential to achieve a balanced tension to reduce complications during the production of an adequate woven textile. This was also critical when weaving a warp with elastic qualities with a taut tension. For example, if the tension of the warp was taut during weave production, when released and taken off the loom, the woven sample would predominantly reduce in size, which may not have been required. It was necessary to review the setting of the warp and weft, i.e. the number of ends per inch (EPI) and the number of picks per inch (PPI). To consider the SME within the woven structure low EPI values of 24 and 16 EPI were used, which allowed the SMM to move within the structure. With regard to a double-cloth structure, if conventional yarns were additionally applied a higher setting of 32 EPI was used.

The warp was positioned in the reed in variations to experiment with the EPI as well as to create deliberate sequenced spacing to particularly assist the SMP to move and to visually enhance the shape transformation. This provided a practical understanding of adjusting the setting of the warp and its effect on the woven structure with regard to the SME. The SMM enabled the facility of the woven structure to Open' (have transparent sections) and 'close' (contract when stimulated). These characteristics permitted the effect of the yarn formations and aesthetic qualities to be fully exposed while simultaneously changing shape. The sample shown in Figure 14, illustrates this technique using SMP yarn formations. As the SMP is a more ductile material than SMA the handle of the textile is softer and lighter than samples consisting of SMA.

It was established that the SMA coil could perform within a woven structure and within a fancy yarn formation. However, the visual effect of the SMA yarn formation transforming into a coil shape needed to be fully exposed to its aesthetic advantage. To enrich the design concept and relate it to interior applications, the interaction between opacity and transparency was to be continued; thus, nylon monofilament was applied to weave the successive samples. The sample shown in Figure 15, illustrates the SMA yarn formation floating over the transparent monofilament sections with one inch blocks of the gold wool/Lurex to secure the woven structure and illuminate the design. The floats allowed the SMA yarn formation to successfully change into the coil shape when stimulated by a higher temperature. A range of woven samples were produced with the SMA yarn formation floating on the surface of the textile with varying opaque and transparent sections which effectively transformed the appearance (Figure 16).

A variety of samples with effective three-dimensional surface characteristics, again based on the concept of floats were also designed and created. The size and form of the floats were dependent on the weft yarn applied to the structure and the number of picks applied for each float. Figure 17 shows a sample solely woven with SMP yarn formations in regular floats. When the sample is stimulated the whole sample contracts and enhances the design by creating more depth and a three-dimensional effect. These designs additionally were effective on the reverse as a circle pattern was created (Figure 18). Textiles having reversible features would essentially be valuable for interior applications where both sides of the cloth can be observed.

The honeycomb structure was also applied, as this is originally a three-dimensional structure and was specifically used with the SMP yarn formation due to the expanding and contracting movement of the SME. The shape change of the polymer enhanced the woven structure as depth was created. As shown in Figure 19, the structure was not tightly woven as each pick was not heavily beaten down with the reed. This was intentional as the SMP yarn formation was not to be restricted within the woven structure. In addition, the structure was Openly' woven to enable light to filter through the sample and accentuate the movement of the SME. When stimulated each honeycomb a cell became more compacted and defined in form due to the contracting movement of the SMP yarn formation.

The shape memory yarn formations have been exploited to their full potential by reconstructing the woven structure and creating Smart woven textiles. The experimentation and manipulation of the shape memory textiles using a table loom provided the opportunity to be experimental and make new discoveries. These innovative textiles form a new style of adaptable Smart textiles, as the memorable shape-changing capability visually exploits their uniqueness.

## Application Concepts for Shape Memory Textiles

The purpose of this research was to develop SMM while paying particular attention to the textile aesthetics, and hence adapting them to be applied to the woven structure and produce Smart textiles for interior applications. The proposed applications for these textiles would be one where the textile would not be extensively handled. It was apparent that the majority of the yarn formations manufactured would not have a suitable handle or tactile quality that would be comfortable when in contact with the skin. Owing to these aspects, the end applications for these textiles are window treatments, partitions and wall hangings. These applications would exploit their visual qualities, as the textiles would primarily be observed and utilized as a decorative feature. It is, however, envisaged that these textiles would not only perform as a conventional static textile application, but would also be able to sense, react and adapt to the surrounding environment by changing shape, which warrants these textiles being called 'Smart textiles' (Figures 20-22).

Interiors are evolving into multifunctional spaces, as space is becoming sparse and more people are working from home. The application of shape memory textiles would be beneficial as they could emphasize the multifunctional character of spaces, for example, by converting a formal work area to an attractive social space [12].

The utilization of a shape memory partition or wall hanging could enhance the essence and functionality of the space. Figure 23 displays a Smart woven textile simulated as a partition using Adobe PhotoShop. When stimulated the woven structure visually transmutes, exposing the yarn formations and a dynamic design. The shape memory woven structure can have the ability to Open' and 'close' in order to permit privacy when required. As the function of SME in these applications would be on demand, an electric current could be applied to invigorate the textile. In addition, the same applications could voluntarily improve the conditions of a room by sensing the surrounding temperature. Consequently, if the temperature in the interior was below ambient, the woven structure would transform into a 'closed' structure and function as an insulator, permitting the room to become warmer. In contrast, if the temperature was above ambient the shape memory structure would 'open' and allow air to freely circulate around the space to sustain a cooler temperature in the room.

Sunlight can be utilized to stimulate SMM, hence this factor can be employed for window treatment applications whereby the textile would adapt to its environment. The engineering of a shape memory window treatment that is sensitive to sunlight would consequently open the woven structure to allow sunlight to penetrate the room during the day (Figure 24) and the woven structure would close at night. Furthermore, the woven structure could also be programmed to partially close and lessen glare in the interior of the room if there was excessive sunlight through the textile. Figure 25 displays a Smart textile simulated as a window treatment.

These textile applications would be valuable as part of a Smart network within an interior space [13]. Shape memory textiles offers Smart interiors and standard interiors with additional benefits by performing as a decorative feature and a functional textile. Unlike conventional static textiles, the utilization of Smart textiles has the ability to respond and adapt to environmental conditions as well as modifying the function of the space and also being aesthetically pleasing.

## Discussion and Conclusions

This research reflects the successful formation of a multidisciplinary team, merging unorthodox techniques and materials to design and produce innovative and dynamic Smart woven textiles. The textiles industry is becoming increasingly aware of the demand for technological innovative textiles and its significance in an adaptable market. In this research intensive fiber, yarn and fabric development has been developed, manufactured, and further developed into Smart interior textiles.

SMP is a challenging polymer to process. Although a preliminary investigation to improve the mechanical properties was not as successful as anticipated, an adequate SMP fiber was still produced for this research, which was further enhanced into a yarn formation. Following thermal treatment, the SMA transformed into a continuous coil shape and continued to do so within a yarn formation. Shape memory yarn formations incorporated into the woven structure has transformed conventional static textiles and rejuvenated Smart woven textiles. The strain of the SME was not thoroughly tested as the main objectives were to develop the SMM aesthetically and to incorporate them into a woven structure and allow them to move into a predetermined shape when stimulated. These objectives were successfully achieved.

The continued improvement of the SMM mechanical properties, such as a lower start transformation temperature would enable an extensive range of textile designs and applications. Their potential has yet to be fully explored as SMM can be further developed by incorporating pigment into the materials. Methods that could be investigated to achieve this include, incorporating thermochromic and photochromic dyes into the SMP, and coating the SMA using the sputtering technique. As a result, the materials would be able to change shape and color following stimulation. The use of color in an interior space can have an effect on the user by modifying their moods for particular scenarios such as work or relaxation. Hence changes to the color and shape of textiles could assist in creating a required atmosphere in an interior space [13]. The properties of SMM provide an inspirational approach to the design and manufacture of woven textiles. These concepts for SMM would inevitably lead to unique and exciting Smart woven textile designs.

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