JMEPEG (2009) 18:517–521
DOI: 10.1007/s11665-009-9382-1

1059-9495/$19.00

Mechanical Analysis of Hybrid Textile Composites with NiTi Wires

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(Submitted September 15, 2008; in revised form December 10, 2008)

Hybrid textile structures composed by polyamide (PA), Lycra (or Elastane EL), and NiTi thin wires were manufactured. The fabrics were realized by knitting Lycra (EL) as weft and warp filaments and a coupled PA/NiTi yarn through in-laying technique. Superelastic NiTi wire with diameter of 50 μm in both straight annealed and snake-like form and shape memory with a snake-like memorized form were used. The polyamide filament used coupled with the NiTi wire has a diameter around 140 μm, while the textile structure is composed by various Lycra filaments, characterized by different diameters. The textile structures were realized by a circular machine appropriately equipped and used in order to minimize problems related to the use of the thin NiTi alloy filament. To study the influence of NiTi filaments on mechanical properties, specimens taken from textile fabric were analyzed by using a DMA Q800 TA Instruments, equipped with a tension film clamp, in static and dynamic conditions. Force/strain measurements up to 150% in elongation and Tandelta versus frequency were carried out on fabrics with and without NiTi filaments. Finally, some tests strain recovery under load versus temperature are conducted.

Keywords DMA analysis, hybrid fabric, NiTi thin wires

1. Introduction

The opportunity to use the NiTi shape memory or pseudoelastic wires in textile field is today a real interesting application which opens different alternative for new devices (Ref 1).

Smart fabrics with new particular damping, elastic properties, or shape memory effect have chances to be applied in different fields (Ref 2, 3) (biomedical, sport, or other). For example, the articulation rehabilitation after a physical shock, i.e. elbow dislocation, has become of quite high importance in medical and health care area, since it is often particularly difficult to allow the various connection parts in the arm, and the body generally speaking, to return to the initial functionality conditions and to completely repair the occurred damage. Grado Zero Espace has achieved the idea of creating an orthopedic textile support which should not take the place of the classic steel or plastic tutor, but which should become an intermediate step between the rigid tutoring structures and the complete removal of the same, in order to provide a more efficient rehabilitation therapy and to avoid the body part to displace again. Starting from its previous experience in working with NiTi wires, Grado Zero went forward in the development of shape setting, processing, and utilization of the thinnest superelastic or shape memory wires in complex fabric structures which can include the high added value of this innovative material. Physical and mechanical properties of the NiTi wires allow the construction of hybrid semi-rigid textile structures characterized by lightness and complete biocompatibility. The characterization of mechanical properties is then the most important study to clarify the effective role of NiTi wires in the whole fabric, and to measure the force developed and the strain raised. To study the influence of NiTi filaments on mechanical properties, specimens taken from different textile fabrics were analyzed by using a DMA equipped with a tension film clamp. We used several kinds of mechanical tests to investigate static and dynamic properties of the new material. This system is able to characterize article sample limited in size, but it is possible to obtain stable test conditions in terms of temperature and applied load. These are necessary conditions to obtain reliable data.

The textile samples tested in this work are hybrid structures polymer-NiTi thin wire with different design.

2. Materials and Characterizations

2.1 Materials

The new smart materials are hybrid textile structures composed by polyamide (PA), Lycra (or Elastane EL), and three kinds of NiTi thin wires. The fabrics were realized using an industrial circular knitting machine by knitting EL as weft and warp filaments and inserting a coupled PA/NiTi yarn through in-laying technique. The polyamide filament used coupled with the NiTi wire has a diameter around 140 μm, while the textile structure is composed by various Lycra (EL)

This article is an invited paper selected from presentations at Shape Memory and Superelastic Technologies 2008, held September 21-25, 2008, in Stresa, Italy, and has been expanded from the original presentation.

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filaments, characterized by different diameters. The employed machinery had been properly equipped, set up, and used in order to minimize problems related to the use of Ni-Ti filaments: these wires have mechanical and electrical characteristics which are completely different from those usually utilized for textile applications, and that might create processing problems and/or damages to various machine parts. We studied three kinds of fabric:

(1) *Fabric A*: manufactured by using one PolyAmide yarn (with a diameter around 140 μm), two different Lycra (EL) yarns (with diameters around 65 and 130 μm), and a superelastic commercial Ni-Ti wire (with a diameter of 50 μm, which has been properly thermo-mechanically treated by Grado Zero Espace through a treatment process which is currently under patenting) in order to obtain a snake-like (with serpentine shape) set filament.

(2) *Fabric B*: manufactured by using one PolyAmide yarn (with a diameter around 140 μm), two different Lycra yarns (with diameters around 65 and 130 μm), and a superelastic commercial straight annealed Ni-Ti wire (with a diameter of 50 μm).

    Figure 3(a) reports the scheme of these two fabrics, where the knitting structure which has been manufactured consists in the insertion, through in-laying technique, of the Ni-Ti wire coupled with the PolyAmide yarn, closing subsequent turns composed by Lycra (EL) yarns (inserted both in weft and warp directions).

(3) *Fabric C*: for a useful comparison we tested also the fabric without NiTi wires, named in the following like Fabric C.

(4) *Fabric D*: manufactured by using one PolyAmide yarn (with a diameter around 140 μm), one Lycra yarn (with diameter around 65 μm), and a shape memory commercial Ni-Ti wire (with a $T_{Af} \approx 87$ °C and a diameter of 50 μm), which has been properly thermo-mechanically treated (by Grado Zero Espace through a treatment process which is currently under patenting) in order to obtain a snake-like re-memorized filament.

    In this case, the knitting structure (reported in Fig. 3b) which has been manufactured is different from the previous ones and consists, as shown in the scheme, in the insertion of the Ni-Ti wire, coupled with a Lycra (EL)/PA yarn, every two turns.

2.2 Characterization

The Dynamic Mechanical Analyzer Q800 TA Instruments, with a GCA cooling accessory, is a suitable equipment to study all the mechanical properties of thin NiTi or NiTi-based thin wires or ribbons (Ref 4). It is possible to use many test configurations, in static or dynamic experimental mode. Force/strain measurements were carried out on fabrics with and without NiTi filaments, up to 150% in elongation, and mechanical degradation is studied by cycling test. Also, damping properties at room temperature are obtained by isothermal frequency scanning measurements. Moreover, the fabric prepared with NiTi shape memory thin wire were tested in strain recovery configurations. For a suitable comparison, previous tests on the single NiTi superelastic and shape memory wire in snake-like form have been carried out.

3. Results and Discussion

At first some tests on a single snake-form NiTi wire have been realized. For this kind of sample it is necessary, for a correct comparison among the different measurements, to use the same number of loops for the different samples, according to the displacement range of the system (0-25 mm).

For both the NiTi wires (superelastic and shape memory), the snake form is impressed after a first straight annealing process.

We measured the NiTi superelastic in stress strain configuration at 35 and 60 °C in order to assess the temperature effect on the mechanical behavior. Moreover, the aim of these new tests is to study the mechanical behavior of the material from the initial serpentine shape to a linear shape, before reaching the superelastic plateau. Figure 1 shows the comparison of the two curves.

On the shape memory NiTi snake, we made preliminary tests to find information about the recovery capacity of the wire under different loads, from martensite to austenite field. In Fig. 2 it is possible to observe that the wire is able to recover completely the snake-form re-memorized shape only under very low forces, due to the low stress developed by the wire in the bending configuration during heating and also due to the softening of the material after two thermal treatments.

Based on these first results we tested the hybrid fabrics with the structure showed in Fig. 3(a) and (b). For all the specimens, small samples (nominally 20 mm in length and 6 mm in width) have been taken from the fabric. In every article test it is possible to find 5 NiTi wires and the results have been normalized to a single NiTi wire.

The fabric A was composed by PolyAmide, Lycra (EL), and a superelastic NiTi filament, 50 μm of diameter, in the snake-like form. Static tests, static force versus strain to 150% in strain, showed an hysteretic behavior and we can observe an important (about 20%) residual strain after the first cycle which is reduced to zero in the next cycles, showing a good stabilization of the recovery. The curves of this sample are reported in Fig. 4.

To investigate also the damping properties of this new hybrid materials we carried out dynamic tests, in particular we

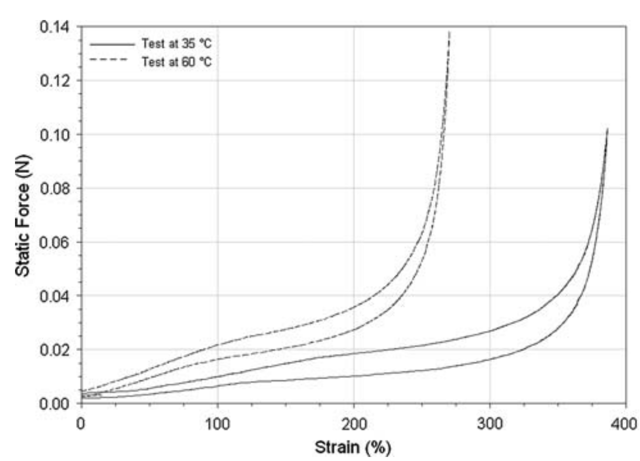

Fig. 1 Static force vs. strain curves for NiTi 50 μm snake-form wire; the curves are registered at 35 °C (solid line) and at 60 °C (dot line)

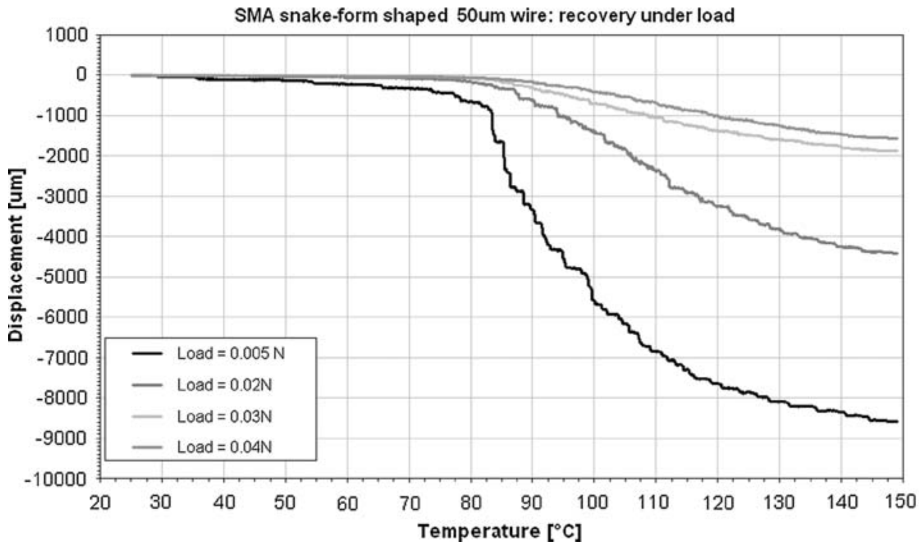

Fig. 2 Recovery under load vs. temperature (°C) of NiTi SMA snake form 50 μm wire

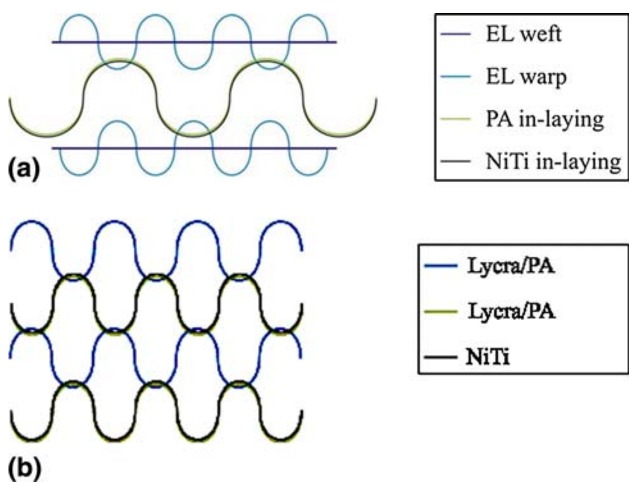

Fig. 3 (a) Fabrics structure for fabric A (PA + EL + NiTi superelastic snake-form wires) and fabric B (PA + EL + NiTi superelastic straight annealed wires). The height of the NiTi loops is 2 mm. (b) Fabrics structure of fabric D (PA + EL + Shape Memory Ni-Ti wires). The height of the NiTi loops is 2 mm

measured the internal friction coefficient, Tandelta, which gives a measure of the mechanical energy dissipation properties, in isothermal condition at different frequencies, ranging from 1 to 100 Hz. Moreover, the pattern obtained in this way can represent a characteristic pattern to use like product quality assessment of the different kind of fabrics.

The frequency scanning on fabric A (reported in the complete comparison of Fig. 7) shows two peaks in the Tandelta curve at 44 and 56 Hz.

The fabric B, composed by PolyAmide, Lycra (EL), and a superelastic NiTi filament, 50 μm of diameter, in the straight annealed form, was tested following the same protocol of measurements. The static tests, reported in Fig. 5, showed a hysteretic behavior with a lower hysteresis than the fabric A and lower residual strain after the first cycle (about 17%). Also,

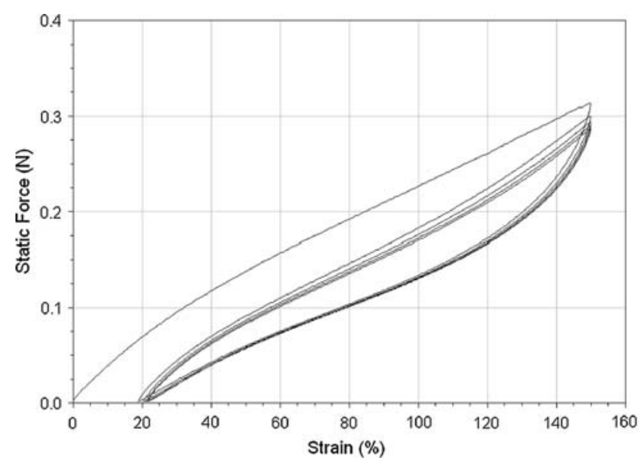

Fig. 4 Static force vs. strain cycling curves for fabric A (PA + EL + NiTi superelastic snake-form wires)

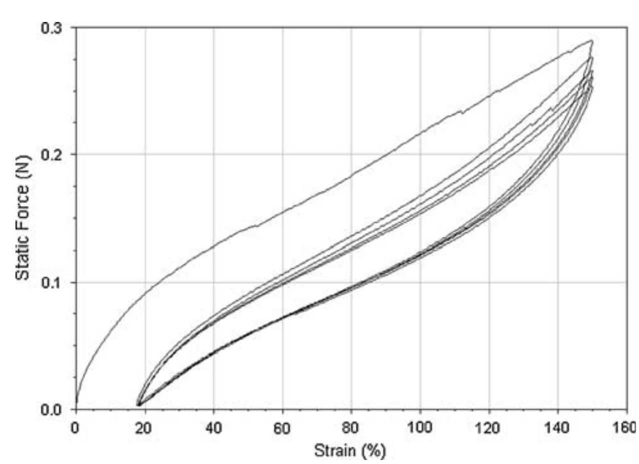

Fig. 5 Static force vs. strain cycling curves for fabric B (PA + EL + NiTi superelastic straight annealed wires)

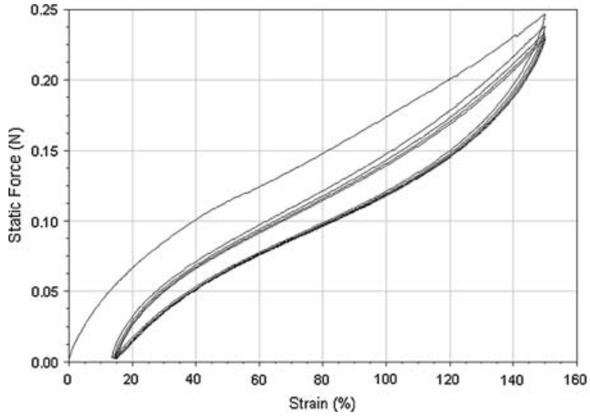

Fig. 6 Static force vs. strain cycling curves for fabric C (PA + EL, no NiTi wires)

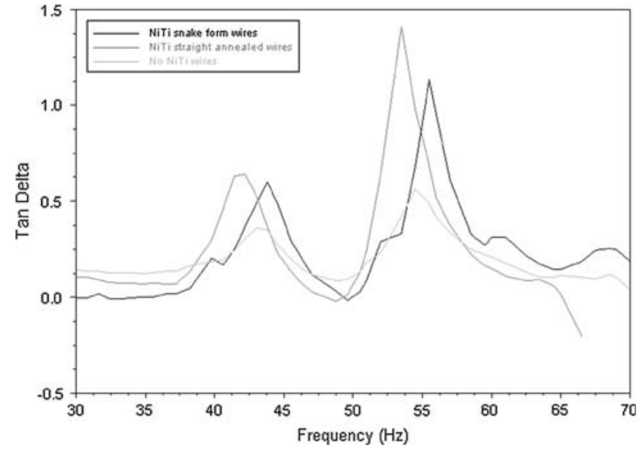

Fig. 7 Tandelta vs. frequency curves comparison for fabrics A, B, and C

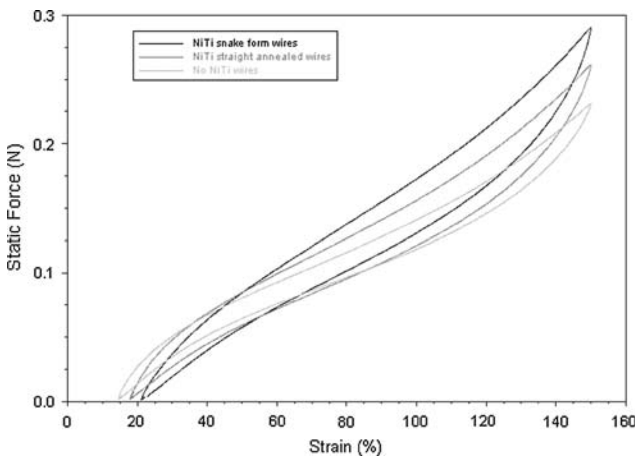

Fig. 8 Static force vs. strain curves comparison for fabrics A, B, and C

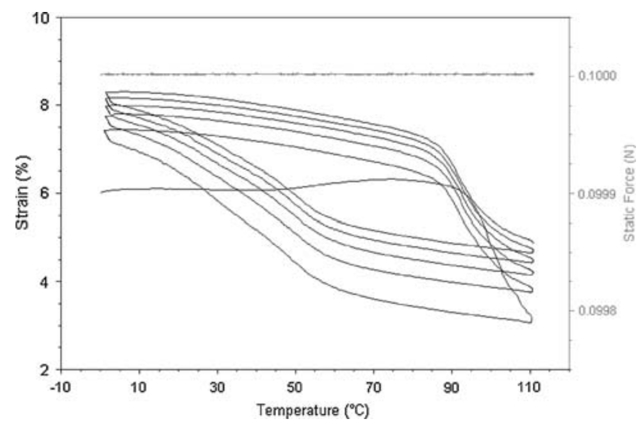

Fig. 9 Strain recovery under load cycles vs. temperature for fabric D and load = 0.1 N

for this sample, residual strain after the first cycle is reduced to zero in the next cycles. In the frequency scanning measurements (Fig. 7), the peaks are different in frequencies and intensities (41 and 53.5 Hz).

In order to evaluate the influence of the presence of the NiTi wires, further test on the fabric C has been conducted. Small samples without NiTi wires have been taken from the fabric too and tested in the same way. In Fig. 6, the static tests to 150% in strain present the smallest hysteresis and the best residual strain after the first cycle. The pattern in dynamic conditions (Fig. 7) shows shift in frequencies and intensities. At the end in Fig. 8 we report a suitable comparison among the curves force versus strain of the three fabrics for the last cycle.

Dynamic tests (Tandelta vs. frequency at room temperature) on the fabric with and without NiTi showed the contribution of the NiTi wires in terms of Tandelta. It seems that the damping properties increase with the presence of the NiTi wires and the different shape of the NiTi wires changes the frequency of the peaks. The shift in the peaks position and the change in the intensities associated to each kind of fabric give us a characteristic Tandelta pattern for fabrics A, B, C. Then we can use this pattern like a control test of the good result of the fabric production.

In the force-strain tests, the presence of NiTi wires generally increases the rigidity of the fabric. Moreover, superelastic NiTi filament enhances the textile stiffness without reducing the elastic performance of the hybrid structures. The plastic deformation seems to be more probable with the snake-like form NiTi wires, according to softer microstructure due to the two thermal treatments.

Finally we tested the fabric D sample, obtained from a textile structure, composed by a Lycra (EL)/PolyAmide yarn and a snake-form re-memorized shape memory NiTi wire ($T_{Af} \approx 87$ °C).

The results on a single snake-form shape memory wire provided information about the recovery capacity of the wire under different loads, from martensite to austenite field. After these measurements we chose the applied load to investigate the recovery strain behavior of this last fabric in 5 cycles of heating-cooling. In Fig. 9-11 it is possible to observe the recovery of the yarn in terms of strain recovered versus temperature.

It is possible to observe that the higher the load, the larger the recovery, due to the larger initial deformation of the yarn. For all the measurements it is possible to note a residual strain after each cycle, this residual strain is bigger when bigger load

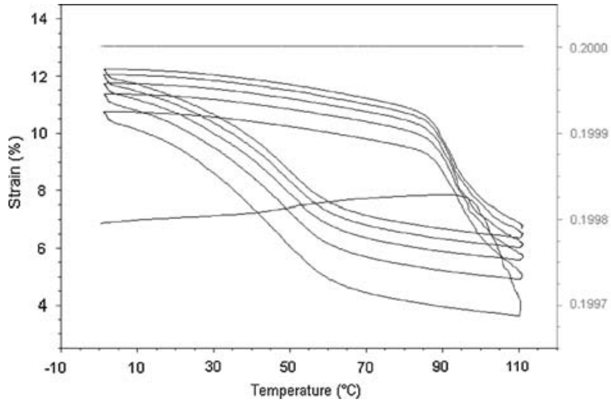

Fig. 10 Strain recovery under load cycles vs. temperature for fabric D and load = 0.2 N

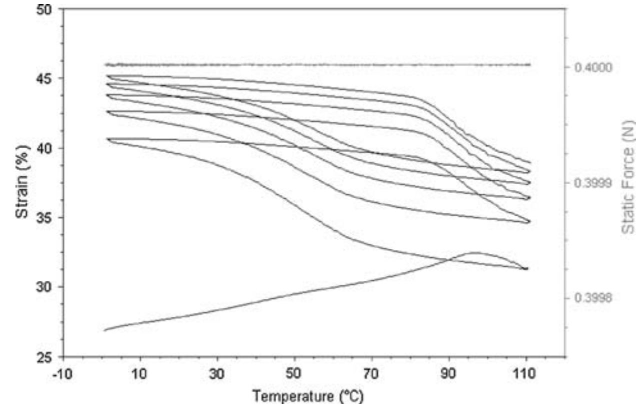

Fig. 11 Strain recovery under load cycles vs. temperature for fabric D and load = 0.4 N

is applied. In any case, the stabilization of the recovery is visible in the reduction of the residual strain with the number of cycles for the load 0.1 and 0.2 N.

The collected data for all the tests should be considered reliable, because at the end of the tests, all samples were intact.

4. Conclusions

The DMA equipment proved to be a suitable instrument to investigate the mechanical properties of non-conventional samples with hybrid and composite structures. The data obtained are reproducible and significative, or well correlated with the physical and mechanical properties of the hybrid material.

The fabric NiTi wires-PA-Lycra(EL) with different kinds of NiTi wires showed good elastic properties. The presence of NiTi wires increases the stiffness of the materials, giving the particular intermediate rigidity useful in articular rehabilitation. It will be interesting to study in depth the influence of NiTi wires in other microstructural conditions (cold worked or different thermal treatment of annealing) and also the tests in bending or torsion will be important for a complete characterization. The dynamic tests versus frequency showed first remarkable damping properties which can also be better studied in future to obtain an exhaustive description of the material from various points of view.

In the strain recovery under constant load tests, the fabrics showed good properties only for low applied loads. For the future activities it is possible to improve this aspect changing the thermal treatment of the NiTi wires; in this way we can obtain a more hard microstructure which is able to give better performance in terms of recovery under applied load.

Acknowledgment

These studies were carried out in the framework of the European IP AVALON EC Contract NMP2 CT 2005-515813.

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