AUTEX Research Journal, Vol 2, No1, March 2002 © AUTEX

DEVELOPMENT OF SHAPE MEMORY ALLOY FABRICS FOR COMPOSITE STRUCTURES

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Abstract

Shape memory alloys (SMAs) are a unique class of alloys which are able both to 'remember' their shape at high temperature during their modification at lower temperature under their transition domain, and able to recover that initial shape when heated. This ability is known as the one-way shape memory effect. Moreover, SMAs present two other interesting properties, superelasticity and damping capabilities, which can be more or less combined with the first one.
An SMA wire of Nitinol mesh was manufactured into technical fabric, in order to examine its weaving adaptability in comparison with a stainless wire and to investigate the different possibilities of use of the material inside composite structures. Several tests have been or will be carried out in order to check the effect of the weaving operation, and later to measure the efficiencies of damping and shape modification.

Key words: *shape memory alloys, shape memory effect, super-elasticity, damping capabilities*

Introduction

In the early sixties, Shape Memory Alloys (SMA) were largely considered as curiosities; nd were not widely disseminated because of their relatively poor ageing properties, low deformation repeatability and an excessive elaboration cost which was unfavourable to general public applications. After a quiet period, which saw few large applications but also an improvement in the quality of materials with the development of new compositions, SMAs are once again receiving considerable interest from various common industrial fields [1]. Applications are only developed from two great families: nickel titanium and copper based alloys. Shape Memory Alloys, whether thermally or electrically activated, are attractive when great forces and large displacements are both required in order to attain complex and noticeable three-dimensional shapes, but at the price of unfortunately slow modifications. Indeed, if the transition from the martensitic to the austenitic phase can be rapid depending on the heat gradient, the return to the originate state by cooling often takes a longer time. Instead of a Joule effect, heating can take place thanks to close hot aerodynamic convective flow. Simple shape memory and superelastic effects can be used as well. Superelasticity allows a large stroke to be covered at constant effort. For a given mass, wire geometry procures the optimal work with a uniform solicitation which can naturally only consist of tension. ONERA was interested in these exotic materials for the first time because of the shape memory effect and its potential use in cryogenic model technology to manufacture screw caps and assembly devices [2]. They were also used as actuators for the modification of aerodynamic profiles [3, 4].

Their introduction into inner composite material structures in order to improve or extend their initial possibilities constitutes the leading axis of the present development. Much research using large wires individually embedded in the composite plies have already demonstrated the potential interest of such a combination. But, unfortunately, to the best of our knowledge no wire fabric exists as of now allowing further investigation (at a lower cost) of the effect of more distributed elements, particularly inside thin panels. The expected properties, with aligned individual wires giving a certain anisotropic character, as was partially demonstrated in the US, concern the damping of continuous fatigue or shock vibrations, the potential reduction of damage under impacts and/or perforation, the straightening to buckling of panels and a slow-speed but noticeable and more selective shape control of structures. Some preliminary work has been carried out at ONERA on the damping capability of composite panels with embedded SMA wires [5, 6]. Tests on thick naval panels have been less conclusive [7]. According to the type of material used (temperature transition domain and education mode), the suitable influences of the shape control and damping properties may be judiciously combined. The purpose of this preliminary weaving study has been to demonstrate the possibility of weaving nickel-titanium yarns, to show the effective improvement of the properties and to manufacture some simple demonstrators which could not be easily conceived without fabric. The reinforcement texture consists in a grid plain weave fabric, which ensures a relatively good stability of the mesh, with a quasi-isotropic contribution inside the composite. This choice allows the material to be embedded in either fibreglass or carbon fibre composites. The favourable gap of damping and damage reduction properties is compared to the non-effect of a similar mesh reinforcement using stainless wire with comparable geometric (wire Tex number) and weaving (warp and weft counts, weave diagram) characteristics.

Properties of shape memory alloys

A metallic alloy presents a simple shape memory effect if, after having been deformed (typically by a few per cent) in a permanent state at a low temperature, it recovers its original shape by heating above a transition domain. (Figure 1). The return to the low temperature takes place without volume increase by an accommodation effect of the 24 possible martensite variants. This phenomena which consists in a reversible martensitic transformation appears between two temperatures, called 'low' and 'high', but which do not prejudge their level towards ambient temperature. The cycle of martensitic transformation which presents a hysteresis is defined by four critical temperatures: Ms, As, Mf, Af. (Figure 2). The main definitions, properties and tests of shape memory alloys are specified in AFNOR Norm n°51-080.

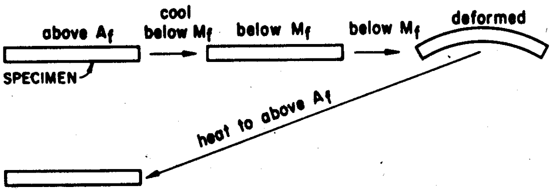


Figure 1. Principle of the simple memory effect.

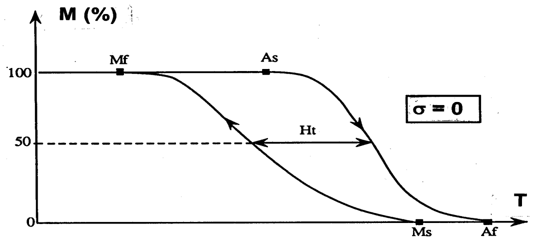


Figure 2. Martensitic transformation cycle.

Below Mf temperature, the alloy is completely in a martensitic phase; above Af temperature, it is in an austenitic state. The crystalline structure varies from a centre-faced cubic lattice to a centred cubic lattice (Figure 3). These typical temperatures essentially depend on the nature and the chemical composition, and in some degree on the various thermomechanical treatments used to elaborate the finish products. Under service stress, these temperatures are afterwards modified by a few 1/10ths of a degree of a megaPascal.

The super-elastic behaviour is characterised by the fact that the material deformation under stress is obtained by a partial transformation of austenite into oriented martensite (Figure 4). On exceeding the first yield point, often called 'plateau stress', several percent of strain can be accumulated with only little stress increase. This property provides a high energy storage capacity to the material, making it suitable for various applications with damping capability. The original shape can be recovered by heating above the complete austenite temperature Af. The temperature range where the stressinduced martensitic transformation (pseudoelasticity) occurs lies between Ms and Md (Md slightly greater than Af).

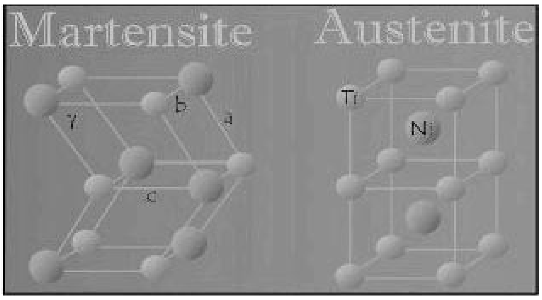


Figure 3. Crystalline lattice transformation.

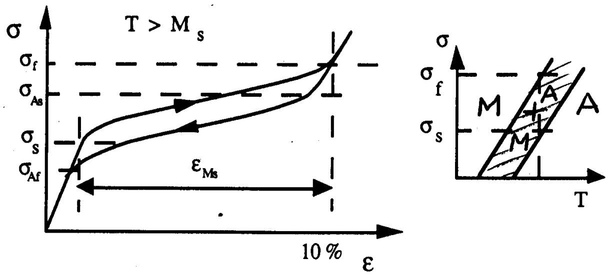


Figure 4. Super-elastic effect.

Damping properties of shape memory alloy

Damping, issued from the mechanical energy dissipation by internal friction, is very high in the pure martensitic domain, but can be still more important in the transition zone where martensite and austenite phases coexist. The modelling of the interaction between defects and the various interfaces is rather complex [8]. Two types of situation have to be considered (Figure 5). Damping to shock is more efficient in the transition zone, whereas damping of continuous vibration is readily solved in the martensitic domain. Whereas Nitinol is interesting for its high energy density of actuation, potential damping properties are half that of Cu-Al-Zn alloy (SDC=15% instead of 30%, SDC is Shock Damping Capacity), this latter alloy presents poor mechanical properties and is no longer produced. According to literature, optimum damping properties would be obtained by a SMA volume reinforcement of about 10%, and a pre-stress of the material corresponding to an elongation of 1.5 to 2%.

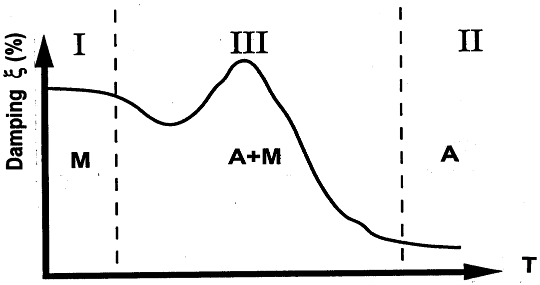


Figure 5. SMA damping capabilities.

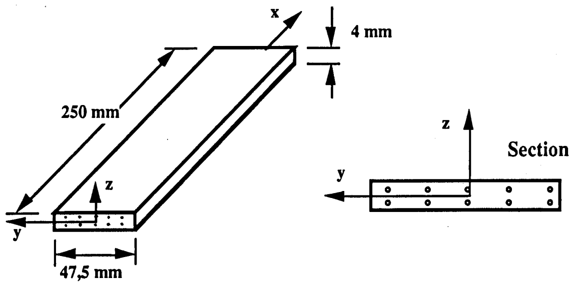


Figure 6. SMA reinforced beam for damping tests.

The first tests were investigated at ONERA on the damping of 32-ply carbon-epoxy beams, reinforced by several unstressed Cu-Al-Zn wires (As=15°C). The beams (Figure 6) were clamped at one end, and submitted to impacts. Four or ten ∅ 1.15 mm wires, simple effect treated or untreated, corresponding respectively to 2.15% and 5.30% volume ratio, were embedded in the composite plies. At 20°C, in the transition domain, damping increases, particularly for the second flexure and 1 st torsion modes, when at 50°C, in the austenite state, a sharp decrease can be noted (Table 1).

Table 1. First vibration modes of a beam clamped at one end and reinforced with some SMA wires.

Modes	Flexion				Torsion	
	1st Mode		2nd Mode		1st Mode	
Cases	F1 (Hz)	ξ1 (%)	F2 (Hz)	ξ2 (%)	F3 (Hz)	ξ3 (%)
unreinforced	103.9	0.12	639	0.18	381.8	0.98
4 untreated wires	102.6	0.17	637.1	0.36	371.4	**0.67**
4 treated wires	102.8	0.17	638.8	0.31	380.5	**0.88**
10 untreated wires	100.9	**0.14**	625.7	**0.20**	371.1	**1.10**
10 treated wires	83.2	**0.31**	526	**0.98**	325.8	**1.40**

a - tests at 20°C

Modes	Flexion				Torsion	
	1st Mode		2nd Mode		1st Mode	
Cases	F1 (Hz)	ξ1 (%)	F2 (Hz)	ξ2 (%)	F3 (Hz)	ξ3 (%)
unreinforced	104.4	0.11	639.4	0.18	366.9	0.71
4 untreated wires	102.3	0.15	635.3	0.31	359.9	**0.35**
4 treated wires	103.1	0.17	640.6	0.35	365	**0.70**
10 untreated wires	100.6	**0.14**	622.6	**0.16**	362.8	**0.70**
10 treated wires	83	**0.22**	521.1	**0.58**	312.8	**0.90**

b - tests at 50°C

For our application, we have used Nitinol, which is a shape memory alloy including titanium on the basis of a 50.8% - nickel content, and was discovered at the Naval Ordnance Laboratory in 1960, from which its name comes. It is known that Nitinol in cold worked and annealed conditions exhibits conventional non-linear super-elasticity. The nickel-titanium family offers the larger memory effect (up to 8% of reversible deformation), actuation energy density (up to 4kJ/kg) with high forces (stresses up to 500 MPa), and force gradient versus temperature change ($\frac{d\sigma}{dT} \approx 10$ MPa.C^{-1}). Its resistance to fatigue and corrosion are high, and the material can support rather high temperatures (up to 400°C) for a few moments without any damage. On the other hand, the micro-structure of the polycrystal is finer than that of copper-based alloys, which favours a thin wire product. For the copper family, only a single-crystal material could meet a similar weaving development.

Weaving the metallic wires

If the weaving of stainless wire as a technical textile is relatively common, to our knowledge, no weaving trial has been made in France concerning Nitinol. In the United States, although some local laboratory experiments have been conducted, no large-scale production has been done. This first investigation was made with a 150 µm diameter wire, corresponding to a 8.75 metric number. The wire is cold-drawn through fifty operations from a 1mm diameter, with several intermediate heat treatments to be correctly reduced to that diameter without prejudicial cracks, and to reach the expected temperature of 15°C for As.

Nature of the metallic wires tested

Three wires of a diameter of 150 microns were studied: a stainless wire and two Nitinol wires. The stainless is a classical A304L type. The Nitinol wires have been respectively supplied by the Memry-Raychem US Company (lot reference Dm-1157) and by Mémométal in France (ref. casting 11125). The temperatures of the transition cycle were determined by DSC analysis. The Raychem wire data (Mf=-0.5°C, As=6.5°C, Ms=23.5°C, Af=26°C) are slightly under the required specifications. For Mémométal, As is about 25°C. The surface of the NitinolNitinol wires is slightly oxidised but could be eventually graphitised.

Technical specifications of the fabrics manufactured

The specifications of the wires and of the grid textures are given in Table 2 and Table 3 respectively. The warp and weft parameters retained for this first fabric are equal: ∅1=∅2 and P1=P2 (Figure 13). The choice of the wire diameter is a good compromise between SMA efficiency and the thickness of the composite plies.

Table 2. Wire data.

Yarn	Nitinol	Inox
Diameter of the yarn in mm	0,150	0,150
Nm (Metric number)	8,75	6,25
DTex (Deci tex)	1143	1608,4

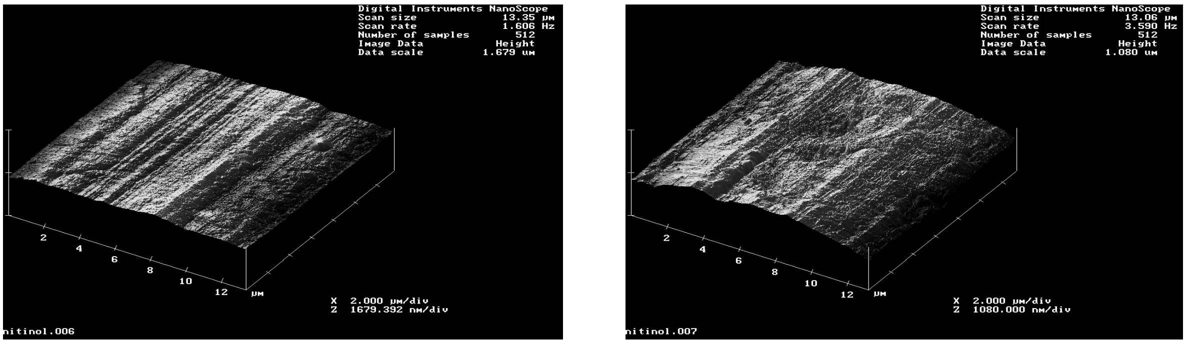
Table 3. Metallic weaving parameters.

Weave diagram	Plain weave
Thread count warp per cm	5
Thread count weft per cm	5
Fabric Width	125 cm
Weight in g/m2	114

More practical details concerning the process are available but cannot be published here for confidential reasons [9]. Some curling defects occur within the fabrics, particularly for stainless wire which is more rigid and twist-sensitive (Figure 14).

Microscopic observation

Observation by means of the AFM technique (Atomic Force Microscope), consisting in 3D microscopy along the full scale of the wire, displays the surface state of the wire according to transverse and longitudinal sections, both before and after the weaving operation.



View a

View b

Figure 7. 3D Views of the Nitinol wire.

Several views have been taken. On view (a) of Figure 7, two kinds of longitudinal grooves coming from the wire-drawing operation are observed. On view (b), two adjacent holes, perhaps resulting from bad handling, can be also seen.

Mechanical tests

Test on wires

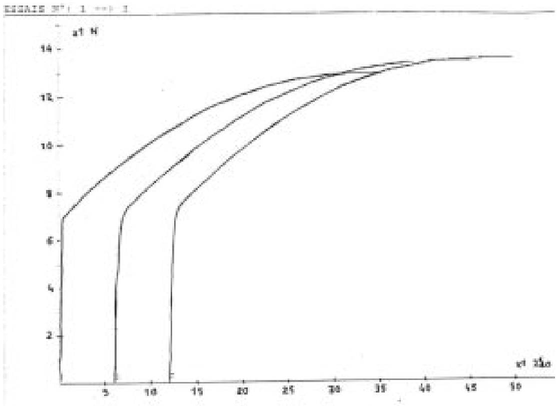


Figure 8. Stainless wire tensile curves (Vt = 10mm/min).

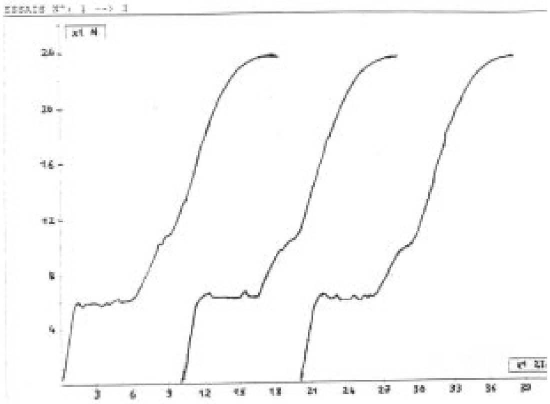
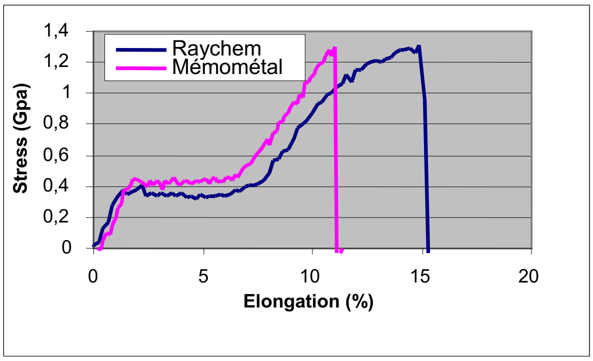


Figure 9. Nitinol-Nitinol wire tensile curves (Vt = 10mm/min).



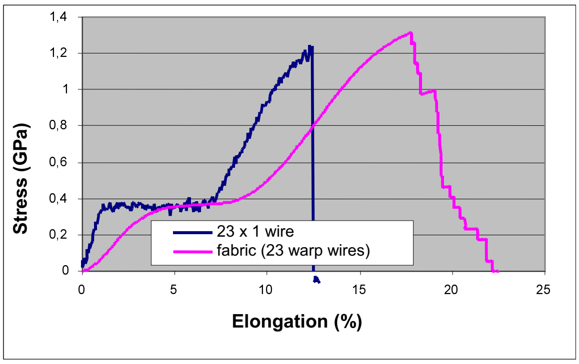


Figure 10. Tensile curves of the two NitinolNitinol wires.

Figure 11. Comparison between fabric and equivalent wires.

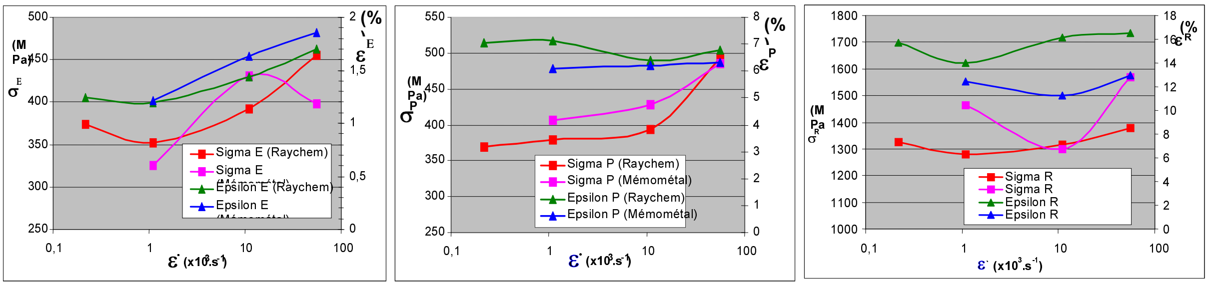
The first tests were made at ENSAIT on the stainless and Nitinol wires (Figure 8 and Figure 9). Nitinol presents a higher resistance to failure than the stainless wire, but with a lower final elongation (17 to 18% compared to 35-36%). Complementary tests were made at ONERA. For the stainless wire, no visible modification of the tensile curve was detected in the [0, 100] s-1 deformation speed range. The two Nitinol wires have identical maximum strengths. The 'plateau' zone is lower but longer for the Raychem sample with a higher elongation to failure (Figure 10).

Tests on fabrics

The fabric was only woven with stainless wire and Nitinol from Raychem. The quantity of Nitinol provisioned by Mémométal was too small to carry out consistent tests. The tensile specimen of size 200x50 mm^2 has been specially treated in the 100-mm long central zone to obtain a pure metallic grid (Figure15).

n the warp direction, the maximum strength of the fabric is comparable to the maximum strength of the average of an identical number of parallel individual wires, indicating that the wire has not been damaged during the weaving operation. The total elongation is representative of the waviness of the grid. The break of each wire is easily detected at the end part of the curve (Figure 12).

For the two Nitinol fabrics, elastic property (elongation and stress) increase significantly with the deformation speed (Figure 12-a), although they are nevertheless still low compared to the weaving speed of about 1 m/s. If the 'plateau stress' increases a little, its length is not modified (Figure 12-b). In the same order, final properties are not profoundly modified within the investigated speed range (Figure 12-c).



a – elastic slope b – "plateau" zone c – failure properties

Figure 12. Influence of the deformation speed on the significant properties of the two Nitinol wires.

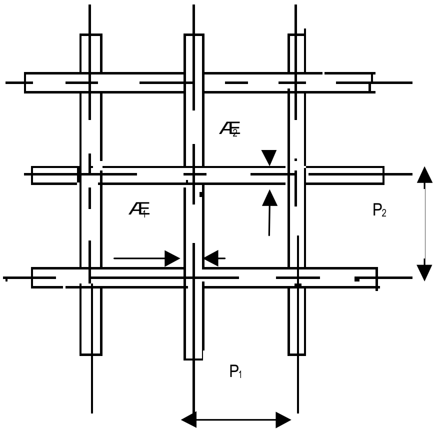


Figure 13. Metallic grid texture.

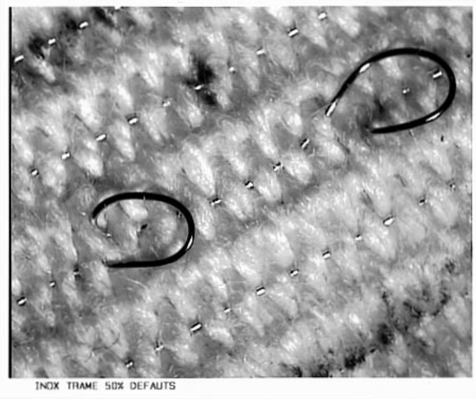


Figure 14. Local weaving defects.

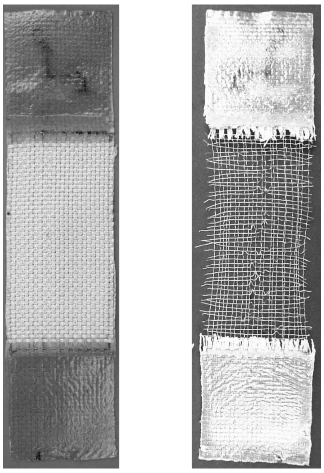


Figure 15. Fabric tensile specimen.

Conclusion

The thin Nitinol wire is becoming easier to obtain in large quantities but is still difficult to acquire. It is nevertheless hard to obtain the good As temperature. The first weaving tests are promising; Nitinol wire has shown a better aptitude to weaving than stainless wire without any serious damage. A second Nitinol weaving campaign is planned in order to complete the various evaluation tests in progress (damping and impact tests, 3D shape control capability), and to examine the influence of a denser texture. Future improvements concern the increase of the weaving speed with an adapted device.

Acknowledgements

The authors acknowledge the support of Dubar Warneton, ANVAR Agency and French MoD Representatives for these works while thanking them for their financial assistance.

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