JMEPEG (2009) 18:691–695
DOI: 10.1007/s11665-009-9407-9

1059-9495/$19.00

SmartFlex® NiTi Wires for Shape Memory Actuators

L. Fumagalli, F. Butera, and A. Coda

(Submitted September 15, 2008; in revised form January 29, 2009)

Shape memory alloys (SMAs) are active metallic materials classified nowadays as "smart" or "intelligent" materials. One of their main areas of interest is that of actuators. The use of SMAs in actuators offers the opportunity to develop robust, simple, and lightweight elements that can represent an alternative to electro-magnetic actuators commonly used in several fields of industrial applications, such as automotive, appliances, etc. SAES Getters S.p.A. thanks to its vertically integrated process and to the scientific and quality approach, developed a NiTi-based wires family which can represent a solution for shape memory actuators. In this paper, the mechanical, thermal, and electrical response of these shape memory wires, with diameters ranging from 20 to 500 µm, will be examined and discussed, with particular focus on the design of the actuator. The thermo-mechanical properties have been investigated and measured by several methods. The most common and useful tests for these commercially available wires will be also described.

Keywords advanced characterization, automotive, mechanical testing, nondestructive testing, titanium

1. Introduction

For simple actuations involving, for example, linear movements of a few millimeters or angular movements of just a few degrees, the usage of a motor rotating at thousands of rpm coupled with gears, clutches, and reducers is certainly not the best solution. The use of "smart materials" for actuation represents an excellent technological opportunity for the development of electro-mechanical components. In particular, the typical characteristic of "smart materials" promotes the development of simple, very compact, reliable actuators that can be integrated in the components or in the structures thus transforming these from static to dynamic or, in some cases, adaptive as they can react directly to environmental stimuli. Component designers can therefore use smart materials to simplify products, to add new functions, to upgrade performance, to improve reliability, and to reduce component cost accompanied by a significant reduction in mechanical complexity and size (see Fig. 1).

Shape memory alloys (SMAs) are functional materials with a multitude of different dependent properties. Among them, the equiatomic system NiTi has been established over the years as a standard alloy covering a wide range of application requirements (Ref 1). NiTi shows the best combination of properties, especially in terms of the amount of work output per material volume and the large amount of recoverable strain compared to any other actuator principles (Fig. 1). The obvious simplicity of the mechanical design and the small number of moved parts is amazing for an actuator and make SMAs particularly attractive for microsystems applications.

SMA actuation is based on the one-way effect. In principle, the effect can be used for generating motion and/or force. The required heating power is supplied either indirectly by variation of ambient temperature or directly by electrical heating of the SMA component (Joule effect). Electrically driven actuators carry out specific functions at ambient temperatures below the M_s temperature, which can be controlled via heating power. Further functions of SMA components may be structural or reset functions.

The principle of work production with an external reset force is applied in most SMA actuators (Ref 2). Depending on the choice of the reset mechanism, different trajectories can be obtained in the stress-strain space. Figure 2 shows various reset mechanisms using a SMA tension wire. In case (a), a weight produces a constant force level. Another widely used variant is passive bias spring (b). The case of decreasing reset force for increasing deflection is described in (c). Moreover, the use of a second SMA tension wire with opposite actuation direction leads to an antagonistic mechanism (d). As the reset mechanism determines the stress profile in the SMA component, the typical hysteretic behavior of the phase transformation can be adjusted or modulated by selecting an appropriate mechanism, according to specific requirements of the final application. Definitely, the reverse bias design concept can open new applications for SMAs actuators. The correct usage of a straight wire shape memory actuator is based on the sensible design of the surrounding mechanical structure that has to provide the resetting force for the actuator. Under optimal design condition, the transformation temperatures can be significantly increased and the maximum actuator stroke can be optimized.

Under pure tension or compression load, high forces but relatively small displacements can be reached. Larger displacements are achieved under torsion or bending loads. Wires and springs are the most important shapes of NiTi that can be used into the design of an actuator. Depending on the kind of

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.

L. Fumagalli, F. Butera and **A. Coda**, Saes Getters S.p.A, Lainate, MI, Italy. Contact e-mail: alberto_coda@saes-group.com.

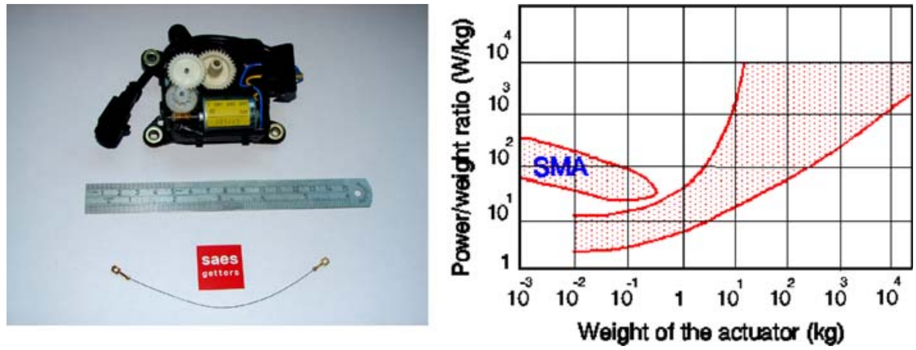

Fig. 1 Comparison between traditional and shape memory actuators in terms of size and power/weight ratio

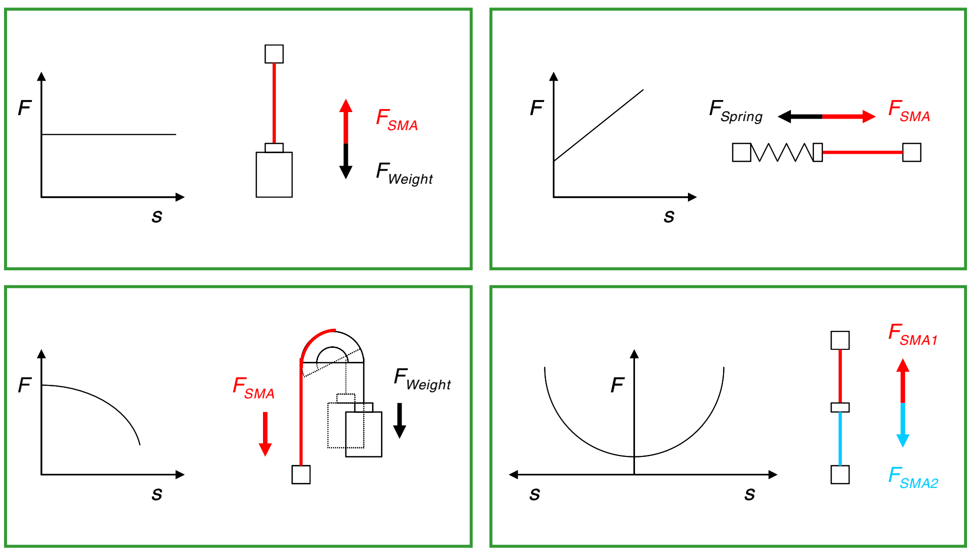

Fig. 2 Some possible reset mechanism for tensile shape memory wire

application, typical distinctions can be made which should be understood as guidelines (Ref 3), as they are not firm rules:

- Straight wire for resistance heated actuators with small displacement (up to 5%),
- Compression or tensile springs for indirect heated actuators with large displacement (more than 5%).

The mechanically stabilized SAES SmartFlex* NiTi (49-51 at.%) actuators show a very sophisticated profile of properties. In this paper, the mechanical, thermal, and electrical response of these shape memory wires, at diameters ranging from 20 to 500 μm, under different working conditions, simulating the actual operating condition in real actuators, will be examined in depth and discussed, in order to direct the design of the actuator so that the functional properties of the material can be completely exploited. The thermo-mechanical properties have been investigated and measured by several methods. The most common and useful tests for these commercially available wires will be also described.

*SmartFlex is a registered trademark of SAES Getters S.p.A., Italy.

2. Discussion

2.1 Hysteresis Test

The knowledge about the transformation and the hysteresis related properties is of importance for the design of shape memory actuators. In this test, the wire is subjected to a constant load and its deformation is measured during a controlled temperature profile in an environmental cell.

In Fig. 3, the test output for Smartflex 76 under constant stress of 150 MPa is displayed. As it can be seen from the graph, some important information can be gathered, such as the maximum stroke (difference in wire length between the cold shape and the hot shape) and the transition temperatures (beginning and end of the direct and reverse transformation) at a given load. Most often, the transition temperatures are determined using the tangent method (Ref 4). In the following curve, the maximum stroke of the wire is around 5%, M_f at 65 °C and A_s at 85 °C.

As it is well known, the applied load is an important parameter that can affect the test: one can run tests with different loads to analyze their influence on the intrinsic characteristics of the wire, such as transformation temperatures and stroke; otherwise a standard load, near to that of usual actuators applications, can be chosen to make a comparison between different wires. In Fig. 4, the transition temperatures measured by hysteresis test on Smartflex 76 wire under different applied loads are reported.

As it can be seen, the Martensite (M)-Austenite (A) transformation temperatures increase by increasing the level of stress. The increase is due to the fact that an applied load during M-A transformation generally supports the transformation

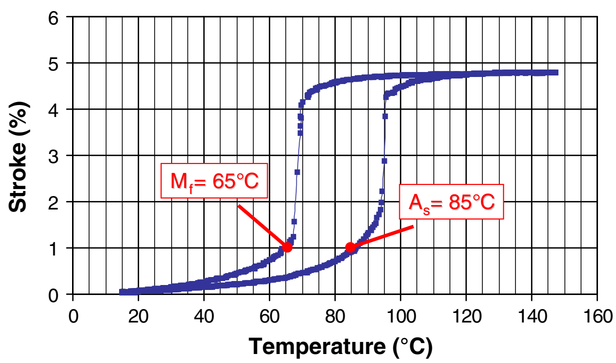

Fig. 3 Constant load test (150 MPa) on Smartflex shape memory wire

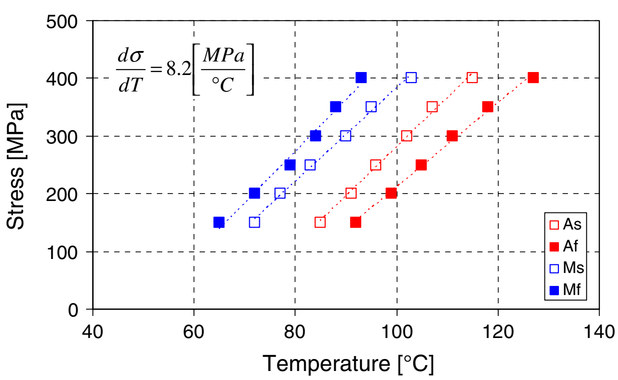

Fig. 4 Transition temperatures behavior of Smartflex shape memory wire under different loading conditions

itself as one can derive from a modified Clausius-Clapeyron equation (Ref 5):

$$\frac{d\sigma_c}{dT} = -\frac{\Delta H^{A \to M}}{T_0 \cdot \varepsilon}$$

Typically, in actuators, the wire deformation is kept below the maximum stroke, since the smaller the difference (maximum—working strain), the shorter the wire lifetime is; so the largest recoverable strain is a very important parameter for a SMA wire.

Wire transformation temperatures are of course fundamental parameters to measure, know, and control (Ref 6): in the case of wire actuated by Joule effect, reverse transition temperatures concern the needed actuation current and time. Also, the A-M transition temperatures are very useful to determine the system speed for recovering the cold shape, once the electrical feeding is removed. A limitation for usage of NiTi wire is the relatively low transformation temperature, which makes applications with environmental temperatures above 80 °C fairly critical: if the environmental temperature increases above this value, the SMA wire does not fully recover the initial shape, so that a certain strain deficit accumulates over the number of cycles. Of course this can be healed by just one cycle at lower temperatures, but it certainly can lead to functional problems during application.

The main problem related with the hysteresis test is the duration (a single cycle between 15 and 150 °C at a rate of 1 °C/min lasts more than 4 h). Another problem is the maximum usable length: in a typical hysteresis system only samples of about 100-150 mm can be analyzed. For this reason, Saes Getters S.p.A. has developed and patented (Ref 7) a new characterization method in which the quality control on the total length of the produced wire is possible. This equipment will enable an on-line 100% product quality control to measure and guarantee NiTi wire thermo-mechanical properties.

2.2 Functional Characterization

By using the equipment shown in Fig. 5(a), it is possible to carry out what we call "one-shot" cycles. The wire is hanged with a weight clamped at the bottom end and heated up by Joule effect under a constant load. A position laser sensor is located at the bottom side of the weight. This means that studies of current, applied load or fixed stroke effects on actuation times can be assessed, in order to optimize the working conditions of shape memory wires.

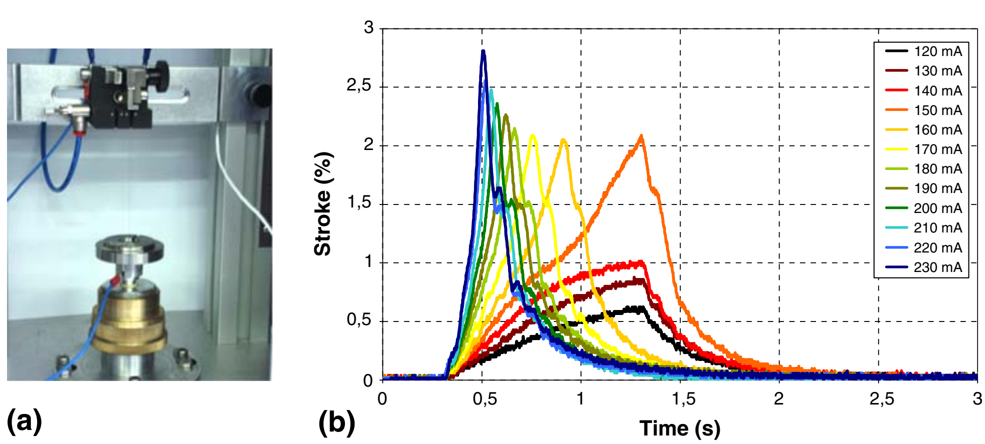

Fig. 5 Experimental set-up for "one-shot" test (a). Actuation times and strokes of Smartflex 76 using different heating currents (b)

For example, in Fig. 5(b) the actuation time and stroke of Smartflex 76 have been measured as a function of the feeding current, by controlling the stroke at 2% during all tests. What can be observed is that for currents <150 mA the wire is not able to reach the fixed stroke. On the other hand, using currents higher than 180 mA, the actuation is so fast that the wire acceleration cannot be exactly controlled by the position sensor, due to its slower response time. These data may be collected varying the wire operating conditions, such as the fixed stroke, so to have a picture of the actuation times using different heating currents. The results on Smartflex 76 shape memory wire have been summarized in Fig. 6. Such a test has been done not only on SmartFlex 76, but also on all the available sizes of SAES shape memory wires. In Fig. 7, the typical actuation conditions (time and current), under a constant stress of 200 MPa and a fixed stroke of 3.5%, have been reported for wires from 500 to 27 µm.

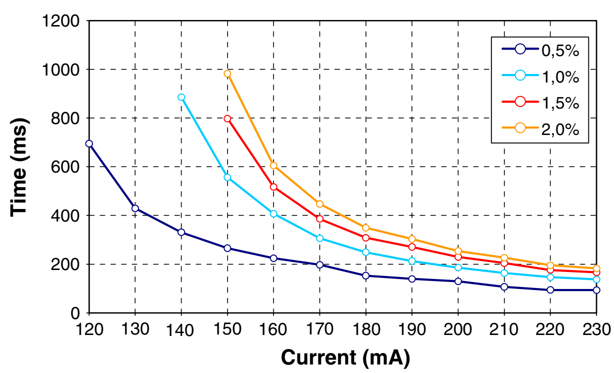

Fig. 6 Smartflex 76 actuation times as a function of different feeding currents and strokes

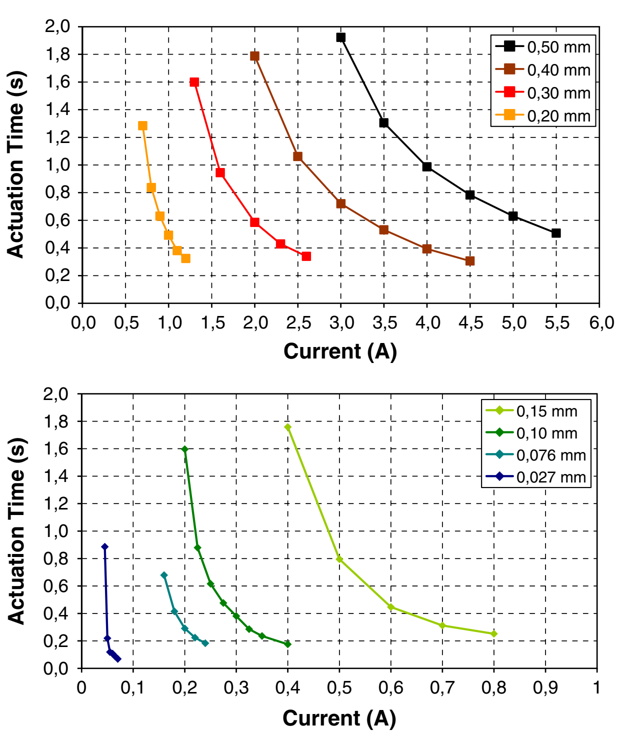

Fig. 7 Typical actuation times and currents for SMA wires from 500 to 27 µm under constant stress and stroke conditions (200 MPa, 3.5% stroke)

As expected, the smaller the wire cross section the lower the actuation time and the electrical power. Particularly interesting is the case of very thin wire SmartFlex 27 whose actuation is so fast that the actuation time seems to be almost constant even varying the heating current. This work is very important since at best it allows exploitation of the material performances and by an appropriate design adapts them to a very wide range of industrial and automotive applications.

2.3 Fatigue Life Test

Beside the maximum stroke and the transition temperatures, a very important feature that defines the wire suitability for a specific application is the shape memory effect stability during cycling and the number of thermal cycles which can accomplish before fracture. Thus, a fatigue life test, in which the wire is subjected to electrical actuation cycles under an applied constant load, is fundamental in the characterization of SMA wires. To do this, the wire is mounted on the equipment shown in Fig. 5(a) and thermally cycled by Joule effect under a constant load. In this test, the heating of the wire is very fast (typically <1 s) and the stroke is fixed so that a position sensor can stop the current passage once this value is reached. This allows to investigate the fatigue wire behavior in a very wide range of operating conditions, being the lifetime strongly dependent upon the heating current, actuation time, applied load, and required stroke.

Different configurations and conditions can be set for the analysis: one can observe the largest stroke setting a constant actuation time high enough to assure the M-A transition to completely take place. Otherwise, it is possible to carry out the test at constant strain (generally closer to the application conditions). In this case, the electrical feeding is stopped when a certain set stroke is reached. One can also choose the electrical feeding conditions (constant I or U). Given the test parameters and configuration, the total number of thermal cycles is a customer's typical specification (on the order of 10^4-10^5 cycles) that must be respected.

Similar to the hysteresis test, the analysis conditions should be chosen close to the ones of the real application, in order to gather useful information about the behavior of the wire during its life. Smartflex 76 shape memory wires have been tested (Fig. 8) by using a current of about 170 mA under a constant stress of 350 MPa and controlling the stroke to 1%. Under these operating conditions, the samples have survived longer

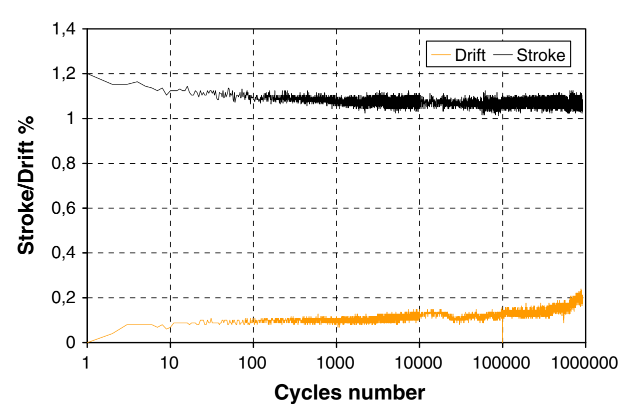

Fig. 8 Fatigue lifetime output (stroke and drift) for Smartflex 76

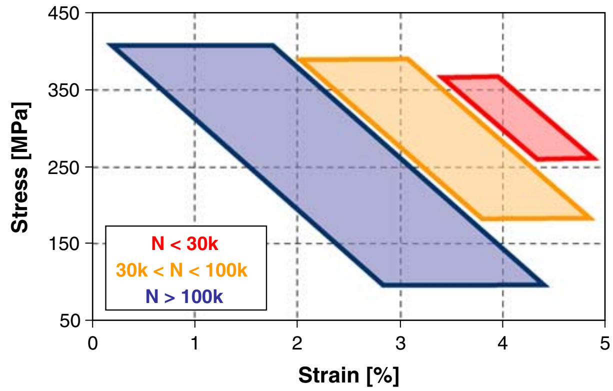

Fig. 9 Fatigue lifetime for Smartflex 76 under different stress-strain conditions

than 10^6 cycles, assuring constant stroke and a drift $<0.2\%$ over the life.

As before mentioned, the dependence of the achievable reversible strain on different stress-strain conditions and the number of cycles is of considerable interest with regard to the service life of SMA actuators. For a deep and complete understanding of the effects of stress and strain levels on the lifetime of SMA wires, a lot of measurements have been carried out. In Fig. 9, for example, three differently colored areas have been identified. In each area, all the experiments have been collected according the utilized stress-strain conditions and the corresponding lifetime. As it can be seen from the graph, increasing both stress and strain, the lifetime of shape memory wires is strongly reduced. On the other hand, by selecting appropriate working conditions, it is possible to obtain very long lifetime and very high reliability from shape memory wires.

3. Conclusions

Shape memory alloys NiTi-based actuators are being used in many different industrial applications. They also have already a great potential as miniaturized sensors and actuators. SAES Getters S.p.A., thanks to its vertically integrated process and to the scientific and quality approach, developed a NiTi-based wires family which can represent a very good solution for shape memory actuators. The trained SAES SmartFlex NiTi actuators show a very sophisticated profile of properties. The performances and the lifetime of SmartFlex wires were tested under different working conditions. They can fulfill the main actuators requirements and are ready for high volume production with a 100% of quality control.

References

1. H. Funakubo, *Shape Memory Alloys*, Gordon and Breach Science Publisher, New York, 1987
2. M. Kohl, *Shape Memory Microactuators*, Springer-Verlag, Berlin, Heidelberg, 2004
3. M. Mertmann, and M. Wuttig, Application and Hysteresis of Different Shape Memory Alloys for Actuators, *Proceedings of ACTUATOR 2004*, 2004, p 72–77
4. H. Luo, E. Abel, J. Hewit, M. Pridham, B. Steele, Z. Wang, and A. Slade, Issues Concerning the Measurement of Transformation Temperatures in NiTi Alloys, *Proc. SPIE*, 2002, **4934**, p 226–233
5. M. Mertmann, S. Kautz, and W. Brown, Design Principles and New Actuator Applications with NiTi Straight Wire Actuators, *Proceedings of ACTUATOR 2002*, 2002, p 85–90
6. K. Otsuka and C. M. Wayman, *Shape Memory Materials*, Cambridge University Press, Cambridge, 1998, p 149–177
7. International Patent Application No. WO2005/106441