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High performance shape memory effect (HP-SME) for new shape memory devices: a diamond-like actuator

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Abstract

Recently, a novel approach was proposed for using shape memory alloys (SMAs) as actuators at higher stress level and temperatures than those conventionally used. This approach is based on a phenomenon named high-performance shape memory effect (HP-SME). It consists in the thermal cycling of stress-induced martensite, so it is suitable for those SMAs that show austenitic phase at room temperature for enabling the development of new shape memory actuators operating at higher working load and temperatures. In this work, a Ni-rich NiTi alloy was selected and a diamond-like geometry device designed, laser machined and tested. Diamond like geometry allowed achieving high displacement recovery and the HP-SME loop increased the working stress level. At room temperature, the austenitic NiTi diamond was axially loaded to induce martensitic state in some specific zone of the element. Then, it was subjected to thermal cycling under a constant load (0.7 N). The SMA element was able to recover a stroke 0.7 mm (about 30 % linear elongation) cyclically.

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Keywords: High-performance shape memory effect; stress induced martensite; nitinol; NiTi; shape memory alloys

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1. Introduction

Shape memory alloys (SMAs) as smart materials are employed in several industrial fields and can effectively be used as sensors and actuators [1,2]. In order to employ these materials as thermal actuators the shape memory effect (SME) must be exploited [1-4]. Moreover, a novel approach was recently proposed for using SMAs as actuators at higher stress level: it was named high-performance shape memory effect (HP-SME) [5]. It consists in the thermal cycling of stress induced martensite (SIM) for achieving extremely high mechanical work (stresses of the order of 1 GPa), higher than that produced by conventional shape memory actuators based on the heating/cooling of detwinned martensite. The schematic of the functioning of the HP-SME actuator working at constant force is depicted in Fig. 1 in comparison with the conventional SME one. When the austenitic phase is loaded above a threshold stress, SIM is produced. As the SIM is heated above the austenite finish temperature under applied force, the inverse martensitic transformation is promoted therefore the parent phase and the macroscopic deformation is restored. Finally, as the material is cooled to the room temperature, a complete SIM state is reproduced and the deformation is reestablished. A complete description of HP-SME is reported in ref. [5-6]. The intermetallic NiTi (also known as Nitinol) is a SMA with extraordinary functional properties and it is enabling most of the commercial available applications based on these smart materials. Within the NiTi compositional range, the Ni-rich alloys show austenitic phase at room temperature [1-3]. Moreover, laser cutting is considered an industrial process capable of producing small elements with precise geometries [7]. According to the possibilities of realizing geometries more complex than the straight linear wire, in this work, a Ni-rich NiTi thin sheet was laser cut in order to manufacture diamond-like actuators. The diamond element, subjected to HP-SME showed extremely good thermo-mechanical performance.

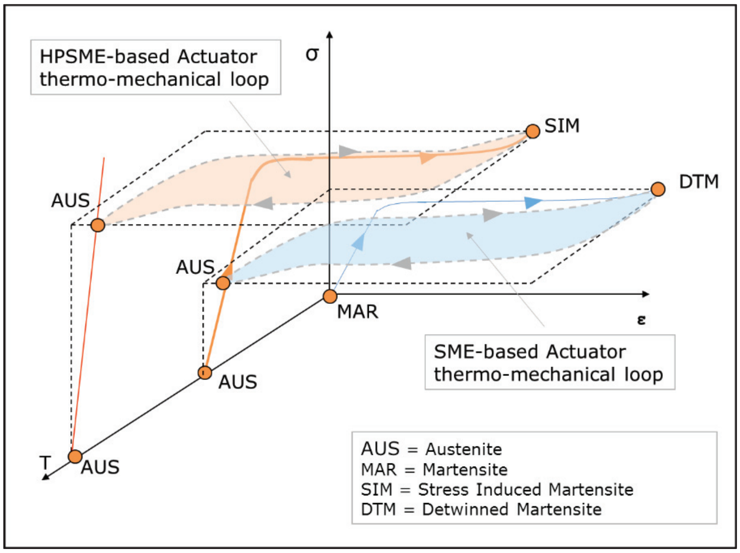

Fig.1 Schematic of the thermo mechanical loops of the SME-based and of the HPSME-based shape memory actuator working at constant stress level.

2. Experimental

Ni-rich NiTi sheet (100 μm thick) was laser processed at CNR IENI, using a continuous wave fiber laser (IPG Photonics mod. YLR-300/3000-QCW). The cutting head LaserMech Mini was used for focusing the laser beam on the top surface of the plate. The head was equipped with a coaxial nozzle for blowing the melted material through a flow of high purity N_2. A 2D motion stage (mod. PRO165ML from Aerotech) was used for controlling the relative movement between the plate and the laser beam. The main process parameters used in the experiments were: (i) power = 25 W; (ii) process speed = 10 mm/s; (iii) laser spot size = 100 µm. The transformation temperatures of the SMA were measured by Differential Scanning Calorimeter (DSC, Seiko 220C) with a scanning rate of 10 °C min^{-1}. Thermal loop under constant load (0.7 N) were carried out by a thermostatic chamber (Angelantoni - Sunrise 250) in the temperature range between 20 °C and 100 °C with a heating/cooling rate of 2.5 °C/min, so it is to be considered a quasi-static test. The displacement was measured by a linear voltage differential transducer (LVDT Macro Sensors HSTA 750-125)

3. Results

The diamond-like Ni-rich NiTi element, laser machined from a 100 µm thick sheet, is showed in Fig. 2. The DSC curve of the material after laser cutting showed Ms and Af temperatures well below the room temperature, therefore the material is in fully austenitic state. No R-phase peak was detected by calorimetric test (see Fig. 3).

For the diamond-like element, subjected to constant vertically applied force, the stress is mainly localized at the curve regions and those zones are subjected to flexion load. Therefore, the necessary force to deform the device is lower than that required by an axially loaded material with the same cross section. It is reasonable to suppose that, under applied load, the SIM is concentrated at the high stress zones of diamond. By heating/cooling the loaded device an alternate vertical movement Δl (see Fig. 2 right) due to the HP-SME phenomenon is established, as below reported and deeply described in ref. [5-6].

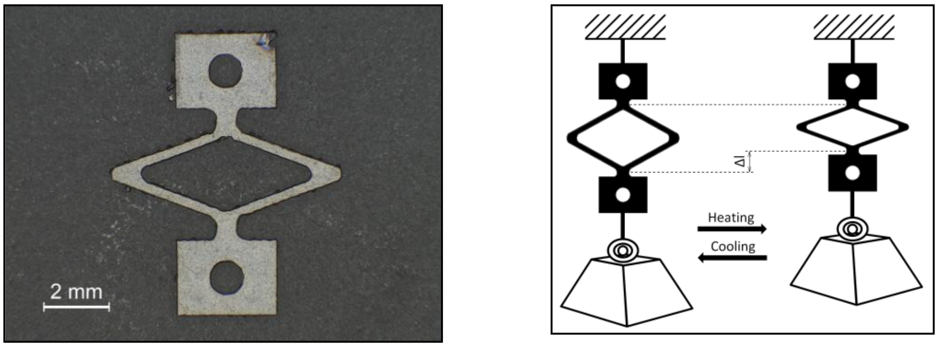

Fig. 2. Laser machined SMA diamond-like actuator (left); schematic of diamond element under applied force (right).

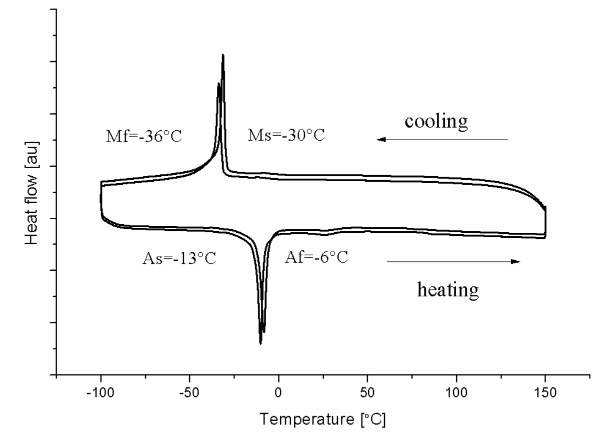

Fig. 3. DSC curve of the SMA laser cut element.

To induce the SIM in the four curves of the SMA element, a weight of 70 N was vertically hanged. Due to the applied load the diamond elongated to its L_0 position. Then it was heated to 100 °C, to restore the austenitic phase and displacement, Δl, was recovered as illustrated in Fig. 2 right. Thus the element was cooled down to room temperature, to re-establish the SIM state. The SMA element was able to recover, reversibly, very high displacement, about 0.7 mm, under constant force of 0.7 N and the thermal loops are depicted in Fig. 4. The narrow thermal-hysteresis (ΔT = 15 °C) between the cooling and the heating branches, evaluated at half recovered strain, is due to both the HP-SME and the special geometry of the device. It is worth noting that the diamond-like element was not trained so the SM actuating properties might be further optimized by heat treatments as well as by thermo-mechanical training.

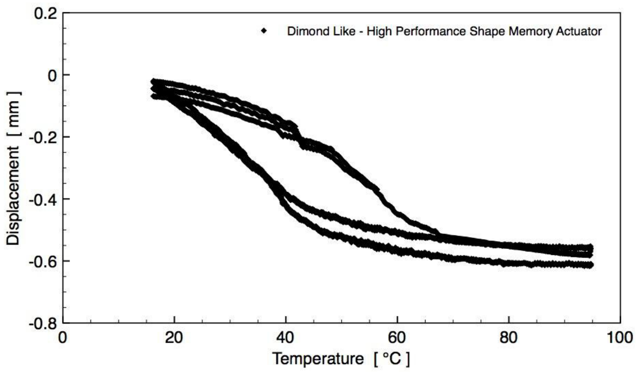

Fig. 4. Thermal loop under constant load (0.7 N).

4. Conclusions

A new SM device based on the HP-SME, showed the capability of recovering extremely high elongation values (stroke of about 30 % of diamond length) under an applied force of 0.7 N. A SMA actuator with a novel geometry was laser machined and tested. The hysteresis between direct and inverse transformation under constant load measured at half recovered strain was 15 °C. Further tests based on HP-SME are in progress on diamond like actuators heated by Joule effect.

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