Photomechanical actuator of Ni-Ti shape memory alloy coated with a carbon composite

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Abstract: We demonstrate continuous-wave laser triggering of the simple shape memory effect of a nickel-titanium alloy. The photomechanical actuator shows enhanced optical response owing to the use of a carbon composite photoresponsive coating.

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1. Introduction

Shape memory alloys (SMAs) are complex materials showing interesting properties such as the single shape memory effect, the double shape memory effect and the superelastic effect. These features are due to a martensitic transformation, in which a body centered cubic parent phase (austenite phase) transforms by a shearing mechanism into a monoclinic or orthorhombic martensite phase [1]. The crystalline phase change can be driven by temperature, stress or a combination of both or even by other external stimuli such as magnetic fields. However, activation of the shape memory effect by means of a laser light beam has not been reported yet. Hence the main purpose of this work is to demonstrate that photothermal effects can trigger the single shape memory effect generated on the surface of the SMA when irradiated by an infrared (IR) laser. Furthermore, we demonstrate an enhanced response of the SMA upon coating the surface with a carbon composite acting as an optically driven microheater [2, 3].

The analysis of the thermomechanical behavior of the SMA can be approximated with the Clausius-Clapeyron relationship ($d\sigma/dT$) [4]. This is useful to determine the critical stress for the martensitic transformation (σ_C), considering the room (T_r) and the initial martensite phase temperature (M_s). If the $d\sigma/dT$ for Ni-Ti alloy is known, we can determine some important mechanical parameters such as the critical stress, as well as the elastic and pseudoelastic zones, where the material could be operated as a sensor or an actuator.

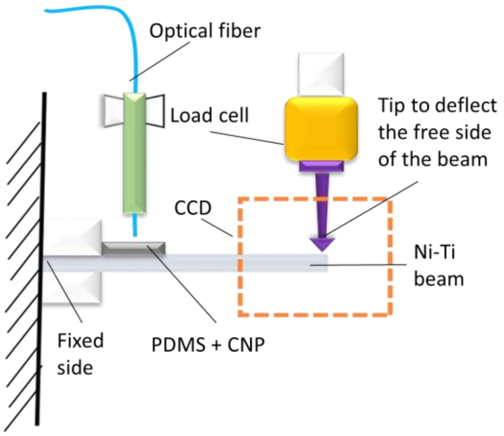

Fig. 1. Experimental setup used to evaluate the mechanical properties and light activated phase transformation in the Ni-Ti shape memory alloy.

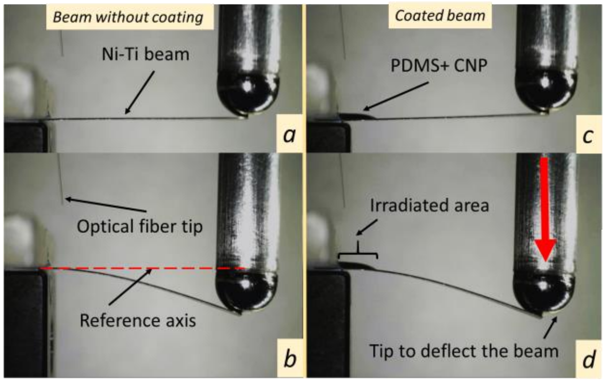

Fig. 2. Images acquired at different stages of the uniaxial test: (a) Pristine SMA beam in the start position; (b) pristine beam in the final position showing the maximum displacement of the neutral axis; (c) and (d) show the start and final position of the SMA beam coated with a CNP/PDMS composite. The irradiated area and the displacement (red arrow) are the same for both cases.

2. Experimental Setup

The mechanical response of the Ni-Ti beam was evaluated with a mechanical tester specifically designed for our experiments. A *LabVIEW* virtual instrument was programmed to acquire data during the experiments including force (registered by a load cell), displacement (registered by a LVDT), and time. Thus, the mechanical tester is capable to register the basic variables involved in a cantilever flexural test using a thin SMA sheet as the beam under test. The beam is fixed on one side while the free side is exposed to a force exerted by a linear actuator. This deflects the beam and the load cell then registers the restitution force of the beam.

Heating of the sample is achieved upon irradiating (throughout 60 s) the SMA sample with a fiber-coupled IR laser diode (975 nm, 300 mW max. output power). The SMA absorbs the laser light and heat is generated in the vicinity of the irradiated area (1.62 mm^2). Enhancement of this photothermal effect was evaluated upon comparing the mechanical response of the SMA sample in its pristine form and with a carbon composite coating applied on the beam. The coating (~ 438 μm thickness) was fabricated in our laboratory and is based on a mixture of carbon nanoparticles (CNP) incorporated by simple mixing in a polydimethylsiloxane (PDMS) matrix (we used a CNP/PDMS ratio of 2.3 mg/g) [2]. Irradiation of the beam is done upon placing the optical fiber above the fixed end of the SMA (see Fig. 1), which corresponds to the zone of maximum deformation in the Ni-Ti alloy during the uniaxial deformation test.

3. Results

Typical reported values for the critical stress (σ_C) of Ni-Ti alloys range from 120 to 140 MPa [4, 6]. In our experiments, analysis of the stress vs. strain curve (see Fig. 3a) yields an estimated $\sigma_C = 109$ MPa. This critical stress value indicates the minimum stress required to induce the phase transformation in this particular alloy. The corresponding elastic modulus (E) was determined experimentally using the registered displacement of the neutral axis of the beam for different loading conditions. As shown in Fig. 3b, the experiments yield E = 38.3 GPa for the SMA sample, falling within the typical values reported for this alloy (28-40 GPa for mixed phases [5]). Thermal analysis (Differential Scanning Calorimetry) of the SMA samples was performed to obtain the martensite phase temperature ($M_s = 3.62$℃) and this value was used to calculate the Clausius-Clapeyron relationship, given by:

$$\frac{d\sigma}{dT} = \frac{\sigma_C}{(T_r - M_s)}$$

The values for σ_C were obtained from the experimental stress vs. strain curve, and the experiments were carried out at a room temperature $T_r = 29$℃ (room temperature). Using these values, we obtain dσ/dT = 4.3 MPa for a pristine cantilever beam of the SMA.

We explored the feasibility of inducing the phase transformation in the SMA cantilever beam with the laser diode. In this approach, a local increase in temperature is generated via optical absorption and subsequent heat generation within the CNP/PDMS coating [2]. The results are presented in Fig. 3c, showing the restitution force of the cantilever beam in its pristine form and with the photothermal coating. Surprisingly, the pristine SMA sample shows a response to IR irradiation for the range of optical powers used in our experiments (50 - 270 mW), suggesting that the temperature is readily increased due to optical irradiation. The effect of using the coating is apparent in the plots shown in Fig. 3c. When using the coating, a larger restitution force exerted by the beam is registered even for lower powers than those used for the pristine SMA beam. Furthermore, as shown in Fig. 3d, the restitution force increases linearly for higher optical powers. Notice that the coated SMA beam yields slightly higher forces when irradiated by the laser. A rough estimate of the enhancement obtained with the coatings can be made upon comparing the slopes of the linear fits for the curves shown in Fig. 3d. For low optical powers, the coated beam yields a 0.3168 mN/mW slope and 0.2423 mN/mW for the pristine sample. Similarly, for higher optical powers the slope of the coated beam is larger than that obtained for the pristine SMA beam (0.0668 mN/mW vs. 0.0628 mN/mW). Hence, the optical absorption and heat generation in the CNP/PDMS coating indeed provides a means to induce the phase transformation in the SMA samples.

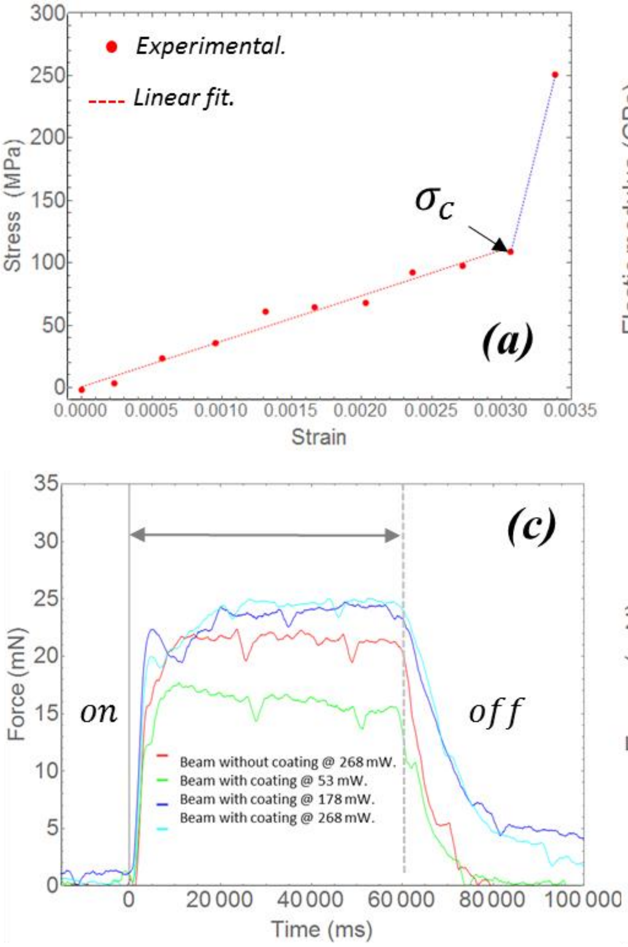

Fig. 3. Mechanical properties of the SMA beam obtained during the tests: (a) Stress vs. strain curve for the Ni-Ti beam without coating; (b) average elastic modulus (E_A= 38.3 GPa), the insets show the registered displacement of the beam used to calculate the modulus. Phase transformation induced by laser irradiation: (c) restitution force registered in the load cell for different optical powers; (d) restitution force as a function of optical power for the pristine and CNP/PDMS coated beam.

Conclusions

An infrared laser can be use used to irradiate the surface of a thin Ni-Ti alloy to trigger the single shape memory effect after uniaxial deformation of the material. This effect can be effectively enhanced with the use of a photothermal coating such as the CNP/PDMS composite used in these experiments.

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