Thermoelastic transformation behavior of NiTi thin strips in bending: experiments and modelling

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Abstract.

This paper aims to give a theoretical and experimental investigation of the bending recovery performances for a commercial NiTi shape-memory alloy (SMA) strip. Firstly, the fundamental material properties, such as mechanical properties and shape setting parameters, are evaluated. They indicate that SMA strips show the best recovery performances when heat-treated at 450 °C for 25 minutes. Then, the strip bending deformation is observed during heating in Ethylene Glycol based water solution and the curvature evolution is estimated through digital image analysis. Lastly, a model based on a phenomenological constitutive equation for SMA material is developed to predict the bending response and to compare it with experimental findings. The theoretical curvature evolution shows good agreement with experimental data.

Keywords: smart materials, experimental mechanics, beams, plasticity

1. Introduction

Due to the capability of large actuation forces and displacements, and to their thermal stability, narrow hysteresis and corrosion resistance, NiTi wires or strips have the potential to be used in the design of actuators, sensors and especially in the design of functional structures, in which they are directly or indirectly embedded in a polymer matrix.

In literature, several works deal with the design of active deformable surfaces, highlighting the complexity of both the structural modelling and the experimental feasibility and testing. Baz et al. [2] propose a composite beam reinforced with NiTi strips, embedded inside sleeves: the strips, prior to insertion into the beam, are thermally trained in order to memorise controlled transverse deflexions. This design allows in-plane displacements of the strips relative to the beam, avoiding degradation of the actuation properties due to de-bonding.

In [6], a composite made of an NiTi strip fixed to a polymeric plate is studied and a preliminary experimental assessment of the heat treatment parameters necessary to memorise a bent shape is given. Typical application of such a composite is the control of the geometry of blades to increase the performance of cooling fans in earth-moving engines [5].

In this paper, we report the experimental and theoretical findings of the thermo-mechanical behaviour of a single NiTi strip associated with stress and temperature induced transformations in bending [7]. The experimental techniques applied to characterise the SMA behaviour and to obtain its material properties are summarised in Section 2. The model based on a phenomenological constitutive equation for SMA material, developed to predict the bending response and a comparison with experimental data, is sketched in Section 3. We introduce simplifying assumptions enabling us to calculate a quasi-closed form solution for the stress and martensite fraction distributions in a SMA beam during bending and shape recovery. We expect that our solution, extending the closed-form solutions given in [1] for the bending of a superelastic SMA beam, will serve as a benchmark for finite element models.

2. SMA characterisation and shape-setting

Differential scanning calorimentry (DSC) and tensile tests at different temperatures are performed to determine the fundamental SMA material properties. The results obtained from DSC tests are given in Table 1. The best shape memory settings required to memorise the maximum recoverable curvature in the beam are experimentally determined. The percentages of the recovered shape, according to different heat treatment parameters, are collected in Figure 1. The SMA bending deformation is also observed during heating in a Ethylene Glycol based water solution and the curvature evolution is estimated through digital image analysis.

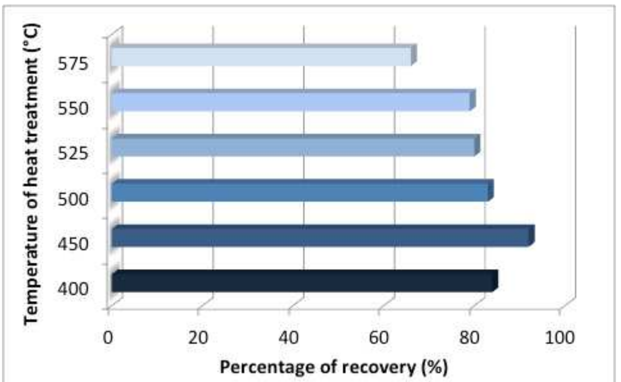

Figure 1: Percentage of recovered shape after heat treatments performed for 25 minutes at different temperatures [6].

Table 1: Transformation temperatures and latent heats per unit mass (ΔH) of the NiTi alloy calculated by DSC.

Cooling and heating rate (°C $\min^{-1}$)	A_s (°C)	A_f (°C)	ΔH_a (J g^{-1})	M_s (°C)	M_f (°C)	ΔH_m (J g^{-1})
10	82.0	104.0	24.7	69.0	46.0	25.3

3. Modelling of shape recovery

Bending deformations of superelastic SMA beams based on a phenomenological model have been theoretically studied by several authors [1, 3, 8]. To simulate the thermo-mechanical behavior of the SMA material, we adopt the model proposed in [4], which is based on the following choice of control variables: the uniaxial stress, σ, and the temperature, $T > 0$. The internal variables are the single-variant martensite fraction, ξ_s, the multi-variant martensite fraction, ξ_m, and the austenite fraction, ξ_a.

It is assumed that the phase production processes from the various phases take place in different regions of the stress-temperature plane and our choice of phase diagram follows that of established literature. Each phase production is also detailed by a kinetic relation describing the evolution of the phase fraction during the phase transformation as temperature and stress are varied. Moreover, we assume all kinetic relations to be linear.

In [7], we study uniform bending and shape recovery under heating of an SMA beam with a rectangular cross-section. We take advantage of the following simplifications: the elastic moduli of the martensitic and austenitic phases are taken to be equal; the tension-compression asymmetry is neglected; the temperature is treated as a parameter and is assumed to be constant throughout the strip cross section. These simplifying assumptions enable us to calculate, in a quasi-closed form, the stress and the martensite fraction distributions in the SMA beam. These distributions extend the closed-form solution given in [1] for the bending of a superelastic SMA beam. A plot of the twinned and detwinned martensite distributions in the upper half of the beam cross-section calculated at shape recovery is given in Figure 2.

Based on the quasi-closed form solution, we also show that the bending response in shape recovery can be approximately described by a cubic relation between curvature and temperature. In Figure 3, the curvature-temperature response is compared with the experimental results obtained during bending recovery in Ethylene Glycol water solution. The theoretical response shows reasonably good agreement with experimental data.

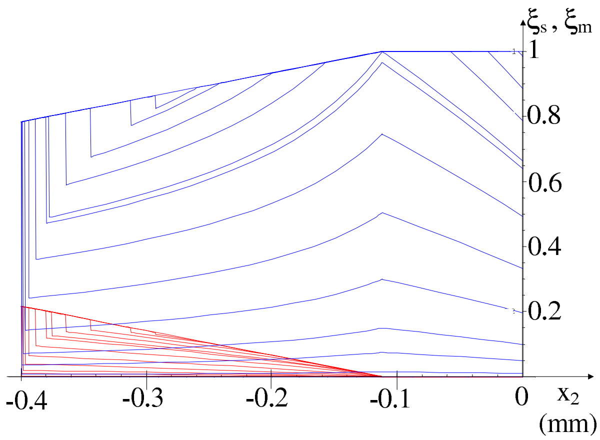

Figure 2: Theoretical twinned martensite (blue line) and detwinned martensite (red line) distribution in the upper half of the beam cross-section at shape recovery [7].

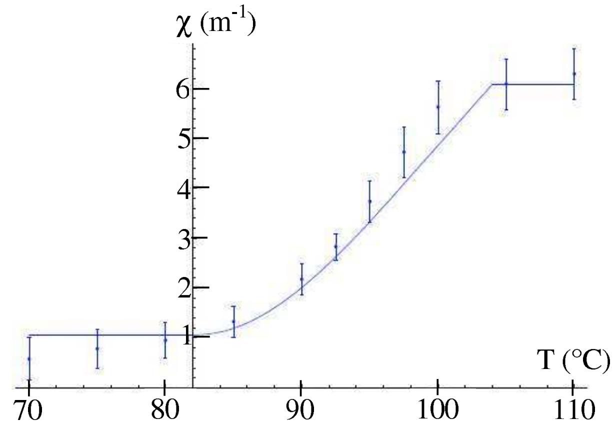

Figure 3: Theoretical curvature-temperature response at shape recovery (solid line), compared with experimental data [7].

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