PURE BENDING OF PSEUDOELASTIC NiTi TUBES

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Summary Pseudoelastic NiTi is known to transform differently in tension and compression. Tension results in inhomogeneous deformation while compression deforms homogeneously but to lower strain and higher stress. These differences are quantified as a function of temperature and their influence on the isothermal bending of NiTi tubes is investigated using a custom pure bending facility.

Nearly equiatomic NiTi exhibits pseudoelasticity that is illustrated in the three isothermal stress-elongation responses shown in Fig. 1a. In this temperature regime the material is initially in the *austenitic* (AU) phase. Under tension, AU initially deforms elastically until at a critical stress *martensite* (MA) starts to nucleate locally in the specimen. The switch from the BCC lattice of AU to the monoclinic one of MA results in macroscopic local elongation. Under displacement control, MA continues to nucleate along the length of the specimen tracing the stress plateaus seen in the figure. In the process two deformation regimes co-exist corresponding to the two phases (e.g., [1-3]). When most of the specimen is transformed, the martensite continues to deform elastically. On unloading, when the stress drops below a critical level the material transforms back to AU producing a second load plateau and a closed hysteresis force-displacement loop. The critical transformation stresses and deformations depend on temperature as illustrated in the figure. Figure 1b shows compressive isothermal responses recorded on the same material. As reported in the literature (e.g., [4]), transformation requires much higher stress and is completed at smaller strain. Equally important however is the monotonicity of both the loading and unloading responses at all three temperatures, which implies homogenous deformation (confirmed with digital image correlation).

SMAs are increasingly used in a variety of applications such as biomedical devices, MEMS, morphing structures, etc., where they invariably undergo bending and/or tension/compression loadings. The design of such structures requires constitutive models that account for the observed localized deformations and differences in behavior. This dire need is illustrated in a series of pure bending experiments on NiTi tubes made of the same material as that used in the tension/compression tests in Fig. 1. The tubes have 5.1 mm diameters, wall thickness of about 0.61 mm, and a test section 76 mm long. The experiments are conducted in a custom four-point bending facility operated under rotation control. Water from a constant temperature water bath is continuously circulated through the tube to negate temperature changes caused by the latent heat of the phase transformations. Full field images of the deforming specimen and its temperature distribution are recorded by digital photography and infrared imagery respectively. Figure 2a shows the recorded moment-rotation ($M-\overline{\theta}/L\kappa_o$) response for a bending test at 22ºC and Fig. 2b a corresponding photographic sequence of deformed configurations ($M_o=\sigma_{PM}D_o^2t$, $\kappa_o=2\varepsilon_o/D$; σ_{PM} is the upper plateau stress and ε_o is the strain at the start of MA in tension). Initially the material is in the AU phase, the response is stiff, and the tube bends with a uniform curvature κ (conf. ①). When the bending stress reaches the transformation stress, MA nucleates at the two ends (conf. ②). The moment starts to trace a ragged plateau that hovers about M_o while localization of curvature is observed on the LHS of the bent tube in conf. ③. Thus, now two curvature regimes co-exist: most of the tube is bent to curvature κ_o that corresponds to the beginning of the moment plateau, and the transformed zone on the LHS to a larger curvature. In conf. ④, the LHS zone has spread inwards and a second zone of high curvature has developed on the RHS. With further rotation of the ends of the tube, the two zones propagate inwards until the whole length has been deformed to the larger curvature with a significant part of the tube material transformed to MA. The response unloads with a positive slope during which the curvature remains uniform (conf. ⑥). When the moment drops to a low enough moment, MA cannot be sustained and the material starts to transform back to AU. This again leads to localization of curvature, this time with two fronts propagating from near the center of the specimen outwards. Thus, in conf. ⑦ the central part of the specimen has unloaded to a lower curvature whereas the outer ends remain bent at the curvature corresponding to the beginning of the lower plateau (close to ⑥). In conf. ⑧, the lower curvature has consumed more of the specimen and in ⑨ the specimen is back to uniform curvature. Unloading from ⑨ is essentially along the initial loading path. Infrared imaging confirmed that the temperature remained essentially constant throughout the bending history. It will be shown that on the tensioned side transformation led to localized inclined deformation bands that propagated along the length of the tube. By contrast, the compressed side appeared to deform uniformly. The banded deformation patterns are similar to those seen in bending experiments on mild steel tubes with Lüders bands where, of course, the tension/compression asymmetry is absent [5]. In the case of thinner tubes, this complex behavior and the associated localization of curvature can lead to failure by local buckling, a limit state that presently remains unresolved.

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Results from bending experiments at other temperatures will be used to further illustrate the intricacy of the observed behavior. Furthermore, it will be demonstrated that the behavior is more complicated when the latent heats of the reversible transformations are allowed to heat/cool the specimen during bending.

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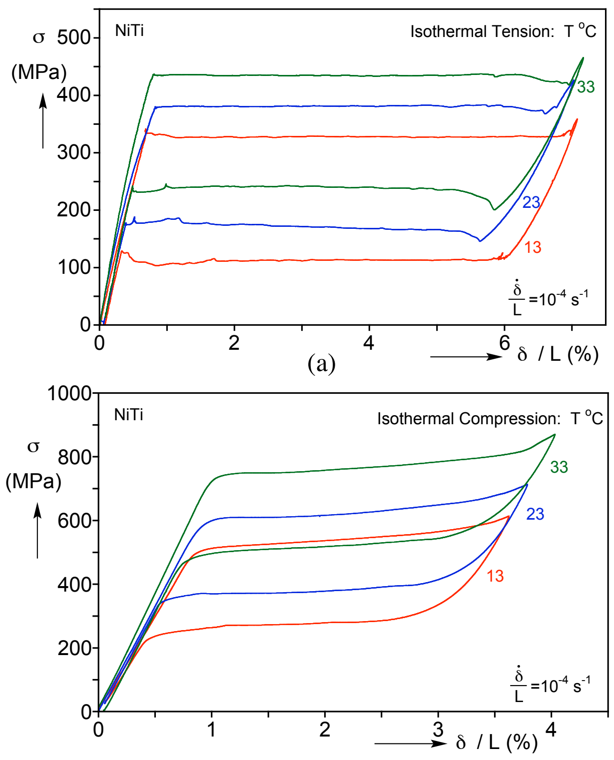
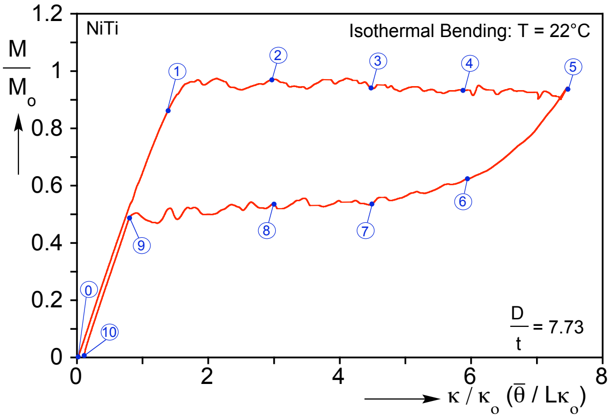
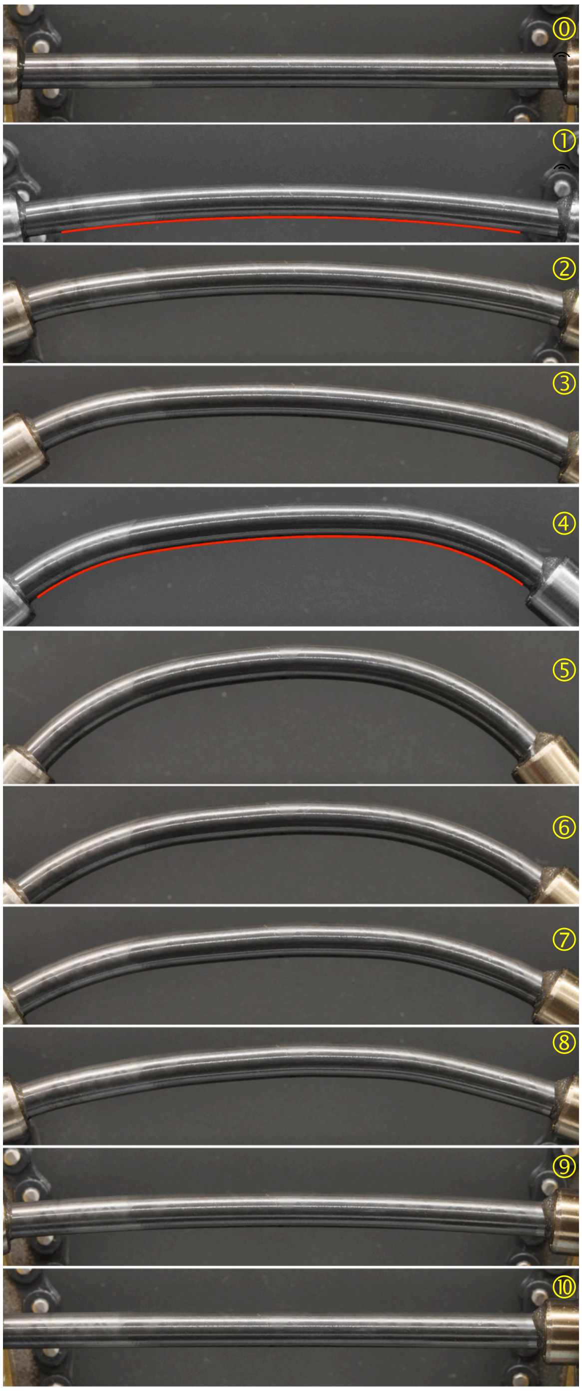


Fig. 1 Stress-displacement responses at three temperatures: (a) tension and (b) compression.





(b)

Fig. 2 Isothermal moment-rotation response for NiTi tube. (b) Sequence of tube deformed configurations.