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Martensitic reorientation and shape-memory effect in initially textured polycrystalline Ti–Ni sheet

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Abstract

In this work we modify the crystal-mechanics-based constitutive model of Thamburaja [J. Mech. Phys. Solids, 53 (2005) 825] for martensitic reorientation in shape-memory alloys to include austenite–martensite phase transformation. Texture effects on martensitic reorientation in a polycrystalline Ti–Ni sheet in the fully martensitic state were investigated by conducting tensile experiments along different directions. By fitting the constitutive model to the stress–strain response for the experiment conducted along the 45° direction the constitutive model is shown to predict the experimental tensile stress–strain response in the rolling and transverse direction to good accord. Shape-memory effect experiments were conducted by raising the temperature of the post-deformed tensile specimens. Austenite–martensite phase transformation material parameters were first determined by fitting the model to a superelastic experiment. With the model calibrated, the experimental shape-memory effect stress–strain–temperature responses were reasonably well predicted by the constitutive model.

Keywords: Shape-memory alloys; Phase transformation; Constitutive model; Finite element analysis; Mechanical properties testing

1. Introduction

Shape-memory alloys (SMA), e.g. Ti–Ni, Cu–Zn–Al, Au–Cd, have the ability to exist in multiple phases depending on their temperature and/or stress state. Some of their applications are in the bio-medical (e.g. stents) and MEMS (e.g. micro-actuation devices) fields. Their ability to undergo reversible phase transformations between the high temperature,low stress and high symmetry phase, austenite, and the low temperature, high stress and low symmetry phase, martensite, leads to two technologically important types of behavior: (1) superelasticity, and (2) the shape-memory effect.

Superelasticity is the transformation of austenite → martensite → austenite under the action of stress at a constant temperature above the austenite finish temperature, θ_{af}, where the SMA will remain in the fully austenitic state without the application of stress.

The shape-memory effect is composed of multiple parts: as the material is cooled to below the martensitic finish temperature, θ_{mf}, where the SMA is in the fully martensitic state, austenite transforms into multiple martensite plates separated by interfaces which will minimize the macroscopic deformation (also called self-accomodation). Upon closer inspection, each martensitic plate (or habit-plane variant (hpv)) consists of two lattice correspondence variants (lcv) or twins separated by interfaces. Guided by Fig. 1(a), as the fully martensitic SMA is deformed under stress martensite reorientation and detwinning of these martensitic microstructures will occur ($b \rightarrow c/d$). The motion of the inter-hpv system interface will be termed as hpv reorientation whereas the motion of inter-lcv interface will be termed as detwinning. Upon the release of load there is a residual strain which exists in the material. This residual

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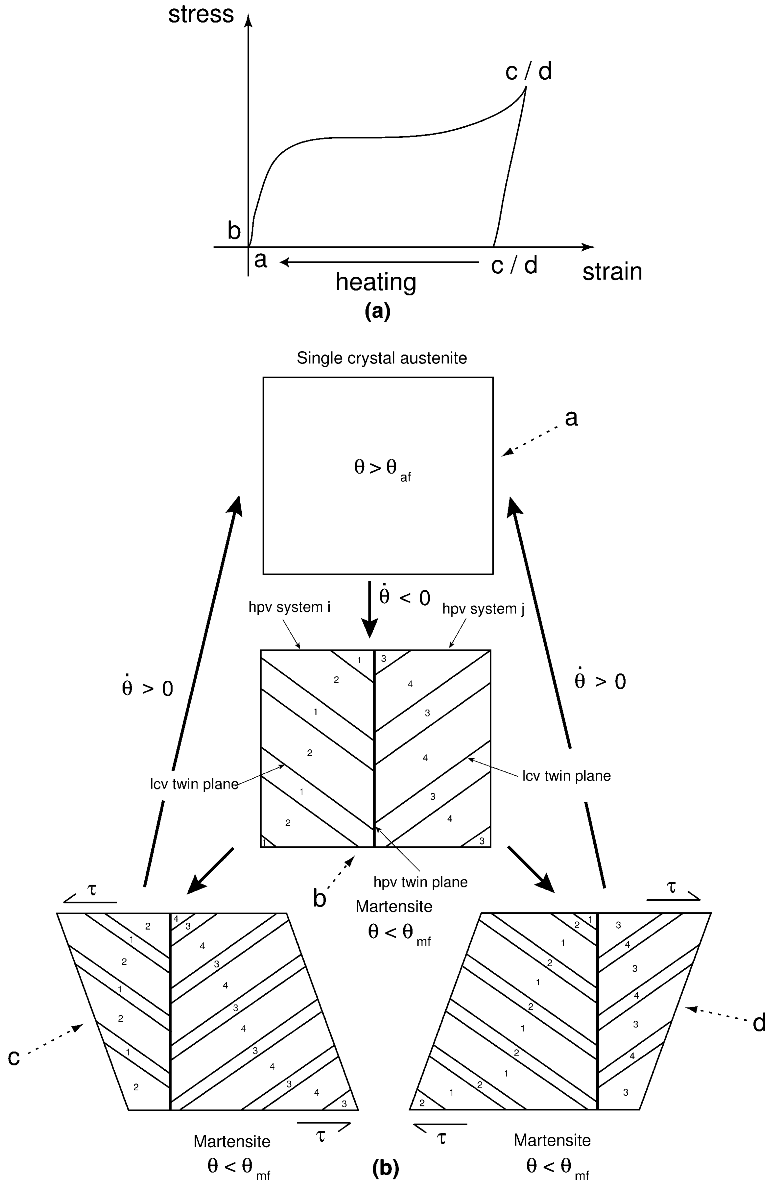

Fig. 1. (a) Macroscopic stress–strain–temperature response of a shape-memory alloy undergoing martensitic hpv reorientation, detwinning, and the shape-memory effect. (b) Schematic diagram for the single crystal austenite to martensite transformation, $a \rightarrow b$; reorientation/detwinning of martensite ($b \rightarrow c/d$); martensite to single crystal austenite transformation ($c/d \rightarrow a$). The corresponding positions of the graph in (a) match with the state of the microstructure shown in (b).

strain will be recovered as the temperature of the material is increased beyond $\theta_{af}(c/d \rightarrow a)$ and martensite completely transforms into austenite. Therefore the shape-memory effect is defined as the transformation from twinned martensite to reoriented/detwinned martensite to austenite.

Extensive experimental investigation on the behavior of polycrystalline Ti–Ni alloys undergoing martensitic reorientation and detwinning have been conducted by van Humbeeck and co-workers [2–4]. In the work of Liu et al. [3] tensile experiments conducted on initially martensitic polycrystalline sheet Ti–Ni along the rolling (RD) and transverse (TD) directions show an asymmetry in the stress–strain response. In their work they explain the asymmetry is due to texture and initial martensitic microstructure. Miyazaki and Wayman [5] have investigated the self-accommodating microstructure and its influence on the shape-memory effect of Cu–Zn single crystals. Miyazaki et al. [6,7] and Madangopal [8] have also tried to determine the self-accommodating microstructure in Ti–Ni by conducting very careful electron microscopic experiments. On the theoretical front studies on the mathematical conditions that need to be satisfied for the self-accommodation of martensite have been conducted by Bhattacharya [9].