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A three-dimensional model of magneto-mechanical behaviors of martensite reorientation in ferromagnetic shape memory alloys

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ABSTRACT

The large strain in Ferromagnetic Shape Memory Alloys (FSMA) is due to the martensite reorientation driven by mechanical stresses and/or magnetic fields. Although most experiments studying the martensite reorientation in FSMA are under 1D condition (uniaxial stress plus a perpendicular magnetic field), it has been shown that the 2D/3D configurations can improve the working stress and give much flexibility of the material's applications [He, Y.J., Chen, X., Moumni, Z., 2011. Two-dimensional analysis to improve the output stress in ferromagnetic shape memory alloys. Journal of Applied Physics 110, 063905]. To predict the material's behaviors in 3D loading conditions, a constitutive model is developed in this paper, based on the thermodynamics of irreversible processes with internal variables. All the martensite variants are considered in the model and the temperature effect is also taken into account. The model is able to describe all the behaviors of martensite reorientation in FSMA observed in the existing experiments: rotating/non-rotating magnetic-field-induced martensite reorientation, magnetic-field-assisted super-elasticity, super-elasticity under biaxial compressions and temperature-dependence of martensite reorientation. The model is further used to study the nonlinear bending behaviors of FSMA beams and provides some basic guidelines for designing the FSMA-based bending actuators.

1. Introduction

Ferromagnetic (or magnetic) Shape Memory Alloys (FSMA) appeared as a new kind of smart (active) materials when a strain of 0.2% was first observed in Ni_2MnGa single crystals under a moderate magnetic field (< 1 T) in 1996 (Ullakko et al., 1996). The observed Magnetic-Field-Induced Strain (MFIS) has the same order as the highest magnetostriction obtained in giant magnetostrictive materials such as $Tb_{0.27}Dy_{0.73}$ and Terfenol-D (Ullakko et al., 1996). Later on, MFIS of FSMA has been increased to 6–10% in off-stoichiometric single crystalline Ni–Mn–Ga alloys (Heczko et al., 2000; Murray et al., 2000; Sozinov et al., 2002; Tickle and James, 1999). The large strain in FSMA is due to the martensite reorientation (switching among different martensite variants) driven by magnetic fields (Chopra et al., 2000; Likhachev and Ullakko, 2000; Ullakko et al., 1996). Therefore, in contrast to the conventional (traditional) temperature-driven shape memory alloys, FSMA can

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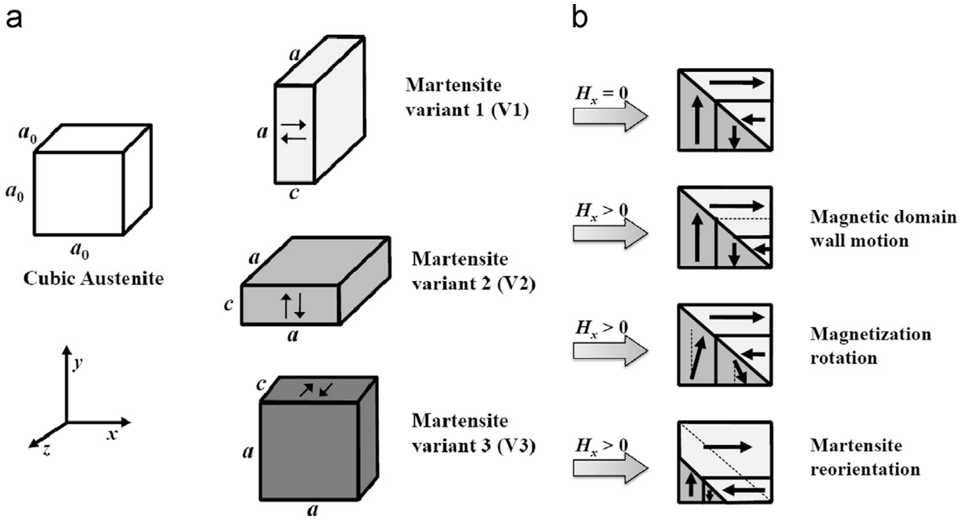

Fig. 1 (a) Schematic diagram of the austenite and the martensite variants of ferromagnetic shape memory alloys. a_0 denotes the length of the austenite lattice; a and c denote the lengths of the long (a-axis) and short (c-axis) axes of the approximated martensite lattice (the difference between a and c is exaggerated in the schematic diagram). In each martensite variant, there is a spontaneous magnetization along positive or negative direction of the short c-axis (magnetic easy-axis). The directions of the magnetizations are indicated by arrows in the figure. (b) Magnetization process via magnetic domain wall motion, magnetization rotation and martensite reorientation. The material is composed of several magnetic domains, and the magnetization direction in each domain is indicated by an arrow. The gray and black areas correspond to V1 and V2, respectively. The dotted lines indicate the initial magnetic domain wall/magnetization direction/twin boundary.

work in a large bandwidth up to 1–2 kHz (Henry et al., 2002; Marioni et al., 2003; Techapiesancharoenkij et al., 2009). The large reversible strain and the high-frequency response make FSMA promising candidates for sensors and actuators in the future (e.g., Kohl et al., 2010; Stephan et al., 2011).

Ni–Mn–Ga single crystals, the most studied FSMA, have three different martensitic phases: i.e., approximately tetragonal five-layered modulated martensite (5M), approximately orthorhombic seven-layered modulated martensite (7M) and tetragonal non-modulated martensite (NMT) (Martynov and Kokorin, 1992). Magnetic-field-induced strain has been observed in both 5M and 7M martensites, and 5M martensite is the most studied martensitic phase in literature. For cubic to tetragonal (5M) martensitic transformation in Ni–Mn–Ga, there are three martensite variants (Tickle et al., 1999; Webster et al., 1984; Zasimchuk et al., 1990): V1, V2 and V3 with their short axes (c-axis) respectively parallel to the x-, y- and z-coordinate of the parent austenite lattice (see Fig. 1(a)). Each variant has a spontaneous magnetization along the positive or negative direction of its c-axis, which is called magnetic easy-axis (Heczko et al., 2001; Tickle et al., 1999). Magnetic domain is defined as a region where the magnetizations are in one direction. Usually, the material is composed of many magnetic domains with magnetizations of different directions (see Fig. 1(b)). Without an external magnetic field, the total magnetization inside the material is zero. But when an external magnetic field is applied, a net magnetization along the field will be induced inside the material via three mechanisms: magnetic domain wall motion, magnetization rotation and martensite reorientation (some martensite variants grow at the expense of the others). The first two mechanisms exist in all magnetostrictive materials, while the third one (i.e., martensite reorientation) only exists in FSMA.

In literature, most of the experiments studying the martensite reorientation in FSMA were conducted in a simple loading condition: a uniaxial mechanical stress plus a non-rotating magnetic field or a rotating magnetic field (e.g., Karaca et al., 2006; Müllner et al., 2002; Straka and Heczko, 2005). However, the uniaxial stress is limited to a few MPa (Heczko et al., 2000; Murray et al., 2000), which leads to the low stress output of FSMA-based actuators. Recent 2D/3D energy analysis (He et al., 2011, 2012) showed that FSMA can work at high stress levels in 2D/3D configurations (multi-axial stresses with a magnetic field). In the recent experiments of biaxial compressions on FSMA (Chen et al., 2013), it is found that the material intrinsic hysteresis and the strain change due to martensite reorientation are constant under various 2D stresses. These findings imply that FSMA under multi-axial stresses still keeps its advantages – low intrinsic dissipation and large reversible strain. In order to predict the material's behaviors under general multi-axial magneto-mechanical loadings for the practical use (especially in complex structures), 3D constitutive models of FSMA martensite reorientation are demanded.

A number of constitutive models for FSMA martensite reorientation have been proposed, emphasizing different aspects of the material's behaviors. Micromagnetics models are focused on studying the fundamental mechanism of the material's behaviors in microscopic scale. James and Wuttig (1998) and DeSimone and James (2002) developed a constrained theory of magnetostriction, which can qualitatively predict the magnetic-field-induced strain in FSMA (Tickle et al., 1999). Phase-field models (e.g., Jin, 2009; Li et al., 2008, 2011; Mennerich et al., 2011; Zhang and Chen, 2005) have been developed by choosing different order parameters, which provide elegant descriptions of the evolutions of magnetic domains and martensite microstructures.