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On the stress-assisted magnetic-field-induced phase transformation in Ni_2MnGa ferromagnetic shape memory alloys

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Abstract

The effect of magnetic field on the martensitic phase transformation in Ni_2MnGa single crystals was investigated under compression. Reversible and one-way stress-assisted field-induced phase transformations were observed under low field magnitudes. The total work output levels achieved during reversible stress-assisted field-induced phase transformation are similar to that attained using field-induced martensite reorientation in NiMnGa magnetic shape memory alloys (MSMAs). However, the actuation stress levels are an order of magnitude higher. Possible magneto-microstructural mechanisms and necessary magnetic and mechanical conditions to accomplish field-induced phase transformation are discussed. A thermodynamical description is introduced to understand magnetic energy contributions to trigger the phase transformation. Materials design and selection guidelines are proposed to search for this new mechanism in other ferromagnetic materials that undergo thermoelastic martensitic phase transformation. The present work output levels achieved in the Ni_2MnGa MSMA and the possibility of further increase place MSMAs above many currently available high frequency active materials.

Keywords: Ferromagnetic shape memory alloys; Martensitic phase transformation; Magnetic-field-induced phase transformation; Ferromagnetic materials; Magnetic-field-induced strain

1. Introduction

1.1. Magnetic shape memory phenomena and magnetic shape memory alloys

Magnetic shape memory alloys (MSMAs) have attracted increasing interest due to their unique actuation, sensing and power generation capabilities [1–7]. Conventional actuator materials such as piezoelectric and magnetostrictive materials have the advantage of fast response and high actuation stress levels [8,9], but yield only small strains. For instance, magnetostrictive Terfenol-D gives a strain of <0.2% and a maximum actuation stress level of ~60 MPa in a magnetic field of ~0.2–0.3 T [10], but rare earth metals are expensive [8] and the tensile strength of Terfenol-D is very low. The recently found Galfenol has high tensile strength, but it has a low magnetostriction of only 0.03% [11]. Moreover, its high permeability results in low cut-off frequencies due to eddy currents [11]. PZT (lead zirconate titanate) piezoceramics give a maximum strain of ~0.1% and a maximum actuation stress level of ~100 MPa [12] in an electric field of several hundred V/cm [9]. However, PZT is an oxide and thus brittle. By contrast, conventional shape memory alloys (SMAs) can yield high actuation stresses (of a few hundred MPa) and strains on the order of 8%, but show slow response due to the

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restriction of heat transfer [13]. The recently developed MSMAs offer the possibility of both large actuation strains, comparable to those of conventional SMAs, and response frequencies in the kHz regime [14]. However, the currently available actuation stress levels are very low (a few MPa) [6].

The large magnetic-field-induced strain (MFIS), on the order of 5–10%, observed in MSMAs, which have been studied extensively since 1996 [2–6], is based on the field-induced reorientation of martensite twins. In this case, the magnetic field triggers the motion of martensite twin interfaces such that twins with a favorably oriented easy axis of magnetization, relative to the external magnetic field, grow at the expense of other twins leading to an external shape change (Fig. 1a) [7]. For a detailed description of this mechanism, the reader is referred to Ref. [6]. This mechanism requires simultaneous application of external stress and a magnetic field to obtain reversible shape change. The field-induced martensite twin reorientation is possible in materials with high magnetocrystalline anisotropy energy (MAE) and low energy of twin boundary motion.

NiMnGa alloys are the most widely explored MSMAs [1–7] among others such as FePt [15,16], FePd [17,18], CoNiAl [19–22], CoNiGa [23–26] and NiFeGa [27,28]. The maximum MFIS levels of NiMnGa alloys reported to date are ~6% in 10M martensite [29] and 10% in 14M martensite [4] (10M refers to the five layered tetragonal structure and 14M stands for the seven layered orthorhombic structure [30]). NiMnGa alloys are unique in the sense that they demonstrate composition, orientation and stress state dependent multi-stage martensitic transformations [31]. Depending on the composition, single crystal orientation and temperature, they can experience the complete or part of the following four-stage transformation sequence, i.e., $L2_1$ parent to intermediate (I-phase) to 10M tetragonal (or X-phase: a new phase with an unknown crystal structure, which is observed only under stress) to 14M orthorhombic (or monoclinic) to nonmodulated (2M) tetragonal martensitic transformations [31–34]. Even though the field-induced microstructural changes in each martensitic phase have been studied in some detail, there are only a few reports on field-induced intermartensitic phase transformations [34,35]. The present work will address this issue for the first two stages.

The main limiting factor in currently available MSMAs, which solely use the field-induced martensite reorientation, is low actuation stress levels of usually <3 MPa [3–6]. The maximum actuation stress, or blocking stress, in this context is defined as the stress level above which MFIS can no longer be induced. In our recent work [6], we have demonstrated that it is possible to increase the blocking

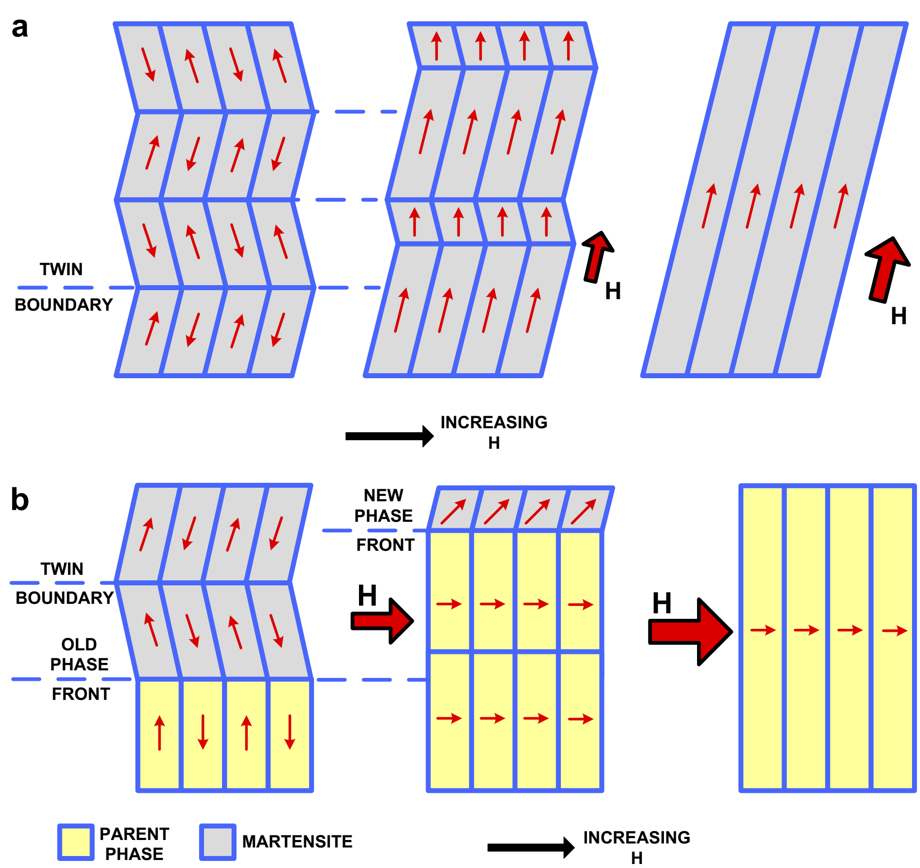

Fig. 1. Effect of applied magnetic field, H, on the reorientation of the martensite twin variants (a), and phase transformation (b) in MSMAs.