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The effect of loading rate on characteristics of type II twin boundary motion in Ni-Mn-Ga

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A R T I C L E I N F O

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A B S T R A C T

We measure the velocities of type II twins in Ni-Mn-Ga over four decades by force-driven pulsed magnetic tests and displacement-driven mechanical tests. Mechanical tests reveal that the twinning stress is a rate-sensitive property, and imply that displacement-driven twin boundary motion follows similar kinetics to those measured under force-driven conditions. All probability density plots of twin boundary velocities demonstrate normal distributions around an average value determined by the kinetic relation. The relative standard deviation of the measured histograms decreases monotonously with increasing velocity. The results imply that the kinetic relation is a valid input for modeling the actuation performance of Ni-Mn-Ga.

The motion of twin boundaries is the physical process responsible for the unique magneto-mechanical behavior of the ferromagnetic shape memory alloy (FSMA) Ni-Mn-Ga [1–5]. This motion is commonly characterized by measurements of the twinning stress property, which quantifies the value of the plateau stress observed in slow rate stress-strain tests [6,7]. Previous studies have not revealed an effect of the loading rate on the magnitude of the twinning stress in type I twins [8]. As a result, the twinning stress was considered to be a single material property that reflects the minimal driving force required for moving the twin boundary at a given temperature. In this sense, the twinning stress does not bear information about the kinetic law for twin boundary motion.

Recently, a new method for studying the motion of twin boundaries in Ni-Mn-Ga was implemented, by evaluating their propagation during short magnetic pulses [9–11]. This method enables measuring the velocity of an individual twin boundary under different controllable values of the driving force that acts on it, and leads to the extraction of a fundamental kinetic relation between twin boundary velocity and the driving force.

The kinetic relation was measured directly for type I and type II twins in 10 M Ni-Mn-Ga alloy [9,10]. For both types of twin boundaries, two regimes were observed and described by different analytical expressions [9,10]. Under low driving force values, thermally activated motion is described by an exponential function of the driving force. Under large driving force values, a-thermal motion is governed by viscous resistance to twin boundary motion and follows a square root relation. The transition between the two kinetic regimes occurs at a well-defined value of the driving force, which is referred to as g_0. The analytical expressions for the kinetic relations and the value of the transition driving force between the two regimes provide evaluations of the energy barriers for twin boundary motion and atomistic scale properties of the twin boundary [10,12,13].

In addition to its scientific importance, the kinetic relation is an essential input for modeling the time dependent macroscopic response of twinning reorientation under external loading conditions [14–16]. Recently, the obtained kinetic relations were implemented in a discrete twin boundary dynamics model that captures the macroscopic behavior of a Ni-Mn-Ga actuator [17,18]. In all previous modeling works, the kinetic relation was expressed as an injective function that matches a single value of the driving force to a single value of the velocity. However, such a representation does not take into account the scattering of twin boundary velocities for a given value of the driving force, which was observed experimentally during pulsed magnetic field measurements [9,10].

Velocity scattering is associated with interaction between the propagating twin boundary and crystal defects [19–21] or the hierarchal twinning microstructure of Ni-Mn-Ga [22–24]. The effect of microstructure is evident primarily in type I twin boundaries in 10 M Ni-Mn-Ga, leading to a stick-slip type of motion [25]. In previous works we assumed that for a large enough number of velocity data points measured using pulsed magnetic field method, the maximal velocity value under each driving force value is associated with a case during which slowing down interactions are negligible [9,10]. Consequently, the maximal velocity values were assumed to represent the fundamental kinetic relation in a "defect free" crystal. Yet, incorporation of the kinetic

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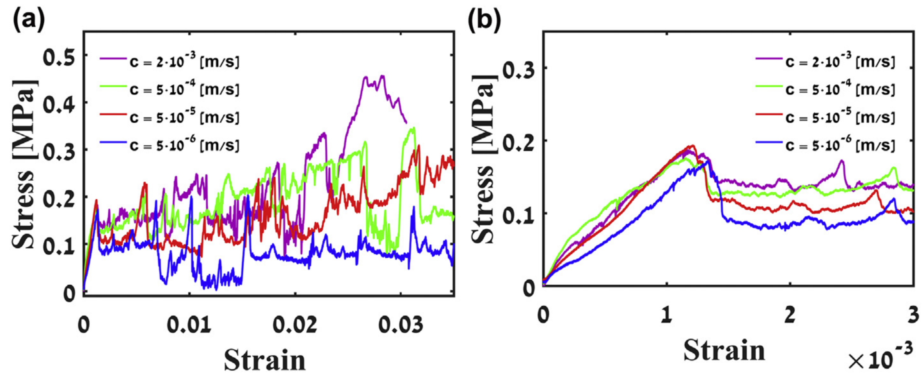

Fig. 1. (a) Typical uniaxial stress-strain curves taken at four different loading velocities spanning three decades. (b) Initial portions of the curves shown in (a). Optical observations validated that within this range twin boundary motion took place at the same region in the crystal during all tests.

relation in models that aim to predict the magneto-mechanical response of a "real" Ni-Mn-Ga crystal must take into account the effects of velocity scattering. For this purpose, the statistics of twin boundary velocities needs to be studied.

In this work, we measure the twinning stress and the distributions of twin boundary velocities in Ni-Mn-Ga, and examine the effects of loading rate. The study is focused on type II twins, which are known for their extremely high mobility [7,10,23,26], and are therefore the preferred choice for Ni-Mn-Ga based actuation applications. In particular, recent pulsed magnetic tests have shown that type II twins can propagate at velocities as high as 40 m/s [27,28]. We note, however, that the kinetic relation measured by our group with maximal velocities of type II twin boundary on the order of 2 m/s (see Ref. [10]) has been recently implemented in simulations of Ni-Mn-Ga actuators produced by ETO MAGNETIC, and provided accurate predictions of the actuators' dynamic strain response over a wide frequency range [18].

Our systematic investigation is executed using two experimental methods, both conducted at a controlled room temperature of 23 °C. Pulsed magnetic field measurements provide force-driven loading conditions and allow measuring twin boundary velocities within a range of $v_{TB} \cong 0.01-1$ m/s [10,12]. Uniaxial mechanical tests provide displacement-driven loading conditions and allow measuring the twinning stress and expanding the range of detectable boundary velocities down to 10^{-4} m/s. The combination of the two methods allows evaluating twin boundary velocities over a range spanning four decades. The tested samples are high quality, electro-polished 10 M $Ni_{50}Mn_{28.5}Ga_{21.5}$ (at. %) single crystals from Adaptamat Ltd., with a transformation temperature $A_f \cong 50^{\circ}C$, in the form of cuboids cut along {100} planes. In both experimental methods, the tested single crystals contain a similar variant configuration that consists of two, nearly tetragonal, martensite variants. Optical observations indicate that twin boundaries that separate adjacent martensite variants are of type II, according to the small inclination angle (~6°) with respect to the crystal edges.

Displacement driven mechanical tests were executed using an Instron 4133 loading frame. Uniaxial compression is performed along the long axis of a 20×2.5×3 mm 10 M Ni-Mn-Ga single crystal, at different constant cross-head speeds within a range of $c=5\cdot10^{-6}-2\cdot10^{-3}$ m/s. The dimensions of the tested crystal were chosen in order to minimize end-effects from the compression plates during uniaxial loading. Optical observations demonstrated that for any given time a single twin boundary propagates in the crystal. Under these conditions, the average velocity of the moving boundary is given by c/ε_T, where $\varepsilon_T \cong 0.06$ is the twinning transformation strain of 10 M Ni-Mn-Ga. This implies that the average twin boundary velocities during displacement driven experiments are in the range of $8\cdot10^{-5}-3\cdot10^{-2}$ m/s.

The force developed in the Ni-Mn-Ga crystal during uniaxial loading is measured using a piezoelectric force sensor (Kistler model 9215), which is mounted inside a custom made anodized aluminum body, and located on the static part of the loading frame. The sensor's full scale is 20 N with a resolution of 1 mN and natural frequency larger than 50 kHz. Sampling rates of $10-30$ kHz are used for force measurements (depending on the loading rate), and the strain is calculated based on the constant velocity of the bridge. The noise level of the stress in our measurements was evaluated to be $3\cdot10^{-4}$ MPa. Between subsequent compression experiments, the crystal was elongated back to its original length by manually pulling its ends.

Stress-strain curves were measured up to a maximal strain of about 0.04 (Fig. 1a). We note that the apparent low magnitudes of the slopes of the elastic portions of the curves (see Fig. 1b) originate from the finite stiffness of the loading frame, particularly at such small force levels. Optical videos demonstrated that the abrupt large stress peaks along the curves are related to instances at which the moving twin boundary stopped and another type II twin boundary started moving.

Fig. 1a indicates that during the majority of the loading profiles, the average magnitude of the stress plateau, commonly referred to as the twinning stress property (σ_{TS}), is rate-sensitive and increases with loading rate. This behavior is demonstrated quantitatively by a closer examination of the initial portions of the stress-strain curves (Fig. 1b), which reveals similar features of the stress profile at different loading rates. Optical videos indicated that in this strain range the same twin boundary propagated in the same region of the crystal during all tests (see also Ref. [29]). The average and standard deviation of the stress values within the range shown in Fig. 1b were calculated for each loading rate and plotted in Fig. 2, revealing the rate sensitivity of the twinning stress property in type II twins. This behavior is in accordance with the kinetic relation measured under force driven conditions, which predicts a monotonous increase in the driving force with an increase in twin boundary velocity [10]. This observation implies that twin boundary

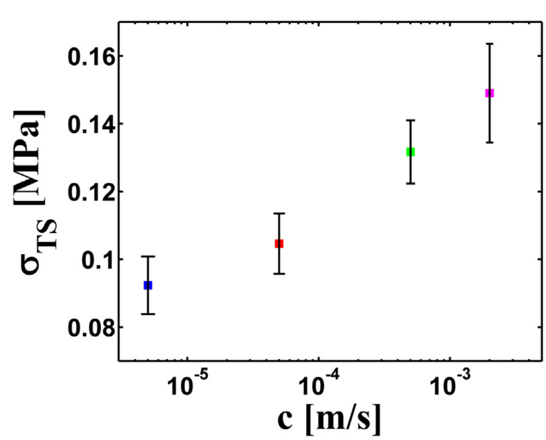

Fig. 2. Dependence of the average twinning stress σ_{TS} on the loading rate c. The vertical error bars represent the variations in stress along the plateau. Data was calculated based on the stress profiles shown in Fig. 1b.