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Coexistence and compatibility of martensite reorientation and phase transformation in high-frequency magnetic-field-induced deformation of Ni-Mn-Ga single crystal

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A B S T R A C T

High-frequency magnetic-field-induced Martensite Reorientation (MR) is one of the most important advantages of Ferromagnetic Shape Memory Alloys (FSMAs), but its stability is threatened by dissipation heat accumulation ("self-heating") of cyclic frictional twin boundary motion, which can cause temperature-induced Phase Transformation (PT) and reduce the output-strain amplitude significantly. In this paper, the interaction of the temperature-induced PT and the magnetic-field-induced MR during high-frequency magnetic actuation on FSMA is studied with in-situ observations of local-strain evolution in conjunction with microstructure compatibility analysis. Based on the nominal strain and temperature responses and the corresponding local-strain maps, it is revealed that, when the temperature-induced PT takes place during the high-frequency field-induced MR, the specimen is divided into three zones: **non-active austenite zone** (with a constant deformation), **active martensite zone** (with cyclic deformations of MR) and **buffering needle zone** (interfacial zone) with a fine-needle-twin structure which plays an important role in maintaining the compatibility between austenite and martensite zones with different cyclic deformations during the dynamic loading. A novel mechanism is revealed that, under the magnetic actuation with changing ambient airflow, the "self-heating" **temperature-driven phase boundary motion** and the **magnetic-field-driven twin boundary motion** can coexist, because the specimen needs to self-organize the different phases/variants to satisfy all the thermo-magneto-mechanical boundary conditions. Taking advantage of this mechanism, the volume fractions of austenite and martensite zones can be adjusted with changing ambient airflow velocity, which provides an effective way to tune the nominal output strain amplitude (from 1% to 6% in the current study) while the working temperature is kept almost constant (around M_s and M_f).

1. Introduction

Ni-Mn-Ga single crystal is a typical Ferromagnetic Shape Memory Alloy (FSMA) which has potential applications such as magneto-caloric refrigerators (Basso, 2011; Li et al., 2014; Singh et al., 2014; Sokolovskiy et al., 2014) and high-frequency large-stroke actuators (Henry, 2002; Smith et al., 2014; Techapiesancharoenkij et al., 2009; Yin et al., 2016) based on the field-induced martensitic phase transformation (transformation between martensite and austenite phases) and the field-induced martensite

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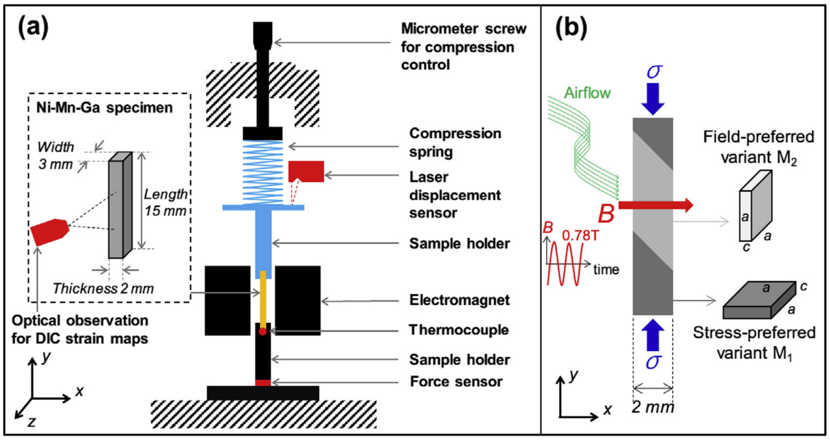

Fig. 1. Schematic of the actuation system.

reorientations (transition among the variants of the martensite phase), respectively. It was reported in the literature that the levels (magnitudes) of the magnetic fields required to drive the Phase Transformation (PT) and the Martensite Reorientation (MR) are significantly different: several Teslas for the phase transformation while less than 1 Tesla for the martensite reorientation (Bruno et al., 2016; Haldar et al., 2014; Karaca et al., 2006, 2009). So most of the existing research work studied phase transformation (Arndt et al., 2006; Karaca et al., 2009; Rogovoy and Stolbova, 2016; Sehitoglu et al., 2012) and martensite reorientation (Heczko et al., 2000; Karaca et al., 2006; Lai et al., 2008; Straka et al., 2006) separately without considering their interactions.

While the magnetic-field-driven phase transformation needs a very strong magnetic field (which is not easy to obtain), the temperature-induced phase transformation can be easily triggered in FSMA by external heat sources (Pinneker et al., 2014) or the self-heating due to the intrinsic dissipation of the cyclic martensite reorientation. For example, the self-heating induced temperature increasing rate during the first 20 s of actuation is around 0.5 °C/s in (Pascan et al., 2015) and 0.3 °C/s in (Lai, 2009). Particularly, in a high-frequency FSMA actuator, the dissipation heat of the cyclic frictional twin boundary motion during the martensite reorientation can be accumulated quickly to increase the specimen temperature to a level comparable with the material characteristic phase-transformation temperatures where the Martensite-to-Austenite (M-to-A) phase transformation can take place (Jugo et al., 2017; Pascan, 2015; Zhang et al., 2018). The phase transformation disturbs the process of the field-induced martensite reorientation, leading to a significant drop in the output strain amplitude of the FSMA actuators (Jugo et al., 2017; Pascan, 2015; Zhang et al., 2018). This instability problem is obviously harmful in developing high-frequency large-stroke FSMA actuators.

Recently, a method of changing the ambient airflow (governing the heat exchange efficiency) to control the specimen working temperature was proposed in (Zhang et al., 2018) to overcome this difficulty and to achieve a large output stain in the high-frequency actuation as shown in Fig. 1, where the combination of the orthogonal mechanical force and the cyclic magnetic field leads to the cyclic switching between the two different martensite variants (so-called "stress-preferred variant" M_1 and "field-preferred variant" M_2). It was shown that the output strain amplitude depended on the controlled ambient airflow velocity. Particularly, when the temperature-induced phase transformation and the field-induced martensite reorientation coexist, the working temperature of the specimen consisting of different phases and variants was kept almost constant (close to the material characteristic phase transformation temperatures) while the output strain amplitude changed significantly from 6% (complete martensite reorientation) to less than 1% (only little martensite reorientation), depending on the airflow velocity. One possible explanation for this phenomenon is that the specimen could self-organize its volume fractions of the Martensite phase (M-phase) and the Austenite phase (A-phase) to satisfy the thermal balance between the martensite-reorientation dissipation heat and the heat transfer to the ambient (controlled by the airflow velocity) (Zhang et al., 2018). To verify this conjecture, a high-frequency magnetic actuation on Ni_2MnGa single crystal is performed under an ambient airflow with stepped changing velocities (to change the heat-exchange efficiency), and in-situ Digital Image Correlation (DIC) observation on local strain distributions and evolutions is conducted in the current study. It is found that the temperature-induced M-to-A phase transformation makes the specimen form **non-active austenite zone** (A-phase with a constant strain) and **active martensite zone** (M-phase with 6% strain oscillation due to cyclic martensite reorientation) during the magnetic actuation, and the volume fractions of the non-active and active zones change significantly under the different ambient airflow velocities. This reveals a novel mechanism that both the **temperature-driven phase boundary motion** and the **magnetic-field-driven twin boundary motion** can be activated simultaneously during the high-frequency magnetic actuation on FSMA, which enables the specimen to self-organize the different phases/variants to satisfy all the thermo-magneto-mechanical boundary conditions and provides an effective option to tune the high-frequency output strain amplitude of FSMAs (from 1% to 6% in the current study).

Moreover, the in-situ observations on the local strain evolution demonstrate how the active zone (with the strain oscillation of the cyclic martensite reorientation) is compatible with the non-active zone (with a constant strain of the A-phase). The compatibility between different phases (and different variants) in shape memory alloys has been widely studied (Bhattacharya, 2003; Seiner et al., 2011; Stupkiewicz et al., 2007); the compatibility analyses are based on the principle of the energy minimization studying the **static** configurations: only some discrete phase/variants fractions satisfy the compatibility. In other words, the phase/variants fractions