Variability of Twin Boundary Velocities in 10M Ni–Mn–Ga Measured Under μ s-Scale Force Pulses

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Published online: 17 January 2020
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Abstract Twin boundary motion is the basic mechanism responsible for fast actuation of magnetic shape memory (MSM) alloys. Previous studies implied on a wide diversity of twin boundary velocities measured under similar conditions. Here, a data set of more than 400 velocity values is measured under conditions that are relevant for MSM applications and represents the dynamic behavior of 73 twin boundaries. Velocities are measured using an electro-mechanical setup that applies a controllable μ s-scale force pulse and combines force measurements with high-speed imaging. The latter allows extracting velocities of individual twin boundaries, which are then correlated to the macroscopic stress in the sample. The appearance of type I twins is more prevalent than type II, resulting a much larger data set for type I twins. Statistical analysis of velocity points of type I twins reveals an increasing trend of the velocity with the macroscopic stress, as well as useful information on the probability distribution of velocity data. Velocities of type II twins exhibit large variability over a relatively narrow stress range. This can reason the large differences in maximal velocities reported

previously for this twin type. The obtained statistical data can improve the design and modeling of MSM actuators.

Keywords Magnetic shape memory · Ni–Mn–Ga · Twin boundary velocity · Force pulse · High-speed imaging

Introduction

High-frequency actuation of magnetic shape memory (MSM)-based devices relies on the fast motion of twin boundaries under an externally applied magnetic field and mechanical loads [1–5]. Thus, studies of twin boundary dynamics are of great importance, as they provide relations between the velocity of a twin boundary and the magnitude of the applied magnetic field or mechanical stress [6, 7]. Because MSM can display high-frequency response under cyclic magnetic field (typically in the 10–1000 Hz range), the characterization of twin boundary motion should be studied at velocities and time scales that are relevant for MSM applications. The kinetic response obtained from such studies provides the basic scientific and engineering baseline for the development of commercial MSM-based actuators [8, 9].

Velocities of individual twin boundaries in Ni–Mn–Ga under high rates were studied in [10], for single crystals subjected to a sinusoidal magnetic field at frequencies of up to 600 Hz. The positions of individual interfaces were tracked using ms-scale time-resolved optical microscopy, from which maximal velocities of up to 0.22 m/s were reported. A more direct approach for measuring the velocities of individual twin boundaries in Ni–Mn–Ga and correlating them to the actual magnitude of the applied driving force was introduced by Faran and Shilo by means of a pulsed magnetic field setup [6, 7]. In this method, μ s-

This article is an invited submission to Shape Memory and Superelasticity selected from presentations at the International Conference on Ferromagnetic Shape Memory Alloys (ICFSMA) held June 2–7, 2019 in Prague, Czech Republic, and has been expanded from the original presentation.

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scale magnetic pulses with a nearly constant amplitude are applied over a sample that is free from mechanical constraints. Optical tracking of the positions of individual twin boundaries before and after each pulse enables measuring their temporary velocities, which can be correlated to the driving force that acts on the moving boundary. Under the experimental conditions used in these pulsed magnetic field works [6, 7], individual twin boundaries propagated back and forth within a narrow region (few hundreds of μm) in the Ni–Mn–Ga single crystal. In addition, it was shown that the effects of inertia and eddy currents are negligible, and the contribution of demagnetization energy to the driving force was evaluated quantitatively to a reasonable accuracy. This allowed good control over the applied driving force that acted on the studied twin boundary during each pulse test. Many magnetic pulse tests were conducted under different field amplitudes and resulted in a large number of velocity values for the same twin boundary. The data revealed a direct correlation between the velocity of a twin boundary and the applied driving force. It was shown that the maximal velocities measured over a wide range of the driving force represent material-specific kinetic relations. At the same time, the entire data displayed significant scattering of the velocity, which was attributed to “slowing down” interactions with crystal defects. In these works, kinetics of both type I and type II twins in 10M Ni–Mn–Ga single crystal were measured, and the results showed that type I twins propagate at velocities of up to 1 m/s, while type II propagated faster reaching maximal values of 2 m/s [6, 7, 11].

Pulsed magnetic field experiments were also reported by Smith et al. [12] and by Saren et al. [13–15]. There, a 10M Ni–Mn–Ga single crystal sample with length of few mm was subjected to μs scale pulsed magnetic field actuation, and the resulting motion of a single twin boundary that propagated throughout the crystal’s length was followed using laser vibrometry and high-speed photography. Few pulse tests were reported on the same sample, showing no scattering in twin boundary velocity. Maximal velocities of about 7 m/s and 35 m/s were reported for type I and type II, respectively. These high velocities resulted significant inertial effects. Moreover, changes in demagnetization energy, which were substantial due to the large propagation distance of the tracked twin boundaries, were not considered in this study. Both inertia and demagnetization contribute to the temporary driving force acting on a twin boundary. Recently, similar pulsed magnetic field tests were performed on μm scale pillars manufactured from mm size 10M Ni–Mn–Ga single crystals, and revealed twin boundary velocities of up to 4 m/s and 20 m/s for type I and type II, respectively [16].

The scattering of velocity data reported by Faran and Shilo [6, 7, 11] suggests that twin boundary velocity is

indeed affected by the magnitude of the driving force, but depends also on other variables/phenomena, which are often hard or even impossible to quantify using the available experimental methods. For example, crystal and surface defects that are always present in a macroscopic crystal interact with mobile twin boundaries and may lead to slowing down of the interfaces. This stochastic effect leads to scattering of velocity values measured at different locations along a crystal. Another variable that influences twin boundary mobility is the microstructure of the moving interface. It is well established that in 10M Ni–Mn–Ga “pure” type II twins propagate much faster than “pure” type I twins [17, 18]. However, due to the monoclinic distortion of the nearly tetragonal unit cell in 10M Ni–Mn–Ga, a complex hierarchical twinning microstructure with various length scales can form across a macrotwin boundary (e.g., mm to μm scale modulation twins, μm scale fine compound twins). This complex structure enables cases in which twin boundaries in 10M Ni–Mn–Ga may be composed of mixed regions of type I and type II that coexist along a single macroscopic twin boundary (Refs. [19–21]). The details of such a versatile microstructure can be fully resolved only by diffraction methods. Therefore, the effects of the hierarchical microstructure on the mobility of a given twin boundary cannot be extracted from experiments that track the motion of twin boundaries using optical methods. These two effects and the fact that each research group studied just few twin boundaries may explain the apparent discrepancies between velocity data reported by different groups.

Another effect that has not been considered so far is interactions between multiple twin boundaries that propagate simultaneously within a sample. In a crystal that contains multiple mobile boundaries, acceleration of a twin boundary causes acceleration of other regions in the sample and thus changes the driving force that is applied on other moving twin boundaries. Thus, inertial effects can lead to different driving forces acting simultaneously on different twin boundaries. This scenario is likely to occur during actuation of macroscopic MSM crystals (see, for example, Refs. [10, 22, 23]). At the same time, pulsed magnetic field experiments are typically conducted under conditions where only one (or maximal two) twin boundary propagates within a crystal and thus cannot capture these phenomena.

The above discussion motivates the need for a statistical-type study of twin boundary velocities that will collect data from a large number of twin boundaries. Currently, there is no such statistical data on twin boundary velocity under real application conditions. In this work, we performed many mechanical force pulse experiments and acquired a large data set of twin boundary velocities from more than 70 different twin boundaries. Measurements

were performed using a dedicated electro-mechanical setup that was recently developed by our group [24], and allows loading of the sample with a μ s-scale force pulse. The setup combines a direct measurement of the force in the sample with high-speed imaging of one of the sample's surfaces. This allows real-time tracking of the position of individual twin boundaries under a known applied load. In addition, the mechanical pulse method allows applying stresses that exceed the limit imposed by the magnetic stress in Ni–Mn–Ga. Thus, this work extends our previous kinetic investigations using the pulsed magnetic field method [6, 7, 23] and provides statistical insights regarding the dynamic behavior of multiple mobile twin boundaries under actuation conditions relevant for MSM actuators.

Experimental Setup and Procedure

The details of the experimental setup are shown in Fig. 1. The actuating element that generates the force is a shape memory alloy NiTi wire (Dynalloy Flexinol 90° ®, [25]).

The NiTi wire is joule-heated by a nearly square electric pulse with a duration in the range of 150–300 μ s, which heats the wire above the martensite to austenite transformation temperature. The temperature to which the wire is heated is controlled by the total transferred energy and can be estimated to a good accuracy (see analysis in Ref. [26]). As a result of the phase transformation, the pre-strained NiTi wire contracts while generating a significant stress, which reaches an equilibrium value after a time period that is comparable to the heating pulse duration. Previous works indicated that pulse durations shorter than $\sim 150 \mu$ s lead to enhanced spring-like force vibrations in the NiTi wire, and thus, longer durations are applied in this work [27, 28]. The equilibrium value of the stress in the NiTi wire is directly determined by its temperature (via the integrated Clausius–Clapeyron equation [26]) and can reach values as high as 1000 MPa for commercial Flexinol wires [26]. For example, this stress corresponds to an output force of 50–70 N for the wire diameters employed in this work (0.254 mm and 0.305 mm).

Fig. 1 Schematic description of the experimental setup used for studying twinning dynamics under force pulse loading. **a** A macroscopic view of the electro-mechanical setup, showing its position under an optical microscope (1), which is equipped with a high-speed camera (2). **b** The different parts of the electro-mechanical setup. A base plate (3) supports the setup. Two micrometer stages (4) are used for adjusting the initial position of the loading and unloading NiTi wires, (5) and (6), respectively. Strain-gauge force sensors (7) are connected between the stages and the NiTi wires, through isolating

ceramic adapters (8). **c** Zoom in on the region where the sliding cart (9) applies the force on the tested sample. The cart (9) is free to slide horizontally within a low-friction plastic track (10) due to forces applied on it by the loading and unloading NiTi wires ((5) and (6), red in figure). The tested sample [(11), blue in figure (c)] is mounted inside the cart and is backed by fixed support (12). A thin force sensor (13) is positioned in-line between the sample and the fixed support and measures the force directly on the sample

Previous measurements showed that under fast joule heating conditions, the equilibrium stress in the NiTi wire remains nearly constant for 1–2 s, and decreases only due to natural cooling [27, 28]. Thus, in order to obtain mechanical pulse duration at the μs scale, active unloading is required. This is accomplished by fast electric heating of the second, antagonistic NiTi wire. The time delay between the activations of the two NiTi wires defines the duration of the force pulse. The magnitudes of the forces in the loading and unloading wires are set to obey $F_{\text{loading}} < F_{\text{unloading}}$ (see Ref. [1]), such that the activation of the unloading wire releases the load from the sample. This ratio between the two forces is achieved by adjusting the amount of energy transferred to each wire (i.e., their temperatures) and by choosing a thicker diameter for the unloading wire. In the experiments presented in this work, loading wires with diameters of 0.254 mm and 0.305 mm were used, while the unloading wire's diameter was 0.381 mm in all cases. The loading and unloading NiTi wires are connected at opposite ends of a metallic frame (referred to here as “cart”) that is free to slide horizontally within a low-friction plastic track. The cart serves as the mechanical element that transfers the loads from the actuating NiTi wires to the tested sample.

The maximal displacement required in this study is 0.3 mm, which is the product of the sample length (5.2 mm) and the maximal longitudinal strain associated with twinning in Ni–Mn–Ga (0.06) [29]. In order to ensure such a displacement, the length of the loading wire was chosen to be 48 mm, which can apply a displacement of up to 1.7 mm. The length of the unloading wire was chosen to be twice the length of the loading wire because its activation starts from a loose state.

The tested 10M Ni–Mn–Ga single crystal (Adapamat LTd) has a cuboid shape with dimensions of $5.2 \times 2.1 \times 0.9$ mm. Prior to each test, the crystal is elongated along its major axis using a strong magnet, transforming it to a state of a nearly single martensite variant. Next, the sample is placed within the metallic cart such that one of its ends faces the cart's cross beam and the other end faces a fixed support (see Fig. 1c). Electrical activation of the loading NiTi actuating wire leads to the application of a pulling force on the cart that is transferred to a compression force on the sample. During this stage, the unloading NiTi wire is kept loose such that it does not apply any resisting force on the cart.

The loading conditions are controlled by adjusting several basic parameters. The first is the energy transferred to the actuating NiTi wire that determines its temperature and thus the maximal force it can apply. Controlling the maximal force in the NiTi loading wire allows setting a value that is higher than the stress required for twinning in Ni–Mn–Ga, and at the same time is lower than the stress

that induces plasticity. This allows performing a large number of consecutive force pulse experiments on the same Ni–Mn–Ga sample without inducing and accumulating plastic damage.

An initial preload can be applied on the tested sample by adjusting the position of the cart prior to the pulse activation. Alternatively, an initial gap between the cart and the sample can be set, that enables the cart to accelerate prior to making contact with the sample. In our previous report [ref], we showed that by setting these parameters we can predict the average strain rate in a given experiment. At the same time, we acknowledge that this control is limited and that the actual mechanical response of the crystal often leads to large variations in the strain rate during a single pulse test. Therefore, in order not to bias the statistical data, we performed many experiments under different loading conditions that induce strain rates in the range of $50\text{--}500\text{ s}^{-1}$.

The force acting on the sample throughout the pulse duration is measured directly by a miniature, 0.2 mm thick, “Flexiforce” sensor [30], which is positioned between the sample and the fixed support (Fig. 1c). The sensor has a response time smaller than $5\text{ }\mu\text{s}$ under impact load. In addition, the forces in the two NiTi wires are monitored using two strain-gauge force sensors. The entire setup is placed under an optical microscope (Olympus BX40) equipped with a high-speed camera (Photron FastCam mini AX-200), as shown in Fig. 1a. The camera has a full resolution of 1024×1024 pixels that allows frame rates of up to 1,000,000 fps (at varying resolutions). The imaging frame rate in each experiment was adjusted according to the anticipated strain rate. For example, in experiments conducted at strain rates of $200\text{--}500\text{ s}^{-1}$, a frame rate of 100,000 fps was used, while for slower strain rates (around 100 s^{-1}), the frame rate was 20,000 fps. In all cases, however, the exposure time of each single frame was equal or smaller than $2\text{ }\mu\text{s}$, to minimize blurring of the image. Image analysis of consecutive frames taken from the top surface of the sample during the force pulse allows tracking the positions of individual twin boundaries and thus calculating their average velocities. The force signal from the “Flexiforce” sensor allows correlating these velocities to the instantaneous stress in the sample. Synchronization of all signals is achieved by triggering all the measurements by the electric pulser that activates the two NiTi wires. The time $t = 0$ is defined as the start time of the electric pulse that is transferred to the loading NiTi wire.

The range of expected twin boundary velocities under the experimental conditions described above can be evaluated from the kinematic relation between the strain rate $\dot{\epsilon}$ and the velocities of moving twin boundaries:

$$\dot{\varepsilon} = \frac{\varepsilon_0}{L} \sum_{n=1}^N v_{TB}^{(n)} \quad (1)$$

Here ε_0 is the twinning strain, L is the sample's length and N is the number of moving twin boundaries. For a given strain rate, the maximal velocity is obtained when only a single twin boundary propagates. In our case, substituting $\dot{\varepsilon} = 500 \text{ s}^{-1}$, $L = 5 \text{ mm}$ and $\varepsilon_0 = 0.06$, the maximal expected velocity of a twin boundary is $v_{TB} \cong 40 \text{ m/s}$. Slower velocities are expected to be measured under lower strain rates and/or in cases where multiple twin boundaries propagate simultaneously.

Results

A series of 20 individual force pulse tests were performed on the same Ni–Mn–Ga crystal under various loading conditions that resulted strain rates in the range of $50\text{--}500 \text{ s}^{-1}$. Two typical force profiles acquired during two individual force pulse tests are shown in Fig. 2. In these experiments, a preload force of 2.4 N and 4.8 N was applied [for profiles (a) and (b), respectively], and the heating pulse duration was $300 \mu\text{s}$, with a total transferred energy of about 1.4 J. The two experiments exhibit a very different twinning structure (see Fig. 2), where in (a) only two twin boundaries nucleated and propagated, while in (b) the number of mobile twin boundaries present in the sample is about ten. The different structures represent the large variability in the response of the same sample under repetitive similar experiments.

A representative pair of consecutive microscopy images captured during each force pulse is shown in Fig. 2. The position of one selected twin boundary (x_i) is marked on each image. The average velocity of a twin boundary is calculated by dividing the displacement by the time interval between consecutive frames, i.e., $\bar{v}_{TB}(i) = \frac{x_{i+1} - x_i}{t_{i+1} - t_i}$. The motion of each twin boundary is accompanied by a strain of 0.06 in the volume swept by the boundary, which affects the positions of all other boundaries in the crystal. In order to exclude these effects and extract the “true” displacement of each twin boundary, the temporary position of a twin boundary (x_i in Fig. 2) is measured relative to a surface defect that is adjacent to that boundary. This procedure was applied throughout the analysis of all moving twin boundaries in this work.

Analysis of the high-speed images acquired during the experiments shown in Fig. 2 indicated that the twinning transformation of the entire sample (i.e., a total strain of 0.06) was completed within about 0.5 ms, which corresponds to an average strain rate of 120 s^{-1} . After twinning is completed, the force in the sample rises sharply to a

value that approaches the equilibrium force in the loading NiTi wire (not shown in the Fig. 2). In all the experiments, the maximal force value in the NiTi wire did not exceed 70 N. This value is equivalent to a maximal stress of about 37 MPa, which is smaller than the stress that leads to dislocation plasticity in 10M Ni–Mn–Ga [31]. Thus, it was possible to perform a series of loading experiments on the same sample without inducing plasticity.

From each force pulse test, the velocities of all detected mobile twin boundaries were calculated, resulting a total of 414 (σ, v_{TB}) data points, which represent 73 twin boundaries (each twin boundary contributed several velocity data points measured during a single pulse test). Figure 3 shows all velocity values plotted as a function of the macroscopic stress that was measured in the sample. The data points are color coded as either type I (red) or type II (blue). The identification of the boundary type was done based on the difference in the average inclination angle of the twin boundary on the observed surface. In 10M Ni–Mn–Ga single crystals cut along $\{100\}$ austenite planes, the projection of type I twins is parallel to $\{100\}$ austenite planes (and thus to the crystal's faces) while that of type II deviates from $\{100\}$ austenite planes at about 5° (see insets in Fig. 2). We note that this average angle is not always a precise indication of the exact type of the macro twin boundary, particularly in cases where the twin boundary consists of a combination of type I and type II segments (see also discussion in the introduction).

Discussion

About 90% of the velocity data points collected in this work originate from type I twins while only 10% from type II. This indicates on the much higher prevalence of type I twins under dynamic loading conditions. Moreover, in accordance with many previous works in 10M Ni–Mn–Ga, there is a direct correlation between the twin type and the range of velocities. The data show that type II twin are considerably more mobile than type I, exhibiting maximal velocities of up to about 14 m/s, while the velocities of type I twins do not exceed 4 m/s.

The relatively low number of type II velocity data points does not enable a reliable statistical analysis. At the same time, some interesting insights can be identified regarding the ranges of the measured values. The two highest velocity data points (about 13 m/s and 14 m/s) are in general agreement with the high values reported by the Ullakko's group [13–15]. About 20 other data points have velocities in the range of 0–3 m/s, which is in agreement with our previous results [6, 7]. The rest of the measured values (about 20 data points) have velocities that fall within

Fig. 2 Load-time profiles and pairs of consecutive high-speed microscopy images taken during two representative force pulse experiments performed on the same sample. Microscopy images were acquired at a rate of 20,000 frames per second with exposure time of $2 \mu\text{s}$ per frame. The positions of the marked twin boundaries are

measured with respect to a surface defect that is adjacent to the boundary (marked with a red dotted circle) and is used to calculate an average velocity value. The insets in both images show a typical inclination angle of 5° between a type I boundary (parallel to crystal edges) and a type II twin boundary (inclined)

these two ranges. This indicates that the different velocities reported by different groups (which were measured using similar experimental setups and on similar crystals) can be a matter of accidentalness.

Interestingly, the type II twin boundaries that exhibited the highest velocities did so under relatively low stresses. A possible explanation could be that a twin boundary that is

nucleated at lower stresses has a higher mobility. This means that there is a hidden variable (e.g., the complex microstructure of the twin boundary), which influences its mobility, its energy, and thus its ability to be nucleated at low stresses.

The large number of data points associated with type I twins in Fig. 3 (371 points) exhibits substantial scattering.

Fig. 3 Velocity data points (total of 414 points) acquired from 73 twin boundaries during a series of consecutive force pulse tests. Data points for type I and type II twin boundaries are shown in red and blue markings, respectively

In order to inspect whether there exists a correlation between the velocity and the stress, some form of averaging is performed (see Fig. 4). The velocity data associated with type I twins were divided into seven intervals along the stress axis, each with a width of 1 MPa (within the range of 1–8 MPa). For each such stress interval, the average and standard deviation of the velocity data were calculated. The resulting trend line that connects the average velocity values shows three major regions with different trends. First, the velocity increases with stress within the stress range 1–3 MPa. This is followed by a nearly constant value of the average velocities (within the standard deviation of the data) up to a stress of 5 MPa.

Fig. 4 Velocities of type I twins (red crosses) measured using the mechanical pulse test. The data include 361 points and represents about 70 different twin boundaries. Average values and standard deviation (black squares and lines) are calculated for groups of velocity points whose stress values fall within 1 MPa stress intervals (intervals' limits are marked by dotted blue lines)

Finally, at stresses between 5–8 MPa the average velocity exhibits a pronounced increase with the stress.

The data shown in Fig. 4 do not represent a kinetic relation in the sense discussed in our previous works [6, 7]. First, a kinetic relation typically describes the velocity–stress relation of a single twin boundary, whereas the velocity data in Fig. 4 are obtained from a large number of twin boundaries. In addition, the horizontal axis in Fig. 4 represents the macroscopic stress acting on the sample, and not the actual driving force acting on each boundary. The differences between the two variables (macroscopic stress and driving force on a twin boundary) originate from the fact that multiple twin boundaries propagate simultaneously and lead to inertial effects which alter the driving force. In addition, possible twin–twin interactions may affect the actual driving force acting on an individual boundary. At the same time, the increasing trend between the average twin boundary velocities and macroscopic stress, in particular at the low stress range of up to 3 MPa, is in accordance with the previously reported magnetic pulse data [6, 7].

Due to the large scattering in the velocity data of type I twins, it is useful to inspect the behavior of the majority of the data. This type of analysis is shown in Fig. 5, in which all velocity data points that fall above the 10th percentile and below the 90th percentile (i.e., 80% of the total data) are marked in blue (10th and 90th percentile points were calculated by dividing the velocity data to seven groups within 1 MPa wide stress intervals, similar to the method described for obtaining Fig. 4). The resulting range that contains the majority of data points follows a trend that increases monotonously with the stress (see points marked in blue in Fig. 5), similar to the behavior of the average values (Fig. 4).

Fig. 5 Velocities of type I twins (red crosses), showing the points that fall above the 10th percentile and below the 90th percentile of the data (blue squares). The bounding bottom and top dashed lines are linear approximations for the 10th and 90th percentile curves, respectively

Summary

Employing a unique experimental setup, a series of dynamic force pulse experiments were performed on a 10M Ni–Mn–Ga single crystal, imposing high strain rate loading conditions. From these experiments, temporary velocities of more than 70 individual twin boundaries were measured as a function of the macroscopic stress in the sample, providing a large data set that was never obtained before. Our results show that the velocities of type I twins exhibit substantial scattering, and at the same time the average values as well as the majority of data points exhibit a monotonous increase with stress. Nevertheless, there are several ‘hidden’ variables that affect the twin boundary velocity (location within the sample, motion of other TBs, the microstructure of the twin boundary), which we don’t control and measure. For type II twins, less data points were acquired and hence statistical calculations have less meaning. At the same time, the results point on a similar conclusion, i.e., that there are several uncontrolled variables (e.g., the complex microstructure of the twin boundaries) that result in a significant scattering of the data. These observations can explain the differences between the maximal velocities of individual twin boundaries that were reported by different research groups. The obtained statistical data provide useful information that has to be taken into account during the development and design stages of MSM actuators.

Acknowledgments This research was supported by the United States-Israel Binational Science Foundation (Grant No. 2016662).

References

- Ullakko K, Huang JK, Kantner C et al (1996) Large magnetic-field-induced strains in Ni_2MnGa single crystals. *Appl Phys Lett* 69:1966–1968. <https://doi.org/10.1063/1.117637>
- Murray SJ, Marioni M, Allen SM et al (2000) 6% magnetic-field-induced strain by twin-boundary motion in ferromagnetic Ni–Mn–Ga. *Appl Phys Lett* 77:886–888. <https://doi.org/10.1063/1.1306635>
- Müllner P, Chernenko VA, Wollgarten M, Kosterz G (2002) Large cyclic deformation of a Ni–Mn–Ga shape memory alloy induced by magnetic fields. *J Appl Phys* 92:6708–6713. <https://doi.org/10.1063/1.1513875>
- Chernenko VA, Chmielus M, Mullner P (2009) Large magnetic-field-induced strains in Ni–Mn–Ga nonmodulated martensite. *Appl Phys Lett* 95:104103
- Pagounis E, Laptev A, Jungwirth J et al (2014) Magnetomechanical properties of a high-temperature Ni–Mn–Ga magnetic shape memory actuator material. *Scr Mater* 88:17–20. <https://doi.org/10.1016/j.scriptamat.2014.06.013>
- Faran E, Shilo D (2011) The kinetic relation for twin wall motion in NiMnGa. *J Mech Phys Solids* 59:975–987. <https://doi.org/10.1016/j.jmps.2011.02.009>
- Faran E, Shilo D (2013) The kinetic relation for twin wall motion in NiMnGa—part 2. *J Mech Phys Solids* 61:726–741. <https://doi.org/10.1016/j.jmps.2012.11.004>
- Faran E, Shilo D (2016) A discrete twin-boundary approach for simulating the magneto-mechanical response of Ni–Mn–Ga. *Smart Mater Struct* 25:095020
- Faran E, Riccardi L, Shilo D (2017) Inertia-controlled twinning in Ni–Mn–Ga actuators: a discrete twin-boundary dynamics study. *Shape Mem Superelast.* <https://doi.org/10.1007/s40830-017-0112-5>
- Lai Y-W, Schäfer R, Schultz L, McCord J (2008) Direct observation of AC field-induced twin-boundary dynamics in bulk NiMnGa. *Acta Mater* 56:5130–5137. <https://doi.org/10.1016/j.actamat.2008.06.030>
- Faran E, Shilo D (2014) Dynamics of twin boundaries in ferromagnetic shape memory alloys. *Mater Sci Technol* 30:1545–1558. <https://doi.org/10.1179/1743284714Y.0000000570>
- Smith AR, Tellinen J, Ullakko K (2014) Rapid actuation and response of Ni–Mn–Ga to magnetic-field-induced stress. *Acta Mater* 80:373–379. <https://doi.org/10.1016/j.actamat.2014.06.054>
- Saren A, Musiienko D, Smith AR, Ullakko K (2016) Pulsed magnetic field-induced single twin boundary motion in Ni–Mn–Ga 5M martensite: a laser vibrometry characterization. *Scr Mater* 113:154–157. <https://doi.org/10.1016/j.scriptamat.2015.10.020>
- Saren A, Nicholls T, Tellinen J, Ullakko K (2016) Direct observation of fast-moving twin boundaries in magnetic shape memory alloy Ni–Mn–Ga 5 M martensite. *Scr Mater* 123:9–12. <https://doi.org/10.1016/j.scriptamat.2016.04.004>
- Saren A, Ullakko K (2017) Dynamic twinning stress and viscous-like damping of twin boundary motion in magnetic shape memory alloy Ni–Mn–Ga. *Scr Mater* 139:126–129. <https://doi.org/10.1016/j.scriptamat.2017.06.010>
- Musiienko D, Saren A, Straka L et al (2019) Ultrafast actuation of Ni–Mn–Ga micropillars by pulsed magnetic field. *Scr Mater* 162:482–485. <https://doi.org/10.1016/j.scriptamat.2018.12.009>
- Straka L, Heczko O, Seiner H et al (2011) Highly mobile twinned interface in 10 M modulated Ni–Mn–Ga martensite: analysis beyond the tetragonal approximation of lattice. *Acta Mater* 59:7450–7463. <https://doi.org/10.1016/j.actamat.2011.09.020>
- Straka L, Soroka A, Seiner H et al (2012) Temperature dependence of twinning stress of type I and type II twins in 10M modulated Ni–Mn–Ga martensite. *Scr Mater* 67:25–28. <https://doi.org/10.1016/j.scriptamat.2012.03.012>
- Chulist R, Straka L, Lanska N et al (2013) Characterization of mobile type I and type II twin boundaries in 10M modulated Ni–Mn–Ga martensite by electron backscatter diffraction. *Acta Mater* 61:1913–1920. <https://doi.org/10.1016/j.actamat.2012.12.012>
- Heczko O, Straka L, Seiner H (2013) Different microstructures of mobile twin boundaries in 10 M modulated Ni–Mn–Ga martensite. *Acta Mater* 61:622–631. <https://doi.org/10.1016/j.actamat.2012.10.007>
- Seiner H, Chulist R, Maziarz W et al (2019) Non-conventional twins in five-layer modulated Ni–Mn–Ga martensite. *Scr Mater* 162:497–502. <https://doi.org/10.1016/j.scriptamat.2018.12.020>
- Straka L, Lanska N, Ullakko K, Sozinov A (2010) Twin microstructure dependent mechanical response in Ni–Mn–Ga single crystals. *Appl Phys Lett* 96:131903
- Zreihani N, Krimer A, Avisar D et al (2019) Microstructure evolution and kinetic laws for the motion of multiple twin boundaries in Ni–Mn–Ga. *Funct Mater Lett* 12:1850102. <https://doi.org/10.1142/S1793604718501023>
- Mizrahi A, Heller U, Faran E, Shilo D (2019) Under-microscope mechanical pulse system for studying deformation processes at

- high strain rates. *Exp Mech.* <https://doi.org/10.1007/s11340-019-00555-7>
25. Dynalloy, Inc. <https://www.dynalloy.com/>
26. Vollach S, Caciularu R, Shilo D (2017) Equilibrium stress during the response of shape memory alloys to an abrupt heat pulse. *Scr Mater* 141:50–53. <https://doi.org/10.1016/j.scriptamat.2017.07.016>
27. Vollach S, Shlagman H, Shilo D (2010) The mechanical response of shape memory alloys under a rapid heating pulse. *Exp Mech* 50:803–811. <https://doi.org/10.1007/s11340-009-9320-z>
28. Vollach S, Shlagman H, Shilo D (2016) Mechanical response of shape memory alloys under a rapid heating pulse—part II. *Exp Mech* 56:1465–1475. <https://doi.org/10.1007/s11340-016-0172-z>
29. Glavatska N, Mogylny G, Glavatskiy I, Gavriljuk V (2002) Temperature stability of martensite and magnetic field induced strain in Ni–Mn–Ga. *Scr Mater* 46:605–610
30. Tekscan. <https://www.tekscan.com>
31. Reinhold M, Kiener D, Knowlton WB et al (2009) Deformation twinning in Ni–Mn–Ga micropillars with 10M martensite. *J Appl Phys* 106:053906. <https://doi.org/10.1063/1.3211327>

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