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ScienceDirect

Acta Materialia 80 (2014) 373–379

Acta MATERIALIA

www.elsevier.com/locate/actamat

Rapid actuation and response of Ni–Mn–Ga to magnetic-field-induced stress

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Received 6 June 2014; accepted 23 June 2014

Abstract

The mechanism that is responsible for the large strains in the magnetic shape memory (MSM) alloy Ni–Mn–Ga is the movement of twin boundaries caused by an internal magnetic-field-induced stress. This is the primary property that makes Ni–Mn–Ga such an attractive material for use as an actuator. Hence, a deeper understanding of the movement and dynamics of twin boundaries in Ni–Mn–Ga would enable the development of applications that could take full advantage of the material's properties. In this study, a novel experimental method was developed that could observe, in situ, the movement of a single twin boundary within a sample of Ni–Mn–Ga. A twin boundary velocity of 82.5 m s^{-1}, an actuation response time of 2.8 μs and an actuation acceleration of 1.6×10^6 m s^{-2} were experimentally observed. These experimental results have also been validated by an independently developed theoretical model. This is the most rapid actuation and twin boundary movement of all actuating materials on this scale and these results may have a significant impact on future applications, particularly in microtechnology where speed and precision are essential.

Keywords: Ferromagnetic shape memory alloy; Magnetic shape memory; Twinning; Twin boundary; Ni_2MnGa

1. Introduction

Actuating materials have revolutionized mechanical and electrical engineering by replacing conventional actuators such as electromechanical actuators, linear motors and solenoids. Modern technological demands, such as actuators being smaller, more efficient and more precise, have been achieved with the use of actuating materials. Examples of actuating materials are piezoelectrics, which strain when a voltage is applied to the material, and magnetostrictive and magnetic shape memory (MSM) materials, which strain when a magnetic field is applied to the material. The strain that is created within the MSM material is caused by a magnetic-field-induced stress which rearranges the crystallographic structure of the material by twinning when a sufficiently strong magnetic field is applied to the material [1]. In particular, Ni–Mn–Ga is an MSM alloy which has shown considerable potential as an actuating material.

Ni–Mn–Ga has attracted significant attention due to its unique combination of properties: it is capable of large (up to 10%), reversible magnetic-field-induced strain [1–3] which can be precisely controlled [4] and has a short actuation time [5]. Due to energy dissipation of the twin boundary motion, the material has a high vibration damping capacity [6,7] which can prevent overshooting and harmonic oscillations during rapid position changes. Twin configurations are stable even when the magnetic field is removed. For this reason, energy is consumed only during actuation, unlike piezoelectric and magnetostrictive material where energy is continuously consumed to sustain the strain. Coupled with an efficiency of >90% [8], Ni–Mn–Ga has very low overall power consumption when compared to other actuator

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http://dx.doi.org/10.1016/j.actamat.2014.06.054
1359-6454/

materials. Additionally, the strain's power source is a magnetic field which means MSM devices can be essentially contact-free [9]. Several Ni–Mn–Ga applications, such as actuators [5,10,11], sensors [12,13] and microdevices [9,14], have already been developed that use these properties, and rapid actuation can further improve their performance.

Fully characterizing the twin boundary and actuating dynamics of Ni–Mn–Ga would allow for further development of applications that take full advantage of its properties. Research has already been performed in this area: Marioni et al. [15] showed that the extension velocity of a sample can reach up to 0.5 m s^{-1}, Shilo et al. [16] reported a twin wall velocity of 0.1 m s^{-1} for Type I twins, Suorsa et al. [17] measured an extension velocity and acceleration of 1.3 m s^{-1} and 5000 m s^{-2}, and Korpiola et al. [18] presented a deformation velocity of up to 2.5 m s^{-1}. None of these results support the original hypothesis by Ullakko [19] that the twin boundary velocity should be a reasonable fraction of the speed of sound within the material. For this reason, we developed a new experimental method to observe the velocity of a single twin boundary.

2. Experimental

The sample was a parallelepiped, single-crystalline 10 M Ni–Mn–Ga element that had, in its compressed state, dimensions of 18.9 mm × 2.4 mm × 0.8 mm with its faces parallel to the (1 0 0), (0 1 0) and (0 0 1) crystallographic planes. The maximum strain was measured to be 5.6%. The element was elongated in the direction of its long dimension so that the *a*-axes of the crystallographic variants were all aligned in this direction (twin variant 1). A single side of the element was then mechanically ground and finally polished using a 0.25 μm diamond suspension to enhance the surface reflectivity. Surface stresses were relieved by electropolishing the element in a chilled solution of ethanol (66%) and 16 M nitric acid (34%). The twinning stress of the sample was measured to be 0.17 MPa. In order to create a magnetic field that was both sufficiently strong to actuate the MSM element and extremely fast, it was determined that a solenoid with a high-voltage pulse was necessary. As such, a solenoid was made, using insulated copper wire of 0.20 mm in diameter, which consisted of a total of 60 turns. The solenoid had an inner diameter of 2.55 mm, a length of 4.20 mm, three layers and a measured resistance of 0.4 Ω. This solenoid was embedded and fixed to the sample holder so that the axis of the solenoid was in plane with the surface of the sample holder. The Ni–Mn–Ga element was made single variant by a saturating magnetic field and then placed in line with the solenoid such that one end of the sample was located at the opening of the solenoid (referred to later as the near end of the sample) and the other end was fixed to the sample holder. Prior to each experiment, the MSM element was microscopically observed to comprise a single variant. The solenoid was connected to a high-voltage generator (EMC, Transient 1000) that created a 2 kV pulse with a rise time of <2 μs. Fig. 1a is a schematic of the experimental setup.

A single twin boundary in Ni–Mn–Ga causes a visible kink in the sample [20]. This change in the surface orientation can be observed visually due to reflected light being in noticeably different directions. Measuring this change in the intensity of the reflected light from the sample is the basic principle used to observe the velocity of the twin boundary in this experiment. In order to measure this change in intensity caused by the movement of the twin boundary, a photosensor with a response delay of 328 ns was attached to the third eye of an optical microscope so that the change in the intensity of the reflected light from the sample could be measured. The entire twin boundary movement was observed by positioning the microscope's viewing area on the free end of the Ni–Mn–Ga element. As such, the sample holder was inclined on the microscope stage in order to create a significant difference in the light reflected back into the objective lens between twin variant 1 and twin variant 2, which is when the *c*-axes of the crystallographic variants were all aligned in the direction of the long dimension of the element. The twin variants show up as distinct light and dark areas. Fig. 1b shows an image of the sample before and after the electric pulse.

The voltage from the generator was used as the oscilloscope trigger and the current and change in illumination digitally recorded by a four-channel 200 MHz oscilloscope (Metrix Scopix III OX 7204). The electric pulse was delivered to the solenoid which created a magnetic field with a calculated maximum strength of 3.0 MA m^{-1} at the face of the sample closest to the solenoid. Fig. 2 is a finite-element analysis of the magnetic field during the experiment. This magnetic field is of sufficient strength to produce the maximum value of magnetic-field-induced stress within the sample and created a single twin boundary at the sample's free end and moved it towards the center of the sample. Due to the kinking, the movement of the twin boundary through the sample created a change in the total reflected light from the sample surface which was measured by the photosensor. The total illumination measured correlates to the relative position of the twin boundary as a function of time in reference to the moving end of the sample. After the measurement was completed, the distance that the twin boundary traveled was measured and used for scaling the position data. This data was then analyzed to determine the relative velocity and acceleration of the twin boundary and the correlating actuation dynamics. The sample was returned to a single variant using a saturating magnetic field and the experiment was repeated. Although the distance that the twin boundary traveled varied ∼10%, the response time and twin boundary velocity remained very similar in each of the 25 experimental trials.

3. Theoretical model

Theoretical calculations for the actuation of an MSM element were independently computed to compare with