# Experimental characterization of the sensor effect in ferromagnetic shape memory Ni–Mn–Ga

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The characterization of a commercial Ni–Mn–Ga alloy for use as a deformation sensor is addressed. The experimental determination of flux density as a function of strain loading and unloading at various fixed magnetic fields gives the bias field needed for maximum recoverable flux density change. This bias field is shown to mark the transition from irreversible (quasiplastic) to reversible (pseudoelastic) stress-strain behavior. A reversible flux density change of 145 mT is observed over a range of 5.8% strain and 4.4 MPa stress at a bias field of 368 kA/m. The alloy investigated shows potential as a high-compliance, high-displacement deformation sensor. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2189452]

Ferromagnetic shape memory Ni–Mn–Ga exhibits strains of up to 10% when exposed to magnetic fields.[1] The effect of magnetic field on strain, or actuator effect, has been extensively characterized and modeled.[2,3] However, the effect of external mechanical input on the magnetic behavior of Ni–Mn–Ga, or sensor effect, has received only limited attention. Mullner *et al.*[4] experimentally studied strain-induced changes in the flux density of a single crystal with composition $Ni_{51}Mn_{28}Ga_{21}$ under external quasistatic loading at a constant field of 558 kA/m. Straka and Heczko[5,6] reported superelastic response of a $Ni_{49.7}Mn_{29.1}Ga_{21.2}$ single crystal with 5M martensitic structure for fields higher than 239 kA/m and established the interconnection between magnetization and strain. Heczko[7] further investigated this interconnection and proposed a simple energy model. Li *et al.*[8] reported the effect of magnetic field during martensitic transformation on the magnetic and elastic behavior of $Ni_{50.3}Mn_{28.7}Ga_{21}$. Suorsa *et al.*[9] reported magnetization measurements conducted on stoichiometric $Ni_2MnGa$ material for various discrete strain and field intensities ranging between 0% and 6% and 5 and 120 kA/m, respectively.

We present experimental measurements on the dependence of flux density with deformation, stress, and magnetic field in a commercially-available Ni–Mn–Ga alloy, with a view to determining the bias field needed for obtaining maximum reversible deformation sensing as well as the associated strain and stress ranges. As shown in Fig. 1, the experimental setup consists of an electromagnet and a uniaxial stress stage. A $6 \times 6 \times 20$ mm$^3$ single crystal Ni–Mn–Ga sample (AdaptaMat Ltd.) is placed in the center gap of the electromagnet. The sample exhibits a free magnetic-field induced deformation of 5.8% under a transverse field of 720 kA/m. For the measurements, the material is first converted to a single field-preferred variant by applying a high transverse field, and subsequently compressed at a fixed displacement rate of $25.4 \times 10^{-3}$ mm/s, and unloaded at the same rate. The flux density inside the material is measured by a $1 \times 2$ mm$^2$ transverse Hall probe placed in the gap between the magnet pole and the face of the sample. The compressive force is measured by a 200 pounds of force (lbf) load cell, and the displacement is measured by a linear variable differential transducer. This process is repeated for several magnetic bias intensities ranging between 0 and 479 kA/m.

Figure 2 shows stress versus strain curves at several bias fields, in which magnetoelastic behavior typical of Ni–Mn–Ga is observed.[5] An initial high-stiffness region until the twin variants become mobile is followed by a low-stiffness twin rearrangement region, followed by a high-stiffness elastic deformation region. The detwinning stress increases with increasing bias magnetic field.

The flux density plots shown in Figs. 3 and 4 are of interest for sensing applications. The absolute value of flux density decreases with increasing compressive stress. As the sample is compressed from its initial field-preferred variant state, the stress-preferred variants are nucleated at the expense of field-preferred variants. Due to the high magneto-crystalline anisotropy of Ni–Mn–Ga, the nucleation and growth of stress-preferred variants occurs in concert with rotation of magnetization vectors into the longitudinal direction, which causes a reduction of the permeability and flux density in the transverse direction.

There is a close correlation between Fig. 2 and Figs. 3 and 4 regarding the reversibility of the magnetic and elastic behaviors. Because a change in flux density relative to the initial field-preferred single variant is directly associated
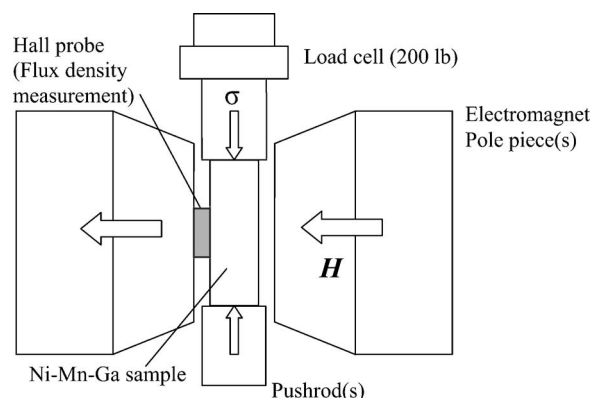


FIG. 1. Experimental setup used for determination of flux density under various strain and bias magnetic fields.

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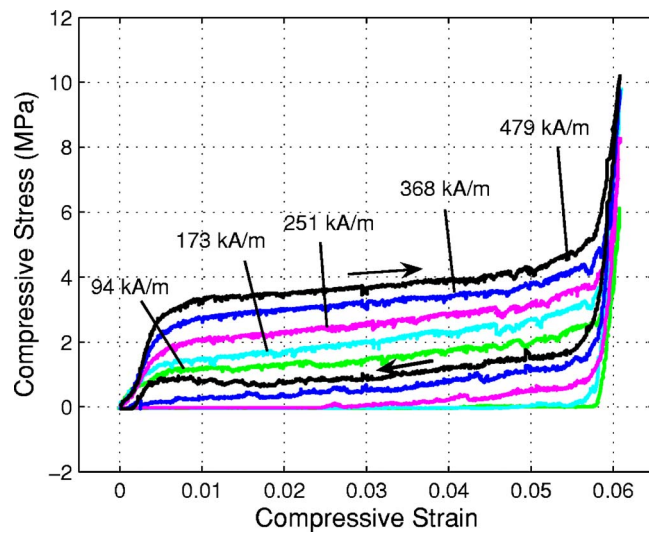[b]Author to whom correspondence should be addressed; electronic mail: dapino.1@osu.edu

FIG. 2. (Color online) Stress vs strain curves at various bias fields.
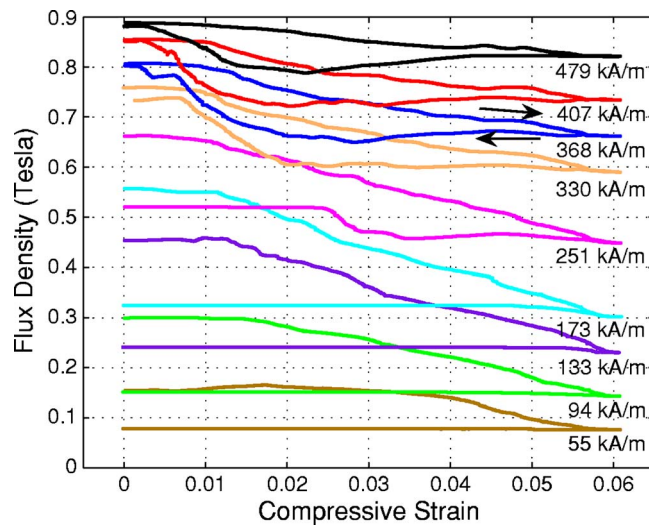


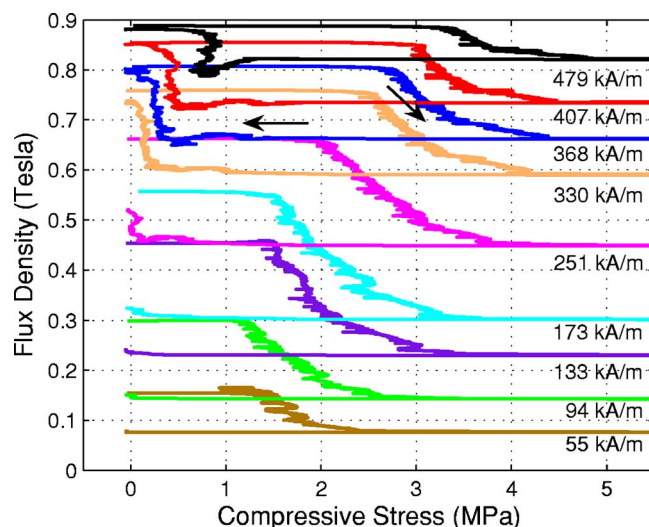FIG. 3. (Color online) Flux density vs strain curves at various bias fields.



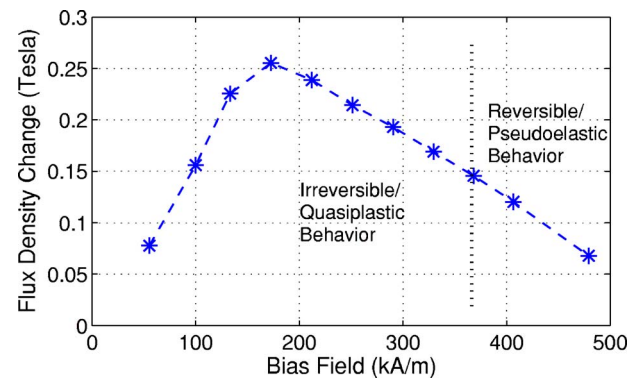FIG. 4. (Color online) Flux density vs stress curves at various bias fields.



FIG. 5. (Color online) Net magnetic flux density change at various bias fields.

with the growth of stress-preferred variants,[4] the flux density value returns to its initial value only if the stress versus strain curve exhibits magnetic field induced pseudoelasticity. This occurs for this alloy at bias fields of 368 kA/m and higher. In contrast, single crystal $Ni_{49.7}Mn_{29.1}Ga_{21.2}$ shows fully reversible strain at much higher fields, 476 kA/m and above.[5] When the sample is unloaded at high bias fields, the magnetic field energy is high enough to initiate and complete the redistribution of variants relative to the single stress-preferred variant formed at maximum compression. During this redistribution the magnetization vectors rotate into the transverse direction, resulting in the recovery of flux density to its original value along with pseudoelastic recovery. At fields of 94 kA/m or lower, the magnetic field energy is not strong enough to initiate redistribution of variants, hence the flux density remains unchanged while the sample is unloaded. Correspondingly the stress versus strain curve also shows irreversible (quasiplastic) behavior.[6]

The flux density starts changing when the initial detwinning stress is reached and continues to change until the detwinning is completed and all the variants are transformed to one variant preferred by stress. The magnitude of total change in flux density during compression can be defined as sensitivity. The sensitivity is found to initially increase with increasing bias fields and then decrease after reaching a maximum at 173 kA/m (Fig. 5). However, the reversible behavior required for sensing applications is observed at bias fields of 368 kA/m and higher.
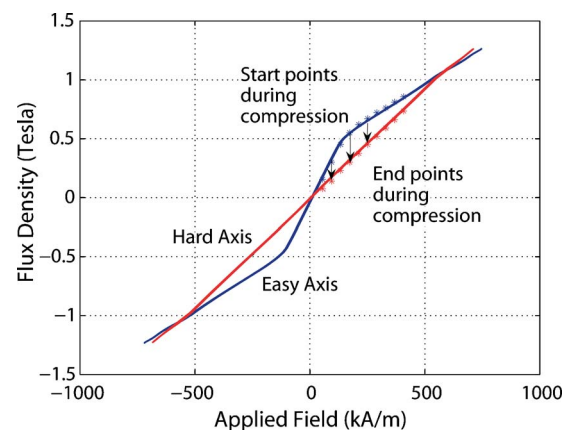


FIG. 6. (Color online) Easy- and hard-axis flux density vs magnetic field curves.

This behavior can be explained from the easy- and hard-axis magnetic flux curves of this alloy, shown in Fig. 6. The easy-axis curve was obtained by first converting the sample to a single field-preferred variant and subsequently exposing it to a 0.5 Hz sinusoidal field while leaving it mechanically unconstrained. To obtain the hard-axis curve, the sample was first converted to a single stress-preferred variant and subsequently exposed to a 0.5 Hz sinusoidal field while being prevented from expanding.

When the sample is compressed at a given constant field, the magnetic induction changes from the corresponding easy-axis value to the corresponding hard-axis value. Hence, the optimum sensing range occurs when the two curves are at the maximum distance from each other *and* the sample shows pseudoelastic behavior. At a bias field of 368 kA/m, a reversible flux density change of 145 mT is obtained over a range of 5.8% strain and 4.4 MPa stress. By way of comparison, Terfenol-D exhibits a higher maximum sensitivity of 0.4 T at a lower bias field of 16 kA/m and higher stress range of 20 MPa.[10] However, the associated deformation is only 0.1% due to the higher Terfenol-D stiffness. The Ni–Mn–Ga alloy investigated here therefore shows potential for high-compliance, high-displacement deformation sensors.

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