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One-way shape memory effect due to stress-assisted magnetic field-induced phase transformation in Ni_2MnGa magnetic shape memory alloys

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One-way shape memory effect is achieved utilizing stress-assisted field-induced martensitic phase transformation in Ni_2MnGa magnetic shape memory alloy single crystals. Depending on temperature, one-way and reversible magnetic field-induced strains of up to 3.1% and 0.3% are attained under stresses as high as 110 MPa and 24 MPa, respectively. These bias stress levels are more than one order of magnitude higher than the previously reported values obtained from field-induced martensite reorientation.

Keywords: Magnetic shape memory alloys; Martensitic phase transformation; Ferromagnetic materials; Magnetic field-induced shape change

There has been an increasing interest in magnetic shape memory alloys (MSMAs) due to their ability to combine the large actuation strains of conventional SMAs and high frequency response of magnetostrictive materials [1,2]. Magnetic field-induced strain (MFIS) in these materials can be obtained due to two possible field-induced mechanisms: (i) martensite variant reorientation [1,2] and (ii) martensitic phase transformation [3–8]. There are two methods to induce phase transformation by a magnetic field utilizing the field-induced shifts in (i) transformation temperatures [8] and (ii) critical stresses for phase transformation [5–7]. The current drawbacks of the aforementioned mechanisms are low actuation stresses in field-induced variant reorientation [2], low MFIS in stress-assisted reversible field-induced phase transformation [7] and high field requirement in field-induced phase transformation [3,4,8].

Stress-assisted field-induced phase transformation in NiMnGa alloys has only been investigated in a few earlier studies where the phase transformation was not reversible with the magnetic field [5,6]. We have recently shown [7] that an applied magnetic field increases the critical stress levels for phase transformation and it is possible to find a stress region where the critical stress for forward transformation under zero field is less than the critical stress for reverse transformation under a magnetic field, i.e. pseudoelastic loops with and without magnetic field are separated. By utilizing this separation, it is possible to achieve reversible field-induced phase transformation between the X phase, a new phase with an unknown crystallography [9], and the parent (P) or premartensitic phase (also called intermediate (I) phase) [10], of a single crystal Ni_2MnGa alloy. This new mechanism makes it possible to achieve actuation stress levels one order of magnitude higher than that of field-induced variant reorientation, requires low magnetic field (<0.5 T); however, the MFIS magnitude is small (0.5%) compared to the other mechanisms.

In NiMnGa alloys, composition, orientation and stress-state dependent multi-stage martensitic transformations occur [11]. Our aforementioned previous study [7] focused on the first stage of a two-stage phase transformation response in the $Ni_{51.1}Mn_{24.0}Ga_{24.9}$ alloy and investigated the stress-assisted field-induced phase transformations from and to the X phase martensite. In this report, we present the effect of magnetic field on the

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second stage phase transformation from and to the 10M martensite. It is shown here that the stress levels under which field-induced strains are possible could be significantly higher, as compared to the reversible field-induced phase transformation and variant reorientation processes, with transformation strains of 2–4%. Additionally, the effect of magnetic field on the pseudoelastic response of NiMnGa single crystals as a function of temperature is investigated to determine the operating temperature range of this new mechanism. Our previously proposed thermodynamic framework [7] is used to explain the change in magnetostress with temperature. Magnetostress is the amount of increase in the critical stress level for the onset of phase transformation due to a magnetic field.

NiMnGa single crystals were grown using the Bridgman technique in a He atmosphere. Inductively coupled plasma-atomic emission spectrometry was used to determine the composition of the single crystals as $Ni_{51.1}Mn_{24.0}Ga_{24.9}$. The single crystals were cut into 4 mm × 4 mm × 8 mm rectangular prisms, using electro-discharge machining with the face normals along the [1 0 0], [0 1 1], and [0 1 $\bar{1}$] directions in the $L2_1$ parent phase. The transformation temperatures were found as −20 °C for P ↔ I, −60 °C for I → 10M, −92 °C for 10M → I phase transformations by using low field thermal cycling in a Quantum Design superconducting quantum interference device (SQUID) magnetometer.

A custom-built experimental test set up was used to characterize the magneto-thermo-mechanical (MTM) behavior of the crystals. The details of the setup have been previously described [2,7]. Compressive stress and magnetic field were applied along the $[1\,0\,0]_{parent}$ and $[0\,1\,1]_{parent}$ directions, respectively.

Figure 1 shows the effect of temperature on the compressive stress–strain response of the single crystals under zero and 1.6 T magnetic fields. At temperatures between −70 and −40 °C, a two-stage martensitic transformation occurs during loading. At these temperatures, the elastic deformation of the I phase (the initial phase at these temperatures [7,9]) is followed by I to X (first stage) and then X to 10M (second stage) martensitic transformations which are fully recoverable upon unloading. Premartensitic phase transformation from P to I phase is a well known phenomenon, which is observed prior to the martensitic transformation in NiMnGa alloys [9,10]. The X phase, on the other hand, is only detected under stress and there is a decrease in the critical stress levels for the onset of the I to X phase transformation with an increase in temperature [7,9]. For temperatures higher than −40 °C, first stage transformation vanishes and only one-stage transformations from I phase to 10M martensite (between −40 °C and −20 °C) and parent (P) to 10M martensite (above −20 °C) take place during loading. The inset to Figure 1 illustrates the schematic definition of the critical stress, stress hysteresis, and magnetostress used in this study.

It is clear in Figure 1 that the magnetic field shifts the stress required to induce the phase transformation to higher levels, i.e. it stabilizes the initial phase, without noticeably affecting the stress hysteresis and transformation strain. The effect of the field vanishes with increasing temperature and both the magnetostress and the transformation strain decrease with increasing temperature. It is important to note that during phase transformation at low temperatures, there is a plateau region without any strain hardening that changes into a region with significant hardening with increasing temperature. This behavior has been observed in other SMAs [12,13] and attributed to the nucleation of single variant martensite at low temperatures and nucleation of multiple martensite variants at high temperatures [12]. At higher temperatures the elastic mismatch between the parent and product phases increases, which could result in an increase in the stress required for phase front propagation and thus in the nucleation of multi martensite phase fronts. The decrease in transformation strain with increasing temperature can be attributed to incomplete transformation/detwinning process under the present applied stress levels.

Figure 2 shows the stress hysteresis and magnetostress levels as a function of temperature for the second stage transformation extracted from the experiments shown in Figure 1. Stress hysteresis and magnetostress were determined at 50% of the transformation strain as shown by the inset in Figure 1. The critical transformation stress increases from 33 MPa to 193 MPa, while

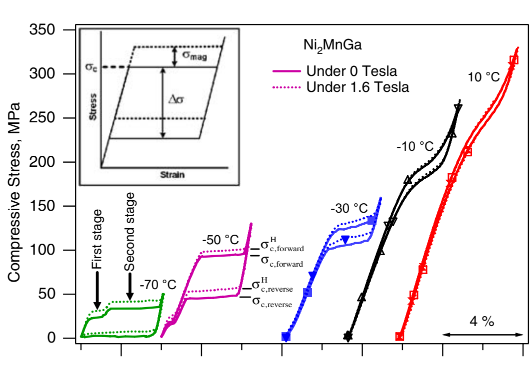

Figure 1. Pseudoelastic response of Ni_2MnGa single crystals as a function of temperature and magnetic field under compression along the $[1\,0\,0]_{parent}$ orientation. σ_c: Critical stress for the onset of forward phase transformation, $\Delta\sigma$: pseudoelastic stress hysteresis, and σ_{mag}: magnetostress.

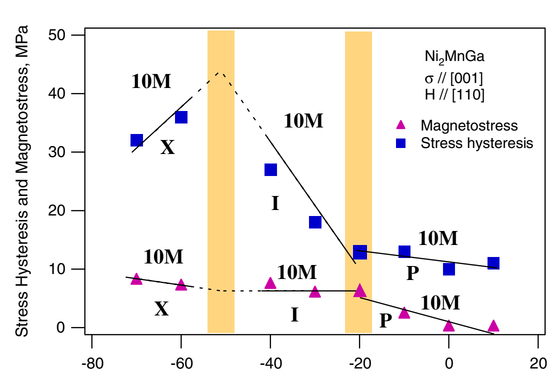

Figure 2. Stress hysteresis and magnetostress in the second stage phase transformation shown in Figure 1 as a function of temperature. The figure is divided into three transformation regions depending on the type of the initial phase as X → 10M, I → 10M and P → 10M.