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Magneto-mechanical actuation of ferromagnetic shape memory alloy/epoxy composites

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ABSTRACT

Ferromagnetic shape memory alloys (MSMA) exhibit magnetic field- and stress-induced twinning when processed into single crystals, but are brittle and difficult to shape. Embedding slender single crystalline MSMA elements into a polymer matrix can thus provide composites with adjustable magnetic strain actuation behavior. Ni–Mn–Ga single crystalline rods were characterized for their magneto-mechanical behavior and embedded in two different types of epoxy matrices with different volumetric fractions. The magnetic actuation of the composites was measured and shown to depend on the Ni–Mn–Ga volumetric fraction and the matrix stiffness. This behavior was well predicted by finite element simulations of the composite using a simple material model for the strain of the MSMA as a function of the magnetic field and applied stresses. Guidelines for composite behavior prediction could thus be proposed.

1. Introduction

Thermal shape memory alloys (TSMA) have found numerous applications over the last thirty years, in medicine, dentistry, robotics, etc [1], mostly owing to their superelastic properties in the austenitic phase. The actuating capacities of TSMA, resulting from the shape memory effect of these alloys, are also of interest for practical applications requiring large strains and recovery stresses but they are restricted to low frequencies ($\leqslant$1 Hz), as a consequence of the relatively slow process of thermally induced martensite to austenite phase transformation [2]. Ferromagnetic shape memory alloys (MSMA) are a subset of the TSMA that show deformations up to 10% and 20% in their martensitic state, upon the application of an external magnetic field or mechanical load, respectively [3]. This response is caused by the reorientation of twins in the tetragonal or pseudo-tetragonal martensite phase. Since twinning is a very fast process, high actuation frequencies of up to 2 kHz can be reached, and new applications can be envisaged [4–6]. Grain boundaries, however, increase the twinning stress, hinder twinning and prevent the magnetic field induced actuation. Thus, applications requiring high strain and actuation frequency have been up to now limited to expensive and brittle single crystals. The Magnetic Field Induced Strain (MFIS) and magnetization response of these bulk materials is in general modeled with a phenomenological approach, which describes their thermodynamic state by means of internal energy functions with mechanical and magnetic variables to minimize [19–21]. These models have shown accurate predictions of the experimental MFIS and magnetization curves in MSMA [22–24], and have been incorporated in 3D finite element models to reproduce the magneto-mechanical material response of the bulk MSMA under different field and stress conditions [25–27]. These models have been generally developed to capture hysteretic or structural effects in the bulk material as a function of its composition and state. Similar methods were also used for modeling thermal SMA materials, where the internal state variable was the martensitic volume fraction, instead of the fraction of variants. Transformation functions, similar to the yield functions of rate-independent plasticity models were often introduced, to govern the start and finish points of the phase transformation [28–30].

Instead of using bulk MSMA materials, in order to alleviate the cost and brittleness limitations, current research considers the use of composites, containing single crystalline powders or slender fibers of Ni–Mn–Ga with grains as large as the fiber diameter that exhibit considerable magnetic activation [7–9,11]. These composites are in principle more easily shaped for a given application, easier to handle, and suitable for applications with tailored magnetic actuation behavior. So far, mostly powder composites have been produced [4,12,13] and have demonstrated increased damping, but very little Magnetic Field Induced Strain (MFIS), of less than 0.1% [14,15]. The use of MSMA fibers in composites is still in its infancy and so far suitable for damping as well [10].

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However, Gans et al. investigated the use of single crystal rods in a PU resin and showed promising actuation strain results with one volume fraction of NiMnGa in the composite, in two simple geometric configurations, which they compared to an analytical rule of mixture [16]. They also pointed out the beneficial role of the matrix material as a bias force to allow cyclic actuation behavior. Linear actuators with high strain output and high frequency, albeit with moderate force output, could then be conceived with this configuration. However, no model was yet proposed and validated to optimize the design of such actuators taking into account the influence of the matrix. In the present work, we thus proposed to further assess the feasibility, design and optimization of linear strain actuators based on MSMA composites comprising unidirectional NiMnGa single crystal rods, embedded in epoxy matrices. For this, Ni–Mn–Ga-epoxy matrix composites with different Ni–Mn–Ga volumetric fraction and matrix stiffness have been processed and investigated for their magnetic actuation behavior. Slender single crystalline MSMA rods were trained to exhibit only 2 types of variants. To simulate the magneto-mechanical behavior of these single crystals along the rod axis, a three-dimensional phenomenological material model was proposed, which simply relies on the identification of a stress–strain compression curve, and a stress-magnetic field curve for the rods. The mechanical response, including the pseudo-elastic behavior produced by the twining microstructure, was described using the formalism of computational plasticity in the plane undergoing the dimensional change. The magnetic field induced response was described from a fit of the stress-magnetic field response of the constrained single crystal. Once the constitutive law of the rods was determined, it was implemented in a model for the composite behavior, taking into account the geometry and properties of both phases as usually performed for traditional fiber reinforced composites [17,18]. In order to leave the possibility to introduce anisotropy or time dependent behavior in the matrix material, a finite element modeling approach was selected to simulate the composite actuation strain. Model results were finally compared to the experimental linear strains, measured for four types of MSMA composites.

2. Materials and experimental techniques

The Ni–Mn–Ga rods used in this work were produced by Adaptamat, Finland, and had a 10 M structure. They were delivered with a stabilizing surface treatment and a dimension of $20 \times 1 \times 1\ mm^3$. To guarantee maximum elongation along the long sample axis, the crystals were cut by Adaptamat so as to keep their faces parallel to the {1 0 0} faces of the high temperature, austenitic phase. In addition, a training of the crystals resulted in an activation of only one out of the three possible twinning planes {1 0 1}, {0 1 1} and {1 1 0}. Thus, the single crystals could only transform between two different twin variants, variant 1 and variant 2 in Fig. 1, and the twinning strain upon magnetic and mechanical activation took place, as shown in Fig. 2, only in the directions *x*, which is the long axis of the rod and *y* [20]. All rods were cut with a wire saw to obtain about 10 mm long samples.

Two epoxy systems of low modulus were selected: LME 10435 (resin)/LME 10436 (hardener) from Huntsman with a mix ratio of 100:123 by weight and SR 8150 (resin)/SD 815 B1 (hardener) from Sicomin with a mix ratio of 100:16 by weight. Four model composite specimens each containing four Ni–Mn–Ga single crystalline rods embedded in the epoxy matrix were manufactured to investigate the magnetic actuation behavior of MSMA composites, with two different Ni–Mn–Ga volume fractions (13 and 34 vol.%), as shown in Fig. 3, and the two different matrices. Epoxy was cast into silicon molds containing the rods. In order to maintain the positions of the rods during casting, the procedure was as follows: the rods were first glued with a drop of epoxy on a cuboid of already cured epoxy using a geometrical device that allowed to position the rods according to the desired volume fraction with a constant intra-rod distance equal to the distance between rod and sample edge. After curing the drops for 2 days at room temperature, the positioning device was removed. To avoid a thermal reverse martensitic phase transformation of the Ni–Mn–Ga rods which takes place at about 53 °C, the composite samples were cured at room temperature during 21 days.

The magneto-mechanical behavior of the single crystalline Ni–Mn–Ga rods and of the four Ni–Mn–Ga composites was characterised with the experimental set-up shown in Fig. 4. It consisted of micrometer screws to measure the displacement of the sample, of a 500 N piezoelectric high-sensitivity tensile and compression force sensor 9217A from Kistler, Switzerland, and of a glass extension bar to ensure that the measurement of the load is not influenced by the magnetic field. Turning the micrometer screws allowed to lower/raise the extension bar. The magnetic field of maximum 1.2 T for this configuration was generated by a dipole electromagnet 5403 from GMW Associates, US, and measured by a MagVector 3D Hall sensor of Sensima technology SA, Switzerland. Magnetic field and force were simultaneously recorded using a LabVIEW program.

The stress–strain behavior of the Ni–Mn–Ga single crystals was determined through uniaxial compression tests. Prior to each test, the single crystals were magnetized in a homogeneous magnetic field of 1.2 T perpendicular to the long sample axis in order to ensure a detwinned, long initial sample state. The samples were compressed in steps of 12.5 μm up to a compression of 50 μm and in steps of 25 μm up to a compression corresponding to the detwinned, short sample state and unloaded in steps of 12.5 μm.

The magnetic field induced stress was measured on a Ni–Mn–Ga single crystal in its detwinned, short state. To obtain this state, the sample was magnetized along the long sample axis in a magnetic field of 1.2 T. During the test, the initial position of the extension rod, just touching the sample, was kept constant while the magnetic field perpendicular to the long sample axis was slowly increased to 1.2 T.

The actuation behavior was analyzed by measuring the MFIS of a Ni–Mn–Ga rod for different pre-loads and of the composites. For these tests, the magnetic field was perpendicular to the long

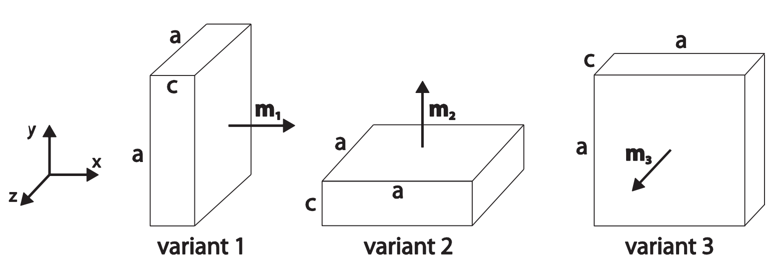

Fig. 1. Possible martensitic variants in Ni–Mn–Ga magnetic shape memory alloys.