



Comparison of magnetic field controlled damping properties of single crystal Ni-Mn-Ga and Ni-Mn-Ga polymer hybrid composite structures

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ABSTRACT

Magnetically controlled hybrid Ni-Mn-Ga composites are potential candidates for actuation and damping applications. The combination of ductile polymer and gas atomized large grained Ni-Mn-Ga powder has many advantages compared to bulk single crystals. These advantages include ease of manufacturing and freedom of shape, while still being magnetically controllable. In this report, Ni-Mn-Ga-epoxy hybrid composite structures are manufactured at three different filling ratios 25, 30 and 35 vol-% and damping properties of the composites are compared to those of 5M Ni-Mn-Ga single crystal. The damping properties are characterized using a laboratory made high-frequency dynamic mechanical testing instrument and a dynamic mechanic analyzer (DMA) in single cantilever mode. The mechanical cycling experiments revealed that the damping ability of the Ni-Mn-Ga composites depends on the filling ratio. The magnetic field induced stiffening observed in the mechanical cycling experiments of the single crystal sample at 100 Hz correlated roughly with that of the composite sample having filling ratio of 35 vol-%.

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1. Introduction

Ni-Mn-Ga Heusler single crystals displayed high and reversible magnetic-field-induced strains (MFIS) up to 6–11%, depending on the composition and martensitic structure of the alloy [1,2]. This makes the material suitable for magnetically controlled actuators, which can be used in damping applications [3]. So far, the costs and the difficulties related to manufacturing of Ni-Mn-Ga single crystals and the brittle nature of the material [4] have hindered its widespread use. As a viable alternative to bulk single crystals, magnetic shape memory (MSM)-hybrid composite structures have been proposed [5–16].

Previously, such Ni-Mn-Ga composite structures have been produced from particulates manufactured either by crushing [7–14] or cutting [15] of single crystals or from specialized processes such as spark erosion [9] or melt-spinning [16]. However, these do not solve the complexity related to single crystal manufacturing. Instead, large grained gas atomized Ni-Mn-Ga powder may be used as MSM-elements in the composite as suggested in the work utilizing the PECS processed porous MSM-

hybrids [17]. It should be then possible to combine large grained gas atomized Ni-Mn-Ga powder with a ductile polymer for damping elements. Gas atomization is a high-volume manufacturing method for metallic powders, which produces round and smooth particles, with a narrow particle size distribution [18]. Previous research has shown that Ni-Mn-Ga composites containing round particles have higher damping capabilities, as the round particles do not have a shape effect in the magnetic anisotropy [9]. The properties of gas atomized Ni-Mn-Ga powders have been studied previously [19] and the powder has been used to manufacture hybrid Ni-Mn-Ga composites [20].

The main advantage of the hybrid composite structures is the easiness of manufacturing compared to the single crystals as the composites can be freely cast into different shapes and these shapes can then be joined together to create the needed shape for the end product. Such damping elements can be designed to match the needs of different applications. In this paper, the damping properties of 5M Ni-Mn-Ga single crystal are compared to the properties of Ni-Mn-Ga composites applying a laboratory built high-frequency dynamic mechanical analysis instrument (HF-DMA) [21] and a DMA in single cantilever mode [22].

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2. Material and methods

The induction melted ingot having composition of $\text{Ni}_{49.3}\text{Mn}_{29.6}\text{Ga}_{21.1}$ was gas atomized at 1308 °C using argon gas at a pressure of 50 bars. The powder was sieved to separate particles having diameter between 20 and 45 μm , with an average grain size of 28.2 μm . Because the fast cooling during the gas atomization process leads to chemically inhomogeneous fine grain structure, the powder needs to be annealed to induce grain growth and to homogenize the powder before composite manufacturing. The sieved powder was therefore heat-treated in alumina crucible by mixing it with NaCl (Ensure[®] from VWR) with the ratio of 10/90 vol-% respectively in argon atmosphere at 770 °C for 28 h. This salt was selected as it does not react with Ni-Mn-Ga, minimizes manganese loss during annealing and keeps the gas atomized powder from sintering during annealing.

After the heat-treatments, the salt was removed by water immersion and the powder surface was cleaned using 10 wt-% citric acid solution. The cleaned powder was magneto-mechanically trained by repeated compression of 10 MPa after orienting the particles perpendicularly to the compression direction with applied magnetic field of 1 T. The phase transformation and magnetic behavior was subsequently studied by using a laboratory built low-field *ac* magnetic susceptibility measuring system at heating and cooling speed of 5 °C/min. The phase composition was studied with X-Ray Diffractometer (PANalytical X'Pert Pro XRD) using Cu-K α and the elemental composition with an energy dispersive analyzer (NSS EDX) attached to a scanning electron microscopy (Mira Tescan SEM 3 FEG-SEM).

The epoxy for the composites was chosen based on its mechanical properties, which need to match the stress to induce twin movement in Ni-Mn-Ga powder particles, as well as on its suitability for composite manufacturing. Polymers with yield strength between 1 and 10 MPa and Young's moduli of 1–1000 MPa were considered as potential matrix materials. The T_g of the epoxy was measured using TA Instruments Q2000 DSC in the temperature range of –80 to 180 °C. The composites were manufactured by mixing 25, 30 and 35 vol-% of pretreated Ni-Mn-Ga powder with Loctite Hysol 9455. The mixture was then degassed using a vacuum chamber and cast into polyoxymethylene molds with dimensions of 5 × 6 × 25 mm. The powder particles were magnetically oriented to form chains along the long axis of the composite sample. The composite was then left to cure at room temperature for three days. Additionally, a reference hybrid composite was manufactured using gas atomized Ralloy[®] WR4 steel powder and the Hysol 9455 epoxy with a filling ration of 35 vol%, using the same composite manufacturing process and magnetic orientation. The single crystal stick used in the experiments was manufactured by Adaptamat Ltd. It was cut along the $\langle 100 \rangle_p$ planes and its average chemical composition was $\text{Ni}_{50}\text{Mn}_{28.3}\text{Ga}_{21.7}$. The dimensions of the single crystal after compression along its longest axis in martensitic state were 1 × 2.5 × 20.1 mm.

The damping properties of the composites were studied using two different methods. First, the damping properties were studied with a TA Q800 DMA in the single cantilever mode at frequencies of 1, 5, 10, 50, 100 Hz at a peak-to-peak stress of 1 MPa with an average sample size of 3 mm × 5.3 mm × 25 mm. Reference measurements were done at 1 MPa with the steel hybrid composite and at 2 MPa using the Hysol 9455 sample without any added particles. To study the effect of the magnetic field in this DMA, a permanent magnetic circuit with a yoke made of $\text{Fe}_{54.1}\text{Co}_{45.9}$ alloy was constructed. The circuit produced an applied magnetic field of 0.3 T and could be attached around the sample so that the field was perpendicular to the direction of particle chains in the composite sample and the direction of the bending movement of the single cantilever beam.

Secondly, a laboratory built high frequency mechanical testing instrument (HF-DMA) was applied to measure the change in the composite strain with and without a magnetic field at frequencies of 21, 41, 61, 81 and 101 Hz with ± 1 MPa in tension-compression mode. The original design of the laboratory built testing instrument is described in Ref. [21]. For the present experiments, it was redesigned such that a linear guide was added to the bottom grip to increase its range of movement to facilitate testing of larger samples. Additionally, the grips were re-aligned and a movable magnetic circuit using permanent magnets producing a 0.5 T perpendicular field to the sample was added to the frame. As previous energy harvesting experiments have showed [23], an applied field less than or equal to 0.6 T should be optimal for Ni-Mn-Ga twin movement. The size of the DMA sample holder and the air gap limited the design of the magnetic circuit, thus only 0.3 T applied magnetic field could be achieved even after adding an iron-cobalt alloy yoke. As there was more space for the magnets in the laboratory built HF-DMA a larger magnetic circuit was possible to place into it. The larger field can produce a more pronounced effect in the composites.

For the HF-DMA experiments, thin pieces with dimensions of 0.6 mm × 2.5 mm × 15 mm were cut from the composite samples using a slow speed diamond saw and a surgical knife. The sample was attached between the two grips in the HF-DMA testing instrument (Fig. 1). The lower grip was forced to vibrate up and down using a speaker element driven with a sinusoidal signal from a TTI TG550 function generator. The signal was amplified using a QSC RMX 2450 audio amplifier to reach the desired stress level. Testing

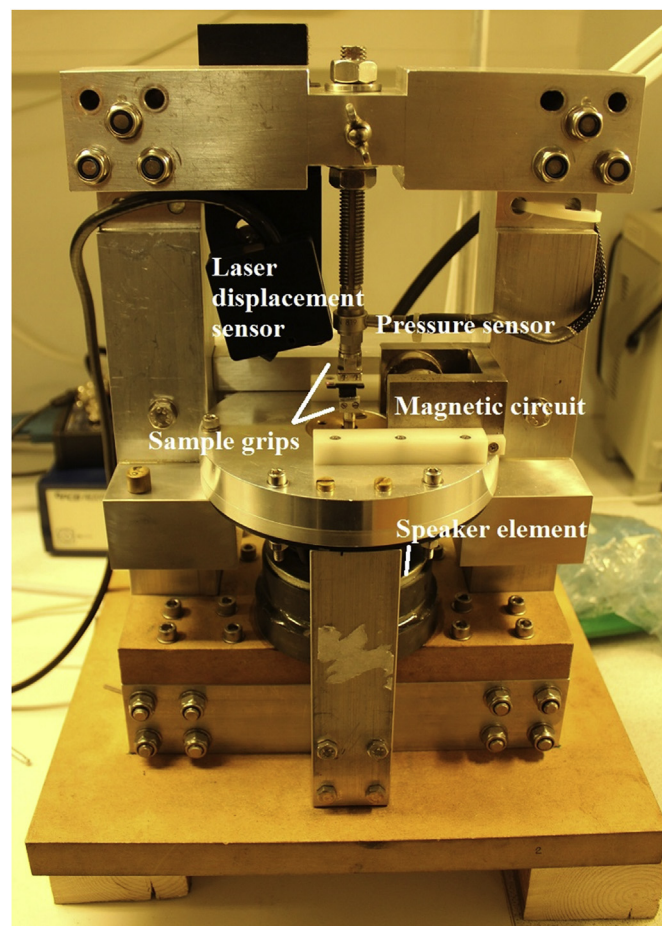


Fig. 1. Laboratory built HF-DMA testing machine.

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