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Magnetic field-induced stress in the Ni–Mn–Ga magnetic shape memory alloy

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Magnetic Shape Memory (MSM) materials generate stress in a magnetic field, which can change the shape of the material. Up to now, little work has been carried out in modeling and measuring the magnetic field-induced (MFI) stress in MSM materials. In the present study, direct MFI stress measurements in a Ni–Mn–Ga MSM material, giving full 6% MFI strain, were performed at different field strengths. The MFI stress was also calculated from the magnetic anisotropy of the material, based on the magnetization curves along the easy and the hard magnetization directions. Both measurement methods are described in detail. The measurement results demonstrated good agreement with the calculated ones. The dependence of the MFI stress on the MFI strain and the magnetic field strength was also revealed. Potential errors during MFI stress measurements in MSM materials are discussed, and avoided by properly selecting the measurement conditions during the study. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1697617]

I. INTRODUCTION

The magnetic shape memory (MSM) alloys are a class of actuator materials that change their shape when exposed to a magnetic field. For the time being, up to 10% magnetic field induced (MFI) strains have been measured.[1] The largest MSM strains have been obtained in the nonstoichiometric Ni_2MnGa alloys.[1] Therefore, this type of alloy was selected for the present study.

The MSM effect is based on the interaction between the proportions of twin variant areas and the magnetic field. The mechanism and the structure of the MSM material have been discussed in several publications.[1–4] Because of its large strain output, the MSM material has been successfully used in electromagnetic actuators and in other motion generation applications.[5,6] The MSM material can also be used in the reverse operation as a sensor.[5] For actuator design considerations accurate modeling of the material's behavior is needed. Several models of the (MFI) strain in MSM materials have been proposed, which can be used in proper actuator design.[7–10] On the other hand, little work has been performed so far in the modeling of the MFI stress, which is of prime importance in actuator applications. Recently, the MFI stress of an MSM material giving 2% MFI strain was measured, and compared with the proposed model.[11] The aim of this study was to compare the quantitative results of the MFI stress model with measured values using a MSM alloy giving full 6% MFI strain.

II. MATERIALS AND EXPERIMENTAL PROCEDURES

A nonstoichiometric Ni_2MnGa alloy with the chemical composition of (wt %) Ni_{49}–Mn_{26}–Ga_{25} was used in the present study. The MSM sample was measured $19.2\times3.0\times5.0\ \mathrm{mm}^3$, and was cut along the (001) direction. The martensite phase of the material consists of internal areas, called twin variants. These variants are anisotropic, with easy and hard magnetization directions, as well as different lattice orientations. Because of the high magnetic anisotropy and low mechanical twinning stress, the external magnetic field changes proportions of the different variants, and the easy magnetization direction becomes parallel to the external field (Fig. 1). This causes large strain and stress generation, which alter the shape of the material.

The magnetic anisotropy between the easy and hard axis of the magnetization curve causes the MFI stress in the MSM materials. This anisotropy corresponds to the driving energy $f(h)$ for the shape change of the MSM material[10]

$$f(h)=\int_0^h[m_a(h')-m_t(h')]dh' = \int_0^h[b_a(h')-b_t(h')]dh', \qquad (1)$$

where m_a and m_t is the magnetization along the easy and hard magnetization direction, respectively, b_a and b_t is the flux density along the easy and hard magnetization direction, and h is the magnetic field strength. The MFI stress also depends on the lattice crystallographic limit strain ε_0, i.e., the maximum field induced field strain. For the alloy studied in the present work this has the numerical value of $\varepsilon_0 = 0.06$. The MFI stress σ_{mag} can be written as[10]

$$\sigma_{\mathrm{mag}}(h)=\frac{1}{\varepsilon_0}\int_0^h[b_a(h')-b_t(h')]dh'. \qquad (2)$$

To solve this equation one has to measure the magnetization curves along the easy and hard magnetization directions of the MSM material. Also, the magnetic field strength h in the material needs also to be determined. Depending on the dimensions of the MSM sample and the twin variant distribution, the field may vary significantly, and it can cause the direct usage of the Eq. (2) to give inaccurate results. Also

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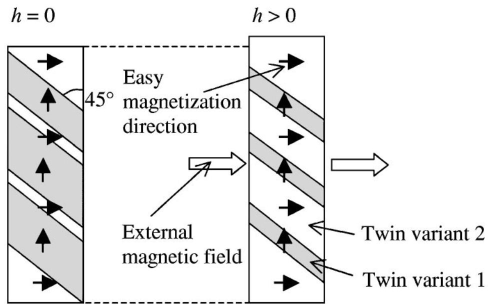

FIG. 1. Schematic representation of the twin variant structure and the effect of the external magnetic field h to the MSM material.

possible static magnetic force on the surfaces of the MSM material may alter the MFI stress. Accordingly, direct measurements of the MFI stress are necessary.

For calculating the magnetic anisotropy of the MSM material and, thus, the MFI stress the easy and hard magnetization curves of the material were measured. In addition, direct measurements of the MFI stress were carried out. In both cases an electromagnet with a bore diameter of 40 mm was used to produce the magnetic field. Magnetic fields were measured with Hall sensors (F.W. Bell 5080, 1% accuracy) and a coil.

A. Magnetization curves and magnetic anisotropy measurements

For magnetization curve measurements the MSM sample was placed in the air-gap of the electromagnet. In order to gain better accuracy the field was applied along the sample's long dimension. The distance between the ferromagnetic core and the MSM material was kept as small as possible, by using moving parts of the core. The electromagnet was run with alternating current at frequencies of 2–4 Hz. The induced voltage was measured with a coil around the MSM sample, thus the magnetic flux density in the element was deduced. The field strength was measured with a Hall sensor from the side of the sample. The measurements were carried out when the MSM material was compressed ($\varepsilon=0$) and when it was elongated ($\varepsilon=0.06$). These two conditions gave the easy and hard magnetization curves and, accordingly, the magnetic anisotropy of the MSM material [using Eq. (1)].

B. Direct MFI stress measurements

Direct measurements of the MFI stress were carried out with the setup shown in Fig. 2. The MSM element was placed in the air-gap of the electromagnet and connected (glued) to the tensile test machine (Lloyd LRX plus). The electromagnet was supplied with different constant current values, and the length of the MSM element was changed with an external force. The strain, stress, magnetic flux density, and the magnetic field strength in the element were recorded. Stress was measured with the load cell of the tensile test machine, and the length of the MSM element was changed with the speed of 0.5 mm/min. The position was recorded with a laser sensor from the top moving part of the machine. The sensor had the accuracy of 2 μm, and the measurement error was 0.2%. Based on the load cell's mechanical stress $\sigma_{mech}(h,\varepsilon)$ curves, the MFI stress σ_{mag} was calculated at the selected constant strain value ε_{meas} using the equation

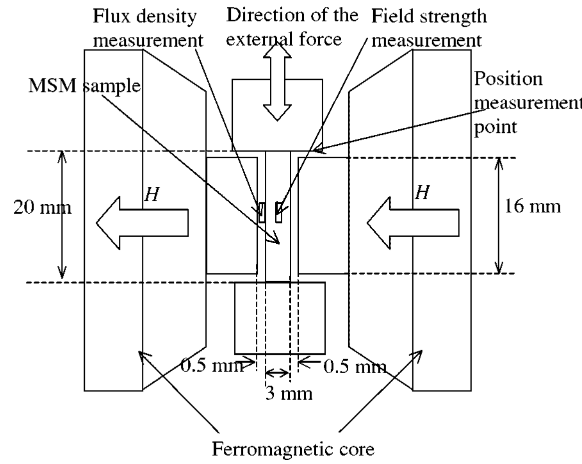

FIG. 2. Experimental setup for direct MFI stress measurements.

$$\sigma_{mag}(h,\varepsilon_{meas})=\sigma_{mech}(h,\varepsilon_{meas})-\sigma_{mech}(0,\varepsilon_{meas}). \quad (3)$$

Direct measurements of the MFI stress with the described method can have three potential error sources. First, accurate measurements of the magnetic field strength inside the MSM sample may be difficult because of the air-gap in the magnetic circuit. The magnetic field strength was measured from the side of the MSM element. In case the permeability of the MSM element is high, the results have significant inaccuracy due to the air-gap. However, in case the permeability is low, the accuracy is acceptable. The magnetic flux density is measured in the air-gap between the core and the MSM element. When the air-gap is small the value of the magnetic flux density in the air-gap is similar to the flux density inside the MSM element.

The second measurement error can arise from the local variations of the permeability in the MSM material during the shape change.[11] The variations in the local material's permeability are due to the two-variant state of the MSM sample. This causes the magnetic field strength and the flux density inside the MSM sample to vary locally. In order to minimize this effect the measurements were performed at a point where the MSM sample is typically in a single variant state.

The third measurement error may come from the mechanical stress measurements, when the slope $d\sigma_{mech}/d\varepsilon$ is large.[11] This occurs at the minimum and the maximum strain. Therefore, these values were not taken into account during the measurements.

Because of these three potential measuring errors the MFI stress was measured when the MSM strain was relatively small. The selected strain value was $\varepsilon_{meas}=0.01$. In this point, the permeability is low in the measurement direction, the element is mostly in single variant state, and the slope $d\sigma_{mech}/d\varepsilon$ is small.

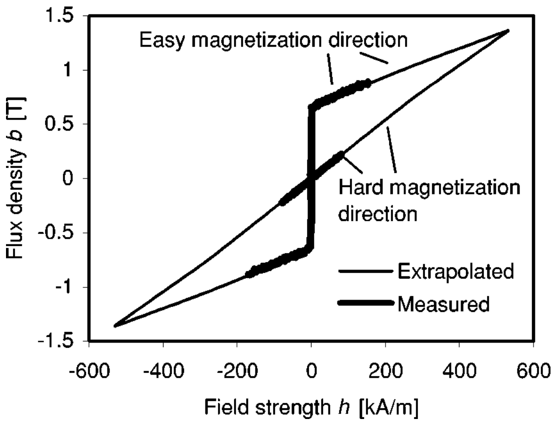

FIG. 3. Measured and extrapolated magnetization curves of the MSM sample along the hard and the easy magnetization direction.

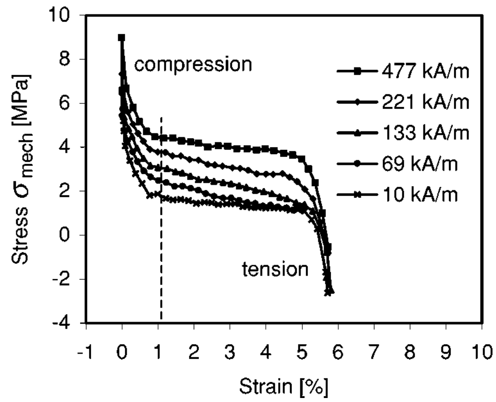

FIG. 5. The compression part of the MSM material stress–strain loops, under different magnetic fields. The chart legend shows magnetic field strength when the MFI strain is 1%.

III. RESULTS AND DISCUSSION

The measured magnetization curves along the easy and the hard magnetization axes can be seen in Fig. 3. Because the magnetization curves were measured along the long side of the MSM element, the required magnetomotive force was large and the curves could not be measured to the saturation level. For calculating the MFI stress the curves were, therefore, extrapolated to the saturation level. Because the hard magnetization axis has low permeability, it was extrapolated based on the magnetization results from the direct MFI stress measurements (setup of Fig. 2). In this setup the air-gap was smaller, therefore, it was possible to make the measurements at higher field strength values. The easy magnetization axis was extrapolated with a line where the slope is equal to the permeability of vacuum. Previous measurements demonstrated this type of behavior of the magnetization curves.[10] The extrapolated curves shown in Fig. 3 were used for calculating the MFI stress.

Magnetization curves were also measured with the setup shown in Fig. 2. The comparison of the results is summarized in Fig. 4. As shown, the magnetization curve along the hard magnetization direction gave similar results with both measurement techniques. On the contrary, along the easy axis the magnetization curves show poor correlation. This is because of the error in the magnetic field strength values observed during the MFI stress measurements. Magnetic flux density measurements show, on the other hand, accurate results with both measurements. This is demonstrated with the similar flux density values on the ''knee'' of the easy magnetization curves in both measurements.

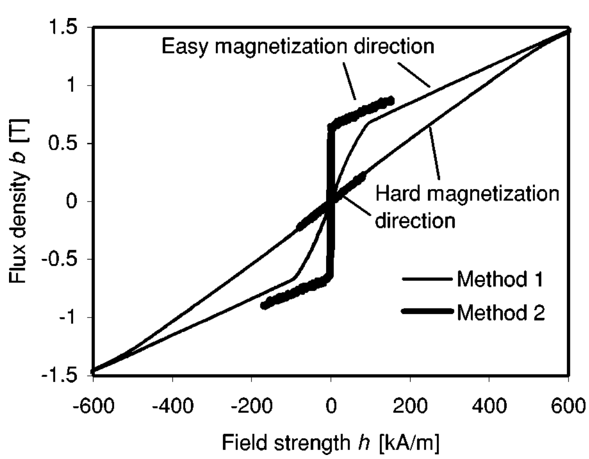

FIG. 4. Comparison of the magnetization curves measured with the MFI stress measurement setup (method 1) and with the anisotropy measurement setup (method 2).

The measurements of the MFI stress σ_{mech} at different current values are summarized in Fig. 5. Only half of the complete hysteretic curve is presented in the figure, which shows the stress as a function of strain when the MSM material is compressed. The results show increased stress output when the magnetic field in the MSM sample increases. It is also seen that the measured σ_{mech} stress is not constant as a function of the strain. This is because of the air-gap between the MSM sample and the ferromagnetic core in the measurement setup (Fig. 2). When the MSM strain increases, the permeability along the measurement direction increases, too. This reduces the magnetic field strength inside the MSM material, thus, decreasing the MFI stress [according to Eq. (2)]. When the external field becomes strong enough, the change in the permeability becomes smaller. Accordingly, the field change becomes less significant for the induced stress. Therefore, when the magnetic field strength is high enough the induced stress is less dependent on the strain.

Based on the curves of Fig. 5 the MFI stress σ_{mag} of the MSM element at 1% strain was deduced using Eq. (3). The results are summarized in Fig. 6 as a function of the magnetic field strength. The calculated MFI stress using Eq. (2) is also visible in the Fig. 6. It is demonstrated that the measured results are in accordance with the calculated ones.

IV. CONCLUSIONS

A method for measuring the MFI stress in MSM materials was developed. The MFI stress in an MSM material giving full 6% MFI strain was calculated from magnetic anisotropy measurements, and directly measured with the proposed experimental setup. A dependence of the MFI stress on the material's MFI strain was observed, which is attributed to the measurement setup rather than to the MSM material. During the direct measurements of the MFI stress the varia-

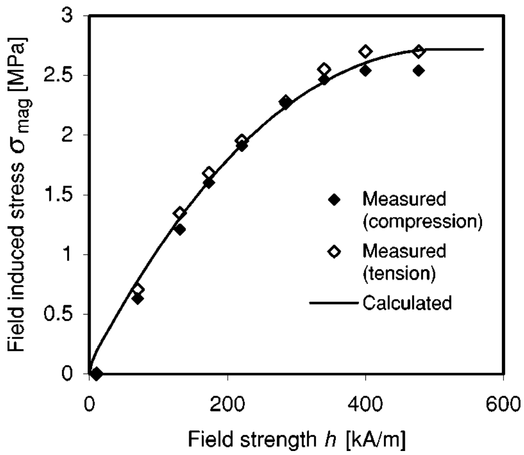

FIG. 6. The calculated [from Eq. (2)] and measured (setup of Fig. 2) MFI stress. The stress is measured both in the tension and the compression curve of the mechanical hysteresis loop. The strain value in the measurements was $\varepsilon_{meas} = 0.01$.

tions in the local material's permeability and the effect of the air-gap in the measurements of the magnetic field strength may cause error in the results. These problems were avoided in the present study by properly selecting the measurement strain value. Accordingly, the MFI stress was measured when the material strain was 1%, and theoretical values of the MFI stress were calculated for comparison. The measured results were in accordance with the calculated values, demonstrating, thus, the applicability of the proposed model and measurement setup.

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