Experimental Characterization of Geometric Aspects of the Behavior of Magnetic Shape Memory Materials and Theoretical Interpretation

Part 1: Experimental Procedure

J. Hernandez, P. Mullner, P. Linquist, and J. Carrera

Abstract—Small samples of a Ni-Mn-Ga single crystal of three different geometries were subjected to bending by applying a rotating magnetic field. The magneto-mechanical behavior of the sample in cantilever was analyzed and special attention was given to elongations and curvature along the deformation process. A sequence of 3000 images was made using a high-resolution camera and the data was analyzed using a code in Matlab. Furthermore, the geometric analysis showed that, when the magnetic field is equal to zero, the sample do not recover its original shape totally and the presence of a pseudo-elastic behavior was observed. Analysis and interpretation of the data allows the presentation of some hypotheses concerning to the crystalline structure and the role of dislocations, represented by a dislocation density, in the martensite phase of these materials. These hypotheses are discussed more formally in the second part of this paper. Some experiments are proposed that would give the opportunity to a wider theoretical knowledge of MSMM.

Index Terms—Magnetic Shape Memory Alloys; Dislocations; Pseudo-Elastic Behavior; Bending Strain.

I. INTRODUCTION

Magnetic shape memory alloys (MSMA) are materials that present several characteristics of wide interest for material science. The first experiments with this kind of materials were made in the mid-nineties using the Ni-Mn-Ga alloy, which is the most widely studied magnetic shape memory alloy Fig.1 [1]. Among its most important and widely studied features is the induction of a reversible plastic deformation under the action of a magnetic field.

In addition to the experimental study of the properties of magnetic shape memory alloys, researchers have searched theoretical insights that could give way to practical mathematical and computational models to better understand the behavior of these materials. This is also the long-term goal of the research project of the authors. Even if the theoretical frame is clear and based mainly in the physical setting and ideas given by Gurtin [2] and Landau [3], there is a lack of experimental data, just like any other theoretical approach in such a young field of research. Efforts have been made using the relationship between temperatures and stresses under the action of an external field; the study of the magnetic behavior of Ni-Mn-Ga alloys and others. Models related to the magnetization process have been proposed in [4].

In general, these theories are based either in microscopic properties and the physics of solids, or in the analysis of macroscopic and thermodynamic properties. Some works are focused on dynamical systems and develop and manufacture of actuators [5], [6]. Some others works are based on crystallographic and thermodynamics properties [7], or related with the polar decomposition of the deformation gradient [8]-[10]. Relatively few focused on the analysis of the process of dislocations in magnetic shape memory materials [9],[11].

Between the techniques used successfully in the last year, advances in image processing and analysis have allowed materials science to make use of several techniques to study the behavior of materials used in current engineering. Rothenbüchler et al [12] used the Hough transformation to characterize the Ni-Mn-Ga alloy and extract quantitative information about the location and motion of the martensite twin boundaries as a magnetic field is applied and the material is deformed.

Several studies of the Ni-Mn-Ga alloy in cantilever field have been carried out over the last 5 years. Kucza et al [13] used a code in Matlab to analyze about 35,000 images and extract information on the behavior of specimens of 1x1 mm2 cross section and between 2mm and 10 mm in length to a variable rotating magnetic field. One of the authors, Hernández, had the opportunity to work in the labor and with the team of Prof. Mullner in Idaho, a team that has made significant contributions in that field [12]-[14]. The experimental work for this paper was made there.

This paper has the two main objectives. First, to continue the process of generating interesting data concerning the behavior of MSMM. Second, to use this information as a feedback in the developments in the mathematical theory of stress, energy and dislocations in crystals, focused on MSMM. Because of the interest by itself of the obtained data and of the experimental process involved, this first paper is concentrated on the experimental aspects, the theoretical discussion is only schematically presented, in order to estimate the relevance of the data and of the proposed experiments.

Presented only qualitatively, the main hypothesis of our research is:

Hypothesis 01. The geometric structure of MSMM in
their martensite phase allows the energy stored in the dislocations to have a noticeable macroscopic mechanical effect. This structure, however, presents some instability that leads to abrupt changes that could be represented by those analyzed in catastrophe and chaos theory. Methodologically, it is assumed that the relation between microscopic theory, at the molecular level, and the macroscopic analysis in the frame of continuum mechanics, has, in this particular case, an intermediate scale, the crystalline structure, whose study allows a better view of the otherwise very complicated relation between micro and macro levels.

II. EXPERIMENTATION

Basically, the behavior of small beams of the Ni-Mn-Ga alloy were subjected to bending by applying a variable magnetic field. Sample dimensions are shown in Table I.

The experiments were carried out with a single crystal grown with composition Ni51Mn27Ga22 grown with the Bridgman-Stockbarger method [15]. The composition of the samples was measured with a Hitachi 3400-N-II analytical scanning electron microscope equipped with an energy-dispersive x-ray spectrometer.

The crystal structure was determined using a Bruker D8 Discover x-ray diffractometer on a sample cut from the single crystal with dimensions 0.8 x 1.1 x 2.2 mm3. The pseudo-tetragonal structure (10M) was identified.

TABLE I: SAMPLES DIMENSIONS

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cross section (mm²)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 x 1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>1 x 1</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>5 x 4</td>
<td>6</td>
</tr>
</tbody>
</table>

III. ROTATING MAGNETIC FIELD

The experiments with the rotating field were carried out with a custom built Optical Magneto-Mechanical Device (OMMD, Fig. 2, described in detail in [13]). The OMMD was used to get images of the sample as it rotates under the influence of a variable magnetic field, at the rate of one image every degree. Once the data is recorded in the form of images, the image analysis is performed using a code in Matlab to obtain numerical results. Samples with three different geometries (Table I), 1 x 1 mm² in cross section and 10mm and 5mm in length were placed in a sample holder in such a way the magnetic field generated by the VSM could be applied at any angle with respect to the sample’s long axis.

We applied a magnetic force at constant angles of 45°, 90°, and 135° with first increasing and then decreasing magnitude, with measurements every 79.58kA/m (0.1T) in order to be able to appreciate the variation of the bending of the sample as the magnetic field was varying. Once the 955 kA/m [1.2T] magnetic field was reached, it was gradually reduced in such a way that a measurement could be made every 79.58kA/m (0.1T) with the objective of observing the material’s recovery capacity, which represents the elastic behavior of the material. This series of tests was also carried out for every sample (Table I).

IV. ANALYSIS OF IMAGES

After the tests were carried out, about 3,000 images were recorded, a Matlab code was used to analyze the images and obtain the value of the deformation due to bending (Bending strain, εB). Bending strain can be calculated by relating some parameters of the dimensions of the specimen and the radius of curvature observed, Fig. 3.

The bending strain can be calculating as follows:

$$\varepsilon_B = \frac{d \times k}{2}$$

where d is the sample width, k = 1/R is the curvature and R represents the radius of curvature.

Fig. 3 shows an example of the data analysis for a 10mm sample and the magnetic field parameters of 45° and 955 kA/m [1.2T], with increasing field strength. The blue and green lines represent the deflection points along the sample and the polar interpolation using in the Matlab code for the analysis, respectively. Bending strain is the normal component of the strain tensor at the lower edge of the beam, red line in Fig. 3(a).
After the experiments were performed it was seen that bending deformation in Ni51Mn27Ga22 single crystal is significant only in those cases where the cross section of the sample is at least one order of magnitude less than the total length [13]. When this is not met (i.e. for short samples), the material tends to strain in normal mode or in shear mode [16].

V. EXPERIMENTAL RESULTS

After the image analysis of about 3000 photos with a Matlab code was done see ref [13], the variation of bending strain was analyzed throughout the experiment and the degree of recovery of the material after reaching the maximum deformation and remove the magnetic field gradually. The following results are presented.

For the case of the sample with length of 6mm and 5x4mm2 cross section a set of deformed configurations were obtained, Fig. 4. In the first instance, it seems that the shear component of the internal stress generated in the sample, which allows the entire dynamic process of the dislocations to occur, tends to be larger than the linear displacement, which causes linear (geometric linearity) significant displacements off the axis of the beam.

The deflection properties of the sample were analyzed as well as the effect of the magnetic field as the direction changes. As can be seen in Fig. 4 in the sample there is no deformation due to a very large bending strain, this mainly due to the dimensions of the cross section of the sample.

For the case of the sample with length of 10mm and 1x1mm2, throughout the process of deformation of the sample subjected to a magnetic field that produces a bending it can be seen that the initial length of the specimen is not kept constant. This is the reason why the classic analysis for the calculation the curvature of the material presented by Feynman does not apply [17].

In the case of Ni51Mn27Ga22 single crystals it has been possible to verify that there is a variation $\delta_x = 22\%$ in the total horizontal length of the beam for a magnetic field of 955 kA/m [1.2T] and a direction of $45^\circ$ with respect to the axis of the beam. In Fig. 5 we can see a variation $\delta_x = 20\%$ when the direction is $\theta = 100^\circ$.

This supposes, according to [12] that in these directions there is a motion of the twin boundaries of martensite variants, being in those directions where the maximum
A much more orderly behavior is observed when the direction of the magnetic field is 45° but the elastic recovery is greater for a direction of 135°. These two directions offer a better magneto-mechanical behavior and it only depends on the application to choose in which direction to work.

In Fig. 9a, 9b and 9c the variation of the radius of curvature for each of the directions analyzed can be observed as the magnetic field increases and decreases. It is at 45° where a more uniform variation can be observed which supposes a better organization of the internal dislocations of the material from the beginning of the deformation until recovers its elastic margin. It is evident that the variation of the radius of curvature is proportional to both the increase and decrease of the magnetic field.
Fig. 7. Real twin patterns in Ni2MnGa alloy along the bending. (a) Almost equal fractions of twins without bending. (b) Combination of bending and axial strain, at this point bending strain begins to increase. (c) Triangular twins induced bending. (d) Small twin triangular patterns can be seen as a result of the combination of bending and axial deformation. A 2.5% bending strain is reached.

Fig. 8. (a) The magnetic field direction is 45°, the intensity increases from 0T up to 955 kA/m [1.2T]. For this case a maximum bending strain of 3.2% is reached and the maximum recover after the magnetic field reaches 0T is 32%. b) In this case the magnetic field direction is 90°, in contrast with image (a) the variation of the bending strain begins to decrease as the magnetic field increases, this means that the density of dislocations generated with the action of the magnetic field is much lower than in image (a) and c). Finally, in this case the magnetic field direction is 135° with a maximum bending strain of 2.88% and the maximum recover after the magnetic field reaches 0T is 37.5%.

Fig. 9. a) Plot of radius of curvature as a function of the magnetic field for 1x1 mm2 cross section and 10mm sample. The direction of the magnetic field is 45° with respect to the axis of the beam. b) Plot of radius of curvature as a function of the magnetic field with 90° with respect to the axis of the beam c). In this case the direction of the magnetic field is 135°.

VII. Analysis

After de analysis of the above results it is evident that the best reversible pseudo-elastic behavior of the material occurs when the direction of the magnetic field is 45° or 135°. Obtaining experimental characterization of the pseudo-elastic behavior which can be completely reversible was the main goal of these experiments. In order to obtain information about the process of dislocations that takes place in the material and the possible geometric mechanism of deformation it is essential to know both the planes and the most probable directions in which a dislocation will occur. From experimental data in Fig. 8 we know that 45° and 135° are two important directions.

For the Ni51Mn27Ga22 alloy it is known that in response to an external magnetic field a dislocation or series of
dislocations will occur in some directions and over a family of planes, for non-modulated or modulated martensite [17], with this information and the concrete characteristics of the 10M Ni-Mn-Ga presented in [19], a discrete analysis of the deformation process will be presented in part 2, using the information data obtained in section 3 and 4 of this paper.

The obtained information has been digitalized and used to make a geometric contrast with basic computational models of the same sample, but assumed first homogeneous and anisotropic, then homogeneous and anisotropic, with anisotropy direction parallel to the local main plane of the deformation. A special technic was developed both to calculate the local planes of deformation and to use it in order to analyze the influence of the anisotropy, defined as a “force” by a vector field.

A theory of structured “density” of dislocations, based on the developments of Landau [3], but where this density has vector form and thus can be introduced as an active element in the mechanical behavior of the material will be formally proposed on the second part of this paper. Experiments tending to support this theory, and interpretations of the data will also be given.

For the present time, it is worth to emphasize the following experimental results that open the door to interesting and practical questions:

A. The recovery of the sample, once the magnetic field is zero, is not complete, neither what the elongation nor what the local rotations is concerned. We hypothesize a correlation of this fact with the energy stored, and used, in the dislocations. As a new hypothesis derived from the observations, the non-recovery of the shape (or deformation) has a correlation also with the difference in the density of dislocations a moment before and after removing the magnetic field, affecting the speed of propagation of the elastic wave. This assumption will be verified experimentally and presented in later developments.

B. There are sections of the deformed sample that apparently correspond to pure elongations. This, together with the ratios of curvature of the other parts, should give hints about the dynamical structuration of the martensite sample.

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