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

Part 1: Experimental Procedure

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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. Rothenbühler 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

Published on March 21, 2019.

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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.

Fig. 1. Ni₂MnGa Single crystal

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

Sample	Cross section (mm ²)	Length (mm)
1	1 x 1	10
2	1 x 1	5
3	5 x 4	6

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.

Fig. 2. Optical Magneto-Mechanical Device, OMMD (Boise State University)

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, ϵ_B). 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:

$$\epsilon_B = \frac{d * k}{2}$$

where d is the sample width, $k = 1/R$ is the curvature and where 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)

Fig. 3. Image analysis with Matlab. (a) 10 mm Ni-Mn-Ga beam with an applied magnetic field of 955 kA/m [1.2 T] at $\theta = 45^\circ$. (b) Plot of the position of the top edge of the beam (red line in a) and the variation of the bending strain along the length of the beam.

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.

Fig. 4. Deformation of a Ni-Mn-Ga single crystal, with length of 6 mm and 5 x 4 mm2 cross section, in a magnetic field of 318.3 kA/m [400mT].

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° with respect to the axis of the beam. In Fig. 5 we can see a variation $\delta_x = 20\%$ when the direction is $\theta = 100^\circ$.

Fig. 5. (a) Scheme of the variation of the horizontal length of the sample as the magnetic field increases. (b) Variation δ_x of the Ni-Mn-Ga sample.

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

number of dislocations in the material occurs. The density of dislocations has to be greater for such directions.

On the other hand, it has been possible to verify that sample deformation consists of a pseudo-elastic behavior (deformation of the lattice by means of rotations and elongations) and a purely plastic part (dislocations due to the displacement of the boundaries of variants of martensite. Fig. 6 shows that this sample along the deformation process manifests both elastic and plastic behavior which can be reversible in the presence of a new magnetic field.

VI. DISCUSSION

In this work, the elastic properties and the ability of the material to recover after strong deformation were analyzed. In turn, the variation in the magnitude and direction of the applied magnetic field offered information about its anisotropic character.

The generation of bending strain induces the displacement of the martensite variants generating a series of twin patterns as the deformation progresses in the sample. The twin boundaries are observed as a kind of triangular borders that are increasingly defined according to the intensity of the magnetic field. Fig. 7. This confirms as adequate the idealization made in [13].

As it can be seen in Fig. 8a and 8c the variation of the deformation is more evident with a magnetic field direction of 45° and 135° . The capacity of the material to recover its shape reaches 32% and 37.5% respectively. This highlights the pseudo-elastic behavior of the sample which may be due to the released energy by the dislocations moving [18].

At the same time, it can be noticed that since it does not recover its shape at all, the deformation that results once the material is elastically recovered corresponds to a plastic deformation which as observed throughout the experiments, this plastic deformation can be deleted entirely if an additional field is applied.

We can say the elastic-plastic deformation is reversible and mechanically active thanks to the organized motion of the dislocations along the deformation process. Regarding the 90° direction, Fig. 8b, it can be deduced that the density of dislocations for this specimen is minimal causing a small deformation in the material.

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. 6. Magnetic field with a 45° , 90° and 135° direction applied to the sample from 0 to 955 kA/m [1.2 T] at increments of 79.58kA/m (0.1T), and finally decreased to 0T. Once the magnetic field is removed, the material "recovers" from C position to B position. This can be understood as a pseudo-elastic behavior according to the discussion in ref [18]. The sample can return to the initial position A until a new field is applied, so this can be understood also as a reversible pseudo-elastic behavior.

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.

(a)

(b)

(c)

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% it's 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%

(a)

(b)

(c)

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.

ACKNOWLEDGEMENTS

To the Boise State University, Idaho, USA, for the facilities in terms of access to the use of laboratories. A special thanks to Dr Peter Müllner for all the emotional and intellectual support throughout the stay. Also thanks to Dr Paul Linquist for the immense support along the samples preparation and for the advice throughout the whole process

of experimentation.

To the National University of Mexico (UNAM) for the financial support through the PhD scholarship.

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