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Experimental Study on the Magnetomechanical Characteristics of Ni-Mn-Ga Ferromagnetic Shape Memory Alloy Single Crystals

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Magnetic shape memory properties of Ni-Mn-Ga single crystals were characterized by measurement of stress-induced martensite reorientation under constant magnetic fields. Also magnetic field-induced strain as a function of the applied magnetic field under different constant compressive stress levels has been investigated. All the experiments were performed at room temperature in which the sample is in its martensite phase. Compressive stress and magnetic field were applied perpendicular to each other, and strain was measured along the compressive load axis. Magnetoelasticity, martensite reorientation, shape memory effect, and pseudoelasticity were observed throughout the experiments. Moreover, twinning stress and blocking stress were obtained.

Keywords: Ni-Mn-Ga, Ferromagnetic shape memory alloy, Magnetic field-induced strain, Magnetic shape memory effect, Martensite reorientation

1 Introduction

Ferromagnetic shape memory alloys (FSMAs) are a recently-discovered member of smart materials. Smart materials undergo a substantial change in one or more properties in response to changes in external conditions such as applied loads, temperature, electrical and magnetic fields. Among these materials, Piezoelectrics, Magnetostrictives and conventional Shape Memory Alloys (SMAs) are more well-known. Piezoelectric materials are the most commonly used smart materials that can generate a potential difference when subjected to a mechanical stress/strain. These materials also frequently exhibit the converse piezoelectric effect, by which they show strain in response to an electric field. These strains are typically on the order of 0.1% [1, 2]. Under the influence of an applied magnetic field, the magnetization direction of a magnetostrictive material may be caused to rotate. Due to magnetoelastic coupling within the material, this may produce strains of up to 0.2%. Shape memory alloys are one of the most popular smart materials, with the ability to release residual strains and return to their initial configuration when heated up to a particular temperature [3]. While actuation frequencies for piezoelectrics and magnetostrictives are in the kHz range, SMAs, which require time to heat up and cool down, can achieve frequencies of only a few Hz [2]. Common smart materials are compared in table (1).

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Table 1 Comparison of actuation strain, stress and operating frequencies of active materials [1].

Activator	Smart Material		Strain (%)	Stress (MPa)	Operating Frequency (Hz)
Heat	Shape Memory Alloy (NiTi)		2-8	400	1
Electric Field	Ferroelectric		0.1	3	100 000
	Piezoelectric (PZT)		0.2	70	100 000
Magnetic Field	Magnetostrictive (Terfenol-D)		0.2	80	10 000
	MSMA (Ni_2MnGa)	Varient Reorientation	5-10	5	1 000
		Phase Transformation	0.5-4	20-100	-

Ferromagnetic Shape Memory Alloys (FSMAs) such as Ni-Mn-Ga have generated great research interest because of their ability to produce large strains in the presence of magnetic fields. The strain magnitude is around 100 times larger than piezoelectrics and magnetostrictives [4]. Maximum magnetic field-induced strain (MFIS) of 6% for five-layered tetragonal martensite (5M) [5] and 10% for seven-layered orthorhombic martensite (7M) have been reported [6, 7]. However, this effect was first observed experimentally by Ullakko et al. who reported a field-induced strain of 0.2% in a single crystal of Ni-Mn-Ga [8]. Magnetic field-induced strain in FSMAs results from twin-boundary motion. As with SMAs, this allows FSMA actuators to exhibit very large strokes. Since they do not depend on heating to function, however, FSMAs are also capable of actuation frequencies approaching those of piezoelectric and magnetostrictive materials. An ideal active material would be the one that has high-frequency response, large strain and force outputs, high durability, and low cost [1]. Ferromagnetic shape memory alloys, thus, have potential to be the best in terms of the both criteria of large strain and high actuation frequency. Their ability to produce response frequencies in the kHz regime [9, 10], high energy density, large stroke, and high bandwidth make FSMAs suitable for a wide range of applications. Common practical usage of the material is in linear motion actuators [11, 12].

Among the known FSMAs, Ni-Mn-Ga alloys are the most widely explored due to their low detwinning stress and sufficiently high magnetocrystalline anisotropy energy [8]. However, unlike most smart materials, they are quite brittle, require large magnetic fields for actuation, and their produced strain may be suppressed by stresses as small as a few MPa [2]. Therefore, one of the main research goals is to produce FSMA in which large MFIS can be induced at high stress levels for the purpose of maximizing the work output. To accomplish this goal, blocking stress must be increased. Blocking stress or maximum actuation stress is the external stress level above which magnetic field-induced reorientation is not possible [1]. The MFIS in FSMAs is most often a result of the reorientation of martensite variants under the influence of a magnetic field [13, 14]. When the magnetic field is zero, at low temperatures, it is assumed that the material consists of two martensitic variants as illustrated in figure (1).

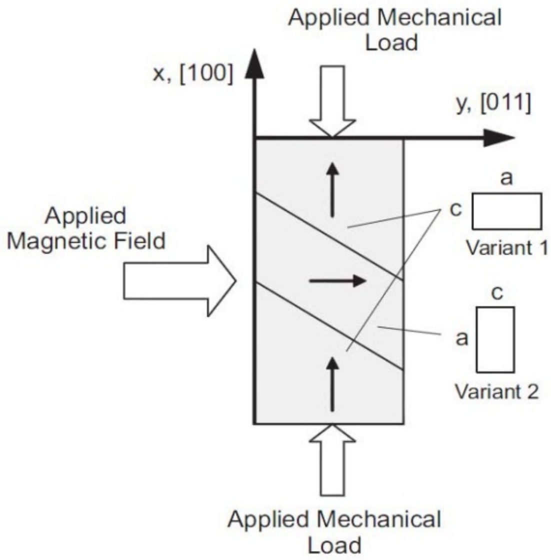

Figure 1 Schematic illustration of two martensite variants.
Compressive stress and magnetic field are applied perpendicular to each other [12].

Each variant has an easy magnetization direction (parallel to c-axis) and a hard magnetization direction (parallel to a-axis). As the field strength increases, the volume fraction of type 2 variants increases. As is shown in figure (2), by using a strong magnetic field, a single variant can be obtained. Since c < a (c/a is about 0.94 for a 5M tetragonal martensite), the total vertical length of the Ni-Mn-Ga specimen increases. When the magnetic field is removed, the strain does not change due to the lack of a driving or restoring force. Subsequently, if the force increases, the volume fraction of type 2 variants decreases. Rotation of type 2 variants induced by the compressive mechanical stress leads to decreasing the macroscopic strain [15]. Referring to figure (3), with the use of a sufficient mechanical load, a single variant type 2 can be achieved.

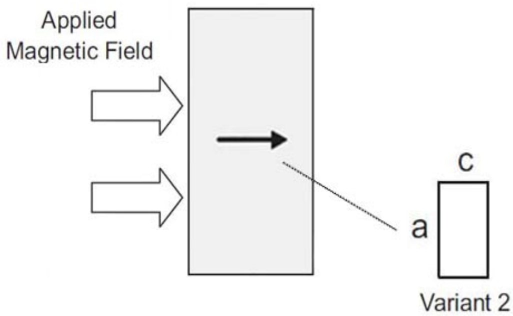

Figure 2 Achieving a single variant by using a strong magnetic field.

In this study, the stress-induced martensite reorientation under constant magnetic fields as well as MFIS by variant reorientation under constant stress levels is experimentally studied for Ni-Mn-Ga single crystals. For this purpose, two types of quasi-static magneto-mechanical tests were conducted: variable stress under a constant magnetic field and variable magnetic field under a constant stress. All the experiments were performed at room temperature where the material is in its martensite phase. The blocking stress and the twinning stress were found based on the MFIS under a constant compressive stress. Twinning stress is one of the most essential parameters which determines the actuating performance of magnetic shape memory alloys [16].

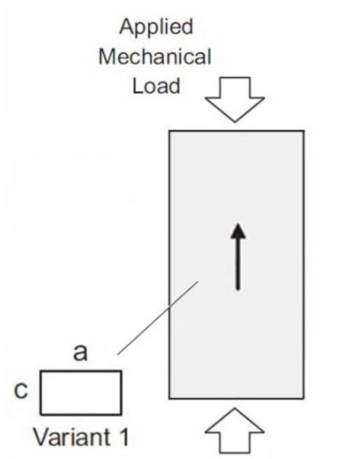

Figure 3 Achieving single variant by using a mechanical load.

2 Experiments

A 5M single crystal of Ni-Mn-Ga alloy got from Adaptamat Ltd. was investigated to determine its magneto-mechanical behaviors under different conditions. Dimensions of the cubic sample were nearly 6 mm × 6 mm × 8 mm, and its edges were parallel to the [100], [010], and [001] directions of the parent cubic phase. A photograph of the specimen is shown in figure (4).

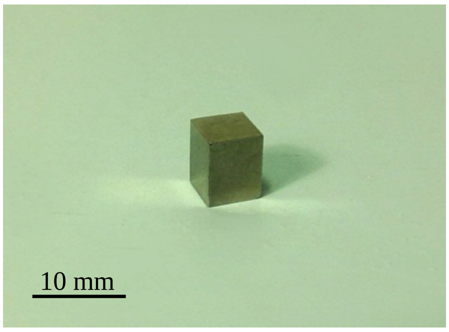

Figure 4 Photograph of the studied Ni-Mn-Ga specimen

Transformation temperatures were obtained using a differential scanning calorimeter (DSC) with the heating and cooling rates of 3ºC/min. Figure (5) shows the DSC results. The martensite start (M_S) and martensite finish (M_f) temperatures during cooling and the austenite start (A_S) and austenite finish (A_f) temperatures during heating for the studied sample are marked in the DSC curves. The M_f was obtained about 48 ºC. Variant reorientation mechanism can only be observed at temperatures lower than the martensite transformation temperatures. All the experiments were performed at room temperature in which the sample is in its martensite phase.

Two types of quasi-static magneto-mechanical tests were conducted in this work: (i) variable stress under a constant magnetic field and (ii) variable magnetic field under a constant stress. All the experiments were performed at a constant temperature (room temperature) where the material is in its martensite phase. Compressive stress was applied along the [1 0 0] orientation, while the magnetic field was applied along the [0 1 0] direction (see figure (1)).

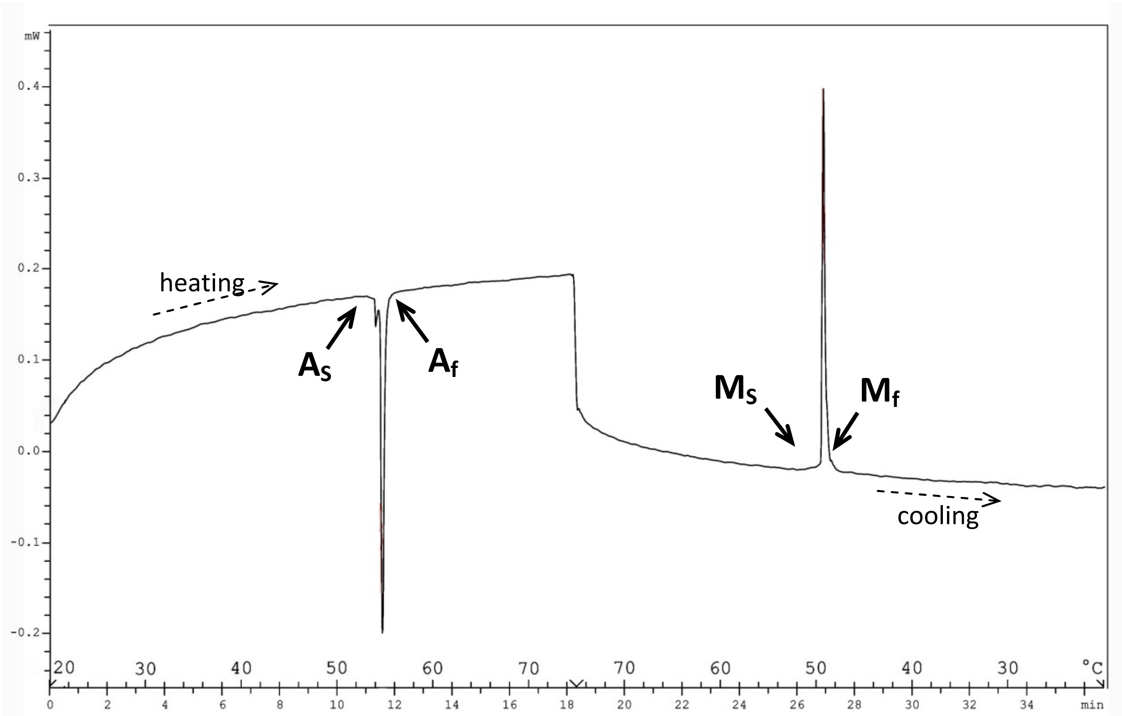

Figure 5 DSC heating and cooling curves of the test specimen

For returning the material's twin variants into an unstrained state after each test, magnetic reorientation was imposed by applying a magnetizing field along the new hard axis direction. The material may be returned to its original state by mechanical means as well. If the material is exposed to a mechanical stress exceeding the blocking stress, a mechanical reorientation of the twins occurs leading to collapsing the twin variants to their original state. Thus, the blocking stress is the external stress level necessary to induce a change from one twin variant to another one by mechanical means [17]. In order to obtain a single variant martensite, 3 MPa compressive stress was applied befor each experiment so that the short c-axis of the 5M tetragonal martensite, and thus the magnetic easy axis, is aligned with the compressive load axis. For the magneto-mechanical characterization, two new setups were designed and manufactured at Isfahan University of Technology. As is shown in figure (6), the first setup consisted of two permanent magnets which were mounted in parallel with a certain distance from each other depending on the desired amount of the magnetic field. Increase in the distance between the two magnets leads to a reduction in the magnetic field strength. Figure (7) shows variations of the acquired magnetic field with distance.

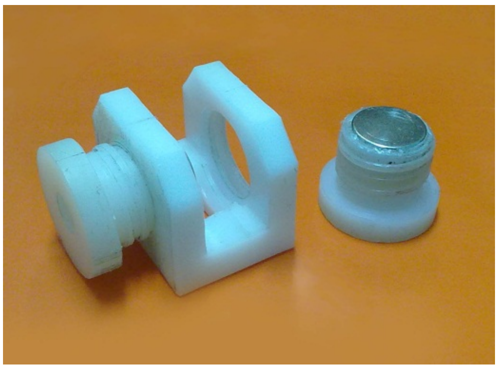

Figure 6 Manufactured setup to apply a constant magnetic field

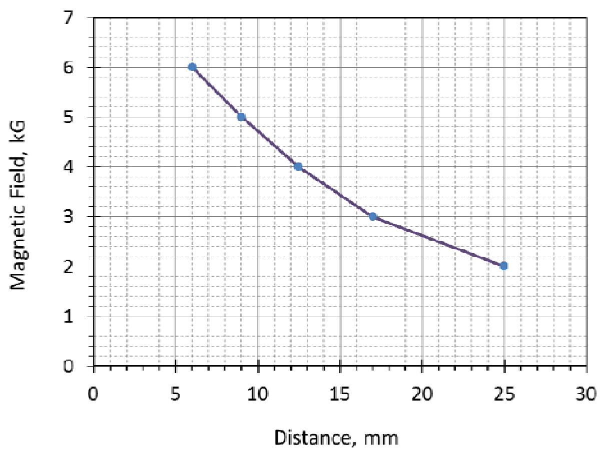

Figure 7 Variations of the magnetic field strength with distance for the utilized magnets [18]

These two magnets were able to generate a uniform magnetic field of up to 5 kG at the region in the center of the magnets. As shown in figure (8), the lines of magnetic field between the unlike poles are parallel.

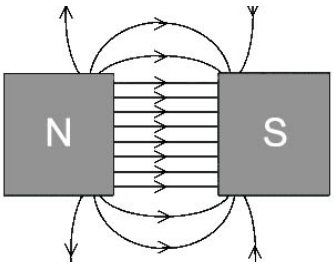

Figure 8 schematic of magnetic field between two unlike poles of the utilized magnets

This setup was supplemented to a Santam STM-50 tensile testing machine. The compressive loading-unloadings were done at the cross head speed of 0.2 mm/min (see figure (9)).

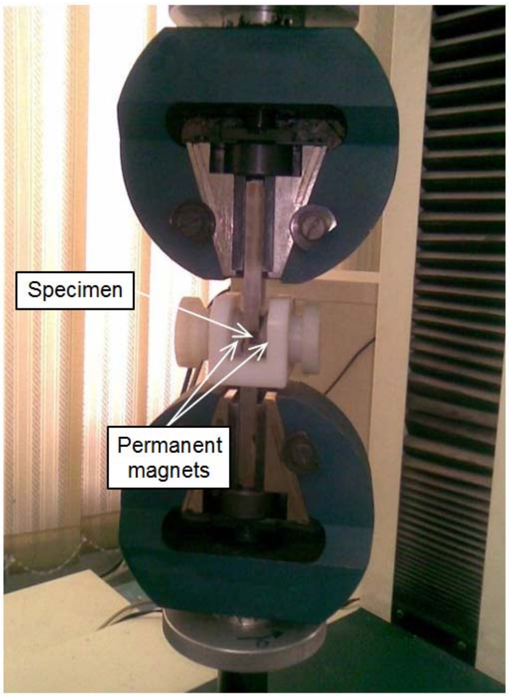

Figure 9 Santam STM-50 tensile testing machine equipped with two permanent magnets.

The second setup was used to generate a constant compressive stress for the case of varying magnetic fields. As shown in figure (10), a Bruker Model B-E 10 electro-magnet is equipped with the manufactured compression rig in order to be able of applying uniform magnetic fields up to 12 kG perpendicular to the direction of the compressive stress.

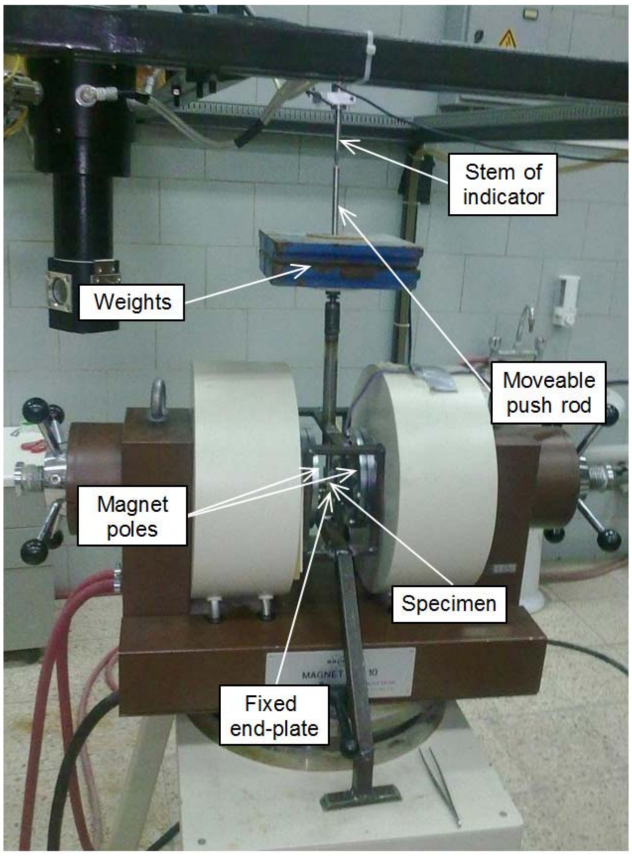

Figure 10 Bruker Model B-E 10 electro-magnet equipped with a compression rig.

The specimen was gripped between a fixed end-plate and a vertically moveable push rod, both of which were made of nonmagnetic steel. Some weights were placed on the push rod to apply a constant stress to the sample. The displacement of the push rod referenced to the end-plate was measured with an ELE digital indicator with the resolution of 0.001 mm. A photograph of the utilized ELE digital indicator is shown in figure (11).

Figure 11 Photograph of the employed ELE digital indicator

The magnetic field measurements were performed using a Bruker field controller B-H15 gauss-meter equipped with a sensitive Hall probe, which was placed near the specimen and perpendicular to the magnetic field lines. The resolution of the gauss-meter was 0.01 G.

3 Results and Discussion

Figure (12) shows the effect of magnetic field on stress-strain behavior of the Ni-Mn-Ga sample subjected to a constant magnetic field, when a compressive loading-unloading cycle is carried out using the test rig shown in figure (9). Five experiments were done under magnetic fields of 0, 2, 3, 4, and 5 kG at room temperature.

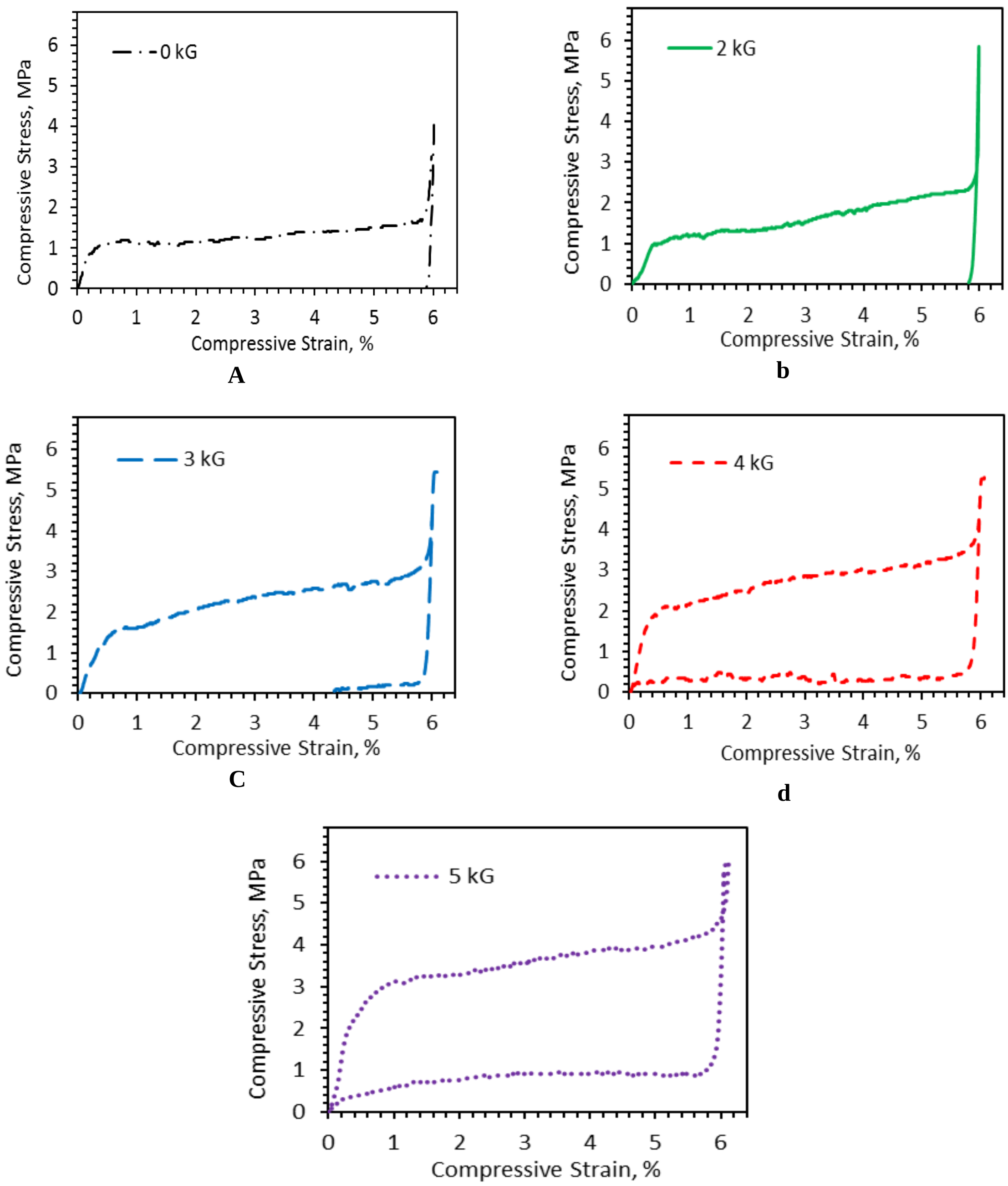

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Figure 12 Effect of magnetic field on the stress-strain response of Ni-Mn-Ga single crystal at room temperature under the constant magnetic field of a) 0 kG, b) 2 kG, c) 3 kG, d) 4 kG, and e) 5 kG

As it is seen, once the load is completely removed, a residual strain of about 5.9% remains in the sample when there is no magnetic field. By increasing the magnitude of the magnetic field, the stress levels in both loading and unloading process increase and the residual strain decreases. For example, the residual strain decreases from 5.8% to 4.4% as the magnetic field increases from 2 kG to 3 kG. However, these residual strains are recovered if the sample is subjected to a magnetic field of 4kG. Moreover, the stress-strain responses at and above 4kG magnetic fields are accompanied with no residual strain just after the complete unloading.

Ni-Mn-Ga exhibits behaviors similar to those of thermal shape memory alloys, such as Ni-Ti. Both materials exhibit shape memory effect and pseudoelasticity. The obvious difference between the two is that Ni-Mn-Ga requires a magnetic field but Ni-Ti requires a thermal field for actuation. If the studied specimen is subjected to a large enough compressive stress, its field-preferred configuration changes to a stress-preferred one. This change leads to a large inelastic strain of approximately 6%. As soon as the specimen is exposed to a sufficient magnetic field (for instance 5 kG) perpendicular to its c-axis, the magnetic field causes twin boundary mobility giving rise to reordering the twin variants and converting the specimen to its original, field-preferred configuration. This phenomenon is the magnetic shape memory effect (MSME). In the case of pseudoelasticity, the material is exposed to a large magnetic field (more than 4 kG) in its field-preferred configuration. Then it is subjected to an increasing compressive stress large enough to change the configuration from field- to stress-preferred one. This change in configuration induces a large inelastic strain that is completely recovered in a hysteresis loop upon removal of the stress. At low magnetic fields (for example 2 and 3 kG), Ni-Mn-Ga can exhibit partial pseudoelasticity as only a portion of the strain is recovered when the stress is removed.

As it is seen in figure (12), at the initial stages of the mechanical loading, the compressive stress is linearly related to the strain meaning an elastic deformation in the alloy. When the axial stress reaches a critical value, the twin boundaries in the martensite become mobile and the stiffness of the material is drastically decreased. Since the twin boundaries are mobile, subsequent small increases in stress are accompanied by large increases in strain. This phenomenon is called magnetoplasticity since the generated strains are effectively plastic in this region. When the level of stress reaches a second critical value, the twin boundaries in the material are completely reordered into a stress-preferred configuration and a sharp increase in the material stiffness occurs (third region). The phenomenon observed at the first and the third regions in the stress-strain curve is called magnetoelasticity.

After examining shape memory effect and pseudoelasticity at constant magnetic fields, strain-magnetic field responses of the alloy at constant compressive stresses are studied using the test rig shown in figure (10). The results are shown in figure (13). When an FSMA is subjected to a varying magnetic field under a constant compression, by increasing the magnetic field magnitude, single variants whose c-axis is along the compression direction reorients to another single variants, whose c-axis is along the applied field perpendicular to the compressive axis. Therefore, a magnetic field-induced strain (MFIS) is generated in the direction of the applied compressive stress. By increasing the constant compressive stress, the maximum MFIS decreases while the critical field magnitude for the start of reorientation increases. When the magnetic field is reduced to zero, at very low stress levels (for instance 0.05 MPa in figure (13)), the whole MFIS constantly remains in the sample. However, by increasing the amount of the compressive stress, the field-preferred martensite variant partially reorients back to the original variant favored by the stress. Finally, at the stress level of 1.41 MPa, the residual strain is almost zero meaning the twinning stress is slightly more than 1.41 MPa. Blocking stress or maximum actuation stress is the external stress level above which magnetic field-induced reorientation is not possible. Using figure (13), one can found that the blocking stress is between 1.95 and 2.22 MPa. Moreover, the maximum MFIS is about 5.7%.

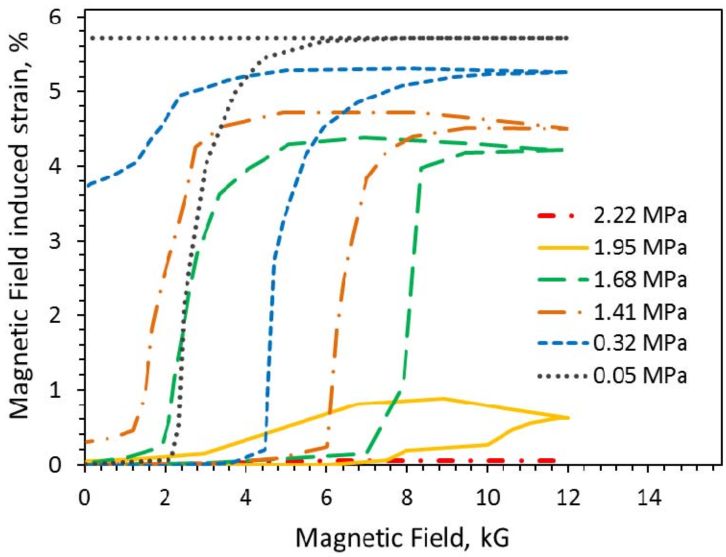

Figure 13 Effect of magnetic field on strain under a constant compressive stress at room temperature

4 Conclusions

The magneto-mechanical behaviors of Ni-Mn-Ga ferromagnetic shape memory alloy single crystals were investigated in this paper. The stress-induced martensite reorientation under constant magnetic fields led to the observation of magnetoelasticity, martensite reorientation, shape memory effect, and pseudoelasticity throughout compressive loading-unloading cycles. Magnetic field-induced strains were also shown due to the variations of magnetic field magnitude under constant compressive stresses. The maximum MFIS was found to be between 5.7% and 5.9% in various experiments. This is close to 6%, which is the theoretical maximum reorientation strain for 5M Ni-Mn-Ga single crystals. For the studied alloy, the blocking stress and the twinning stress were found to be about 2 MPa and 1.4 MPa, respectively.

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چکیده

آلیاژهای حافظه دار فرومغناطیس نوع جدیدی از آلیاژهای حافظه دار هستند که علاوه بر حرارت، تحت میدان مغناطیسی هم تغییر شکل می‌دهند. توانایی بروز کرنش های زیاد و همچنین پاسخ سریع به میدان مغناطیسی در این آلیاژها باعث شده است تا به عنوان یک کاندیدای مناسب در ساخت عملگرها مطرح شوند. نظر به اینکه تاکنون در ایران مطالعات رفتارشناسی روی این مواد صورت نگرفته است، هدف از این تحقیق بررسی تجربی رفتارهای مگنتو- مکانیکی آلیاژ Ni-Mn-Ga است.

بدین منظور بارگذاری مکانیکی تحت میدان مغناطیسی ثابت و نیز اعمال میدان مغناطیسی متغیر تحت تنش های مکانیکی ثابت مطالعه شده‌اند. با توجه به عدم وجود دستگاه مگنتو- مکانیکی در داخل کشور، تجهیزات مورد نیاز برای اولین بار طراحی و ساخته شدند.