Recent advances in Ferromagnetic Shape Memory Alloys:

the Ni-Mn-Ga case

M.J. Szczerba

Institute of Metallurgy and Materials Science, Polish Academy of Sciences
25 Reymonta Street, 30-059 Kraków, Poland

Ferromagnetic Shape Memory Alloys (FSMA) are a group of materials which posses an unique property of changing its shape by an external magnetic field. This effect has been termed Magnetic Field Induced Strain (MFIS). One of the most promising materials for potential applications are the off-stoichiometric Ni_2MnGa single crystals. MFIS was discovered in 1996 and at that time for the applied external magnetic field of 8kOe the value of longitudinal strain initially obtained in Ni-Mn-Ga single crystals was 0.19% [1]. Further intensified research in this field have led to a discovery of giant MFIS of about 10% of longitudinal strain with good reproducibility and the frequency of operation from several Hz to several kHz [2,3]. Bearing in mind that, for example Terfenol D, a material characterized as that possessing the largest magnetostriction effect of being equal to 0,16% found already practical applications, the single crystals of Ni-Mn-Ga alloys with this exceptional large functional strain became very attractive. Other functional features of Ni-Mn-Ga alloys: thermal shape memory effect [4] and magnetocaloric effect [5] as well as pre-martensitic transformation [6], the latter not fully understood to date were a subject of further intensified interest in this group of materials.

MFIS effect is accomplished by reorientation of martensite variants activated by an external magnetic field. Similar situation can be found in conventional shape memory alloys however, in this case martensite reorientation is controlled by mechanical force and temperature changes which act alternately. Important parameters determining MFIS are: (i) magnetic anisotropy (K_U) of Ni-Mn-Ga martensite phase (equals typically about 2.5×10^6 (erg/cm^3) which is an order of magnitude larger than in the cubic high temperature austenite phase [7] and (ii) the critical twinning stress (σ_{tw}) which determines the threshold value for the twin boundary movement to reorient martensite variants.

Depending on the structure itself this value can be as low as 0.1 for modulated martensite and can reach about few MPa in the case of non-modulated martensite [8-10]. Modulations in Ni-Mn-Ga structures are periodic shuffling of (110) planes in the $[1\bar{1}0]$ direction with the period of 10 or 14 layers depending on the degree of modulation (i.g. 10M, 14M). This can be easily determined by electron or x-ray diffraction where the degree of modulation is observed by additional reflections between the main spots in the $[1\bar{1}0]$ direction of the reciprocal space creating a characteristic pattern with four and six satellite reflections for 10M and 14M structure, respectively [11]. In case of non-modulated lattice additional intensities are lacking. Both magnetic anisotropy as well as twinning stress are temperature dependent which also implies strong temperature dependence of MFIS effect itself.

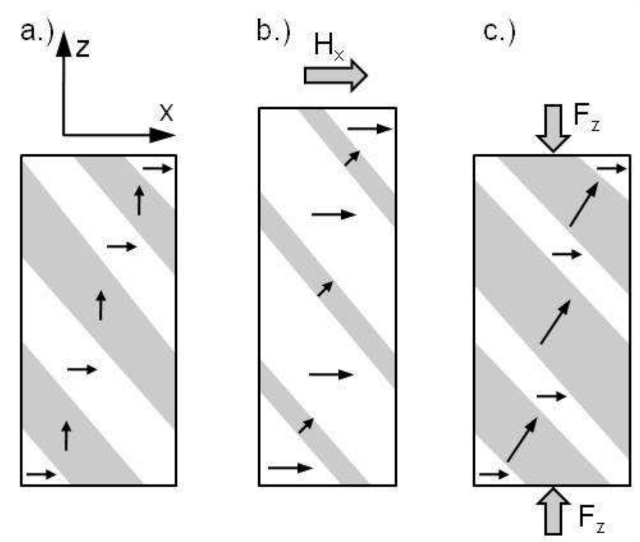

Figure 1. Scheme of MFIS effect. a) Situation without external magnetic field, b) with field H_x causing shape change (note the dominance of martensite variants with easy magnetization direction parallel with the external field), c) return to initial dimensions of the sample by mechanical force acting perpendicular to magnetic field [12].

Figure 1 schematically shows the MFIS effect. In the absence of external magnetic field magnetization directions of different magnetic domains are parallel to the easy magnetization *c* axis of the unit cell. However, with the applied field the magnetization direction has a tendency to rotate as to align parallel with this external field. In such a case, if the anisotropic energy is high and the energy of twin boundary mobility is low, magnetic field can change orientation of the structure from one martensite variant to a different one.

This can be explained if one notices a change of easy magnetization direction across twin boundary observed in Ni-Mn-Ga martensite structures. As a result, the external magnetic field produces an energy difference across the twin boundary causing pressure on twin boundary and as a consequence its movement. In practice it reorients martensite variants and the ones preferentially oriented to external magnetic field grow at the cost of others. Variants with easy magnetization axis parallel to magnetic field will dominate and the material will extend in perpendicular direction. It is important to mention, that MFIS differs from the magnetostriction effect where in the latter case, magnetization direction rotates to direction of the external field without changing orientation of the unit cell. Reorientation of martensite variants induced by magnetic field can be accomplished when magneto-stress σ_{mag} (stress induced by magnetic field) exceeds critical twinning stress σ_{tw}. Bearing in mind, that limiting value for σ_{mag} cannot exceed the ratio of magnetic anisotropy K_u to maximum magnetic induced strain ε_0, than equation for MFIS can be written as:

$$\sigma_{mag} = \frac{K_U}{\varepsilon_0} > \sigma_{tw} \tag{1}$$

Parameter ε_0 is evaluated by measuring the maximum strain obtained during uniaxial compression of a cube oriented Ni-Mn-Ga single crystal. This value can also be expressed theoretically as a function of lattice parameters according to equation:

$$\varepsilon_0 = \left|1 - \frac{c}{a}\right| \tag{2}$$

where *c* and *a* are the unit cell parameters of martensite.

From the structural point of view, MFIS effect is accomplished by reorientation of martensite variants by deformation twinning. This phenomena creates crystallographically twin related regions relative to the untwined matrix. Deformed structure must satisfy condition of continuity of crystal lattice. Therefore, the matrix-twin region must be separated by an undistorted plane called the habit plane which also implies that deformation twinning is a simple shear process. In the case of Ni-Mn-Ga alloys, the habit plane is {110} and the shear direction during martensite reorientation is <110> [13].

Different dislocation based models were developed to explain the martensite reorientation mechanism in Ni-Mn-Ga ferromagnetic shape memory alloys [12,13]. However, only recently it has been proved experimentally, by *in-situ* TEM straining of Ni-Mn-Ga thin foils, that reorientation of martensite variants consists of a large distance movement of dislocation arrangements through the crystal lattice [14,15]. Dislocations were seen to nucleate from the interface separating martensite variants. During straining typical “fringes” originated from stacking faults were observed proving partial character of dislocations. Additionally, using the $g \cdot b$ rule with two-beam conditions the Burger vector of twinning dislocations has been identified to be $[10\bar{1}]$. Experimental evidence of dislocation based mechanism for martensite reorientation in Ni-Mn-Ga alloys has led to a detail analysis of dislocation-dislocation interaction during twin boundary movement [16].

In summary it can be concluded that, Functional Materials showing MFIS must reveal reversible martensitic transformation. Additionally, another three following conditions must be satisfied simultaneously: (i) ferromagnetic nature of martensite phase, (ii) presence of large magnetic crystalline anisotropy and (iii) a very low yield stress for the operation of martensite variant reorientation mechanism, typically a few MPa as to satisfy equation 1. These conditions are met in single crystalline of 10M and 14M martensitic structures which can be relatively easily obtained in Ni-Mn-Ga alloys.

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