JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. **9** No 1, 01026(3pp) (2017)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том **9** № 1, 01026(3cc) (2017)

# Role of the Temperature Dependence of Elastic Modulus in the Basic Characteristics of Giant Magnetically Induced Deformation of Ferromagnetic Martensite

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(Received 30 December 2016; revised manuscript received 07 February 2017; published online 20 February 2017)

The experimental temperature dependence of threshold magnetic field initiating the giant magnetically induced deformation of Ni-Mn-Ga martensitic alloy has been analyzed. The relationships between the temperature dependences of threshold magnetic field, magnetostriction and elastic modulus have been revealed and described theoretically. It has been shown that the temperature limits of giant magnetically induced deformation and the character of temperature dependence of threshold magnetic field are predetermined by the temperature dependence of soft elastic modulus of alloy in the martensitic phase. It has been demonstrated that the careful fitting of theoretical temperature dependence of threshold field to the experimental one results in the characterization of hardly measurable physical values of martensitic phase, such as temperature dependences of elastic modulus and magnetostriction.

**Keywords:** Martensitic transformation, Magnetically induced reorientation, Magnetostriction, Young's elastic modulus.

DOI: 10.21272/jnep.9(1).01026 PACS numbers: 81.30.Kf, 62.20.de

## 1. INTRODUCTION

Ferromagnetic shape memory alloys (FSMAs) undergo ferromagnetic ordering and martensitic transformation (MT) on their cooling below the Curie temperature, $T_C$ and MT temperature, $T_M$, respectively. The Ni-Mn-Ga alloys with $T_M < T_C$ became the most studied FSMAs after the experimental observation of giant deformation of these alloys under the moderate magnetic field. This physical effect was observed then for some other FSMAs as well.

The ferromagnetic martensitic phase of FSMAs is internally twinned and giant magnetodeformation is caused by the magnetically induced twinning/detwinning processes, which go by means of a twin boundaries motion [1-4]. These processes result in the reorientation of principal crystal axes of tetragonal unit cells in the martensitic phase, and therefore, they are referred to as the magnetically induced reorientation (MIR) of martensite. Due to this FSMAs possess unusual properties that are promising for various applications, in particular, the mentioned above giant (up to 12 %) deformations of FSMAs under the moderate (~ 100 kA/m) magnetic field occur [3-4].

It has been shown in Ref. [5] that the magnetostriction plays a decisive role in the MIR of martensite. The magnetic field application leads to the spatially inhomogeneous magnetostriction of the alloy specimen, which causes the crystal lattice misfit between the twin components. When the increasing magnetic field and magnetostrictive strain reach a certain threshold values $H_{th}$ and $\varepsilon_{th}$, respectively, the reorientation of twinned martensite starts [6, 7]. The threshold strain can be considered temperature independent, while the threshold field critically depends on temperature due to the strong softening of elastic modulus during MT.

The width of temperature range of observability of MIR was calculated for the Ni-Mn-Ga martensite in Ref. [5] and a good agreement between theoretical and experimental values was demonstrated. However, the computed in Ref. [5] temperature dependence of threshold magnetic field differs significantly from experimental one.

In the present work it is shown that the quantitative agreement between theoretical and experimental temperature dependences of threshold magnetic field is achieved by using a realistic (qualitatively similar to experimental) temperature dependence of elastic modulus. It is argued, moreover, the thorough quantitative comparison of experimental and theoretical dependences of threshold field can be an effective tool for the determination of magnetostriction and elastic modulus in the martensitic phase. The determination of these values by different experimental methods is an open problem because the twinned martensitic phase appears during experiment and small magnetostrictive/elastic strains are hardly observable in presence of large deformation caused by magnetically and/or mechanically induced martensite reorientation.

## 2. RESULTS

The experimental temperature dependence of the threshold magnetic field was measured for Ni-Mn-Ga alloy in work [8]. This experimental dependence (triangles) is shown in Fig. 1 together with theoretical one (solid line) calculated in Ref. [5]. As it is seen from the figure the shape of theoretical threshold field-temperature curve computed in Ref. [5] is different from the experimental one. This difference stems from a model function prescribing the temperature dependence of Young's elastic modulus used in calculations. To reach the quantitative agreement between theory and experiment the accurate theoretical analysis of experimental results should be performed. To this end the basic characteristics of MIR were computed using the analytical fit to experimental temperature dependence of the threshold field (dashed line in Fig. 1).

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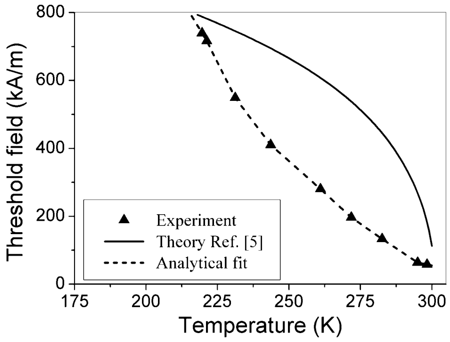

**Fig. 1** – Experimental temperature dependence of threshold magnetic field measured in Ref. [8] for Ni-Mn-Ga martensite (triangles). Theoretical temperature dependence of threshold magnetic field computed in Ref. [5] (solid line). The analytical fit to experimental data (dashed line)

The transversal (with respect to the field) magnetostriction of the tetragonal lattice inherent to Ni-Mn-Ga martensite can be evaluated from a relationship [9]

$$\varepsilon_{zz}^{(ms)}(T,H)=[\sigma_{zz}^{(me)}(T,H)-\sigma_{zz}^{(me)}(T,0)]/E_{zz}^{(z)}(T)\,, \quad (1)$$

where $\sigma_{zz}^{(me)}(T,H)$ is magnetoelastic stress thermodynamically conjugated to the magnetostrictive strain $\varepsilon_{zz}^{(ms)}(T,H)$, $E_{zz}^{(z)}(T)$ is Young's elastic modulus, $T$ is temperature. The maximum value of magnetoelastic stress is achieved in the saturation field, $H_S$, which aligns the magnetic moments of atoms. This value depends on the temperature as

$$\sigma_{zz}^{(me)}(T,H)-\sigma_{zz}^{(me)}(T,0)=-6\delta M^2(T)H^2/H_S^2\,, \quad (2)$$

where $M(T)$ is the temperature-dependent magnetization of the alloy, $\delta=-23$ is a dimensionless magnetoelastic constant estimated for Ni-Mn-Ga alloys [10]. For these alloys, the temperature dependence of magnetization is satisfactorily described by the equation

$$M_S(T)=M_S(0)\tanh[T_C M_S(T)/TM_S(0)]\,, \quad (3)$$

where the Curie temperature $T_C$ is close to 375 K and the low-temperature limit of magnetization value $M_S(0)$ is approximately equal to 715 G [11].

The twin boundary motion (MIR) starts when the increasing magnetic field and magnetostrictive strain reach a certain threshold values $H_{th}$ and $\varepsilon_{th}$. The threshold value $\varepsilon_{th} = const$ characterizes the mobility of twin boundary in the alloy specimen. The temperature dependence of threshold field can be found by solving the equation

$$\varepsilon_{zz}^{(ms)}(T,H_{th})=\varepsilon_{th} \quad (4)$$

for the field value considering the constant values of threshold strain, $\varepsilon_{th}$.

In the work [8], MIR in the twinned martensitic phase of Ni-Mn-Ga alloy was studied and the temperature dependence of threshold magnetic field was measured. This experimental dependence is shown in Fig. 1 by triangles. Using experimental temperature dependence of threshold field and equations (1) – (4) one can find the temperature dependence of Young's modulus $E_{zz}^{(z)}(T)$ and magnetostriction $\varepsilon_{zz}^{(ms)}(T,H)$. To this end the value of threshold strain $\varepsilon_{th}=0.018\%$ estimated in Ref. [5] was used. The saturating magnetic field $H_S=800$ kA/m was taken from the experimental data [8] (Fig. 1). Equating relationship (1) to (2) one can exclude the temperature dependence of magnetostriction and find the temperature dependence of Young's modulus. Figure 2 depicts the temperature dependence of Young's modulus computed using experimental temperature dependence of threshold field (dashed line). The solid line in Fig. 2 presents the model function prescribing the temperature dependence of Young's modulus used in Ref. [5]. As it is seen from the figure the model function and elastic modulus extracted from experiment vary significantly. The Young's modulus is shown in limited interval as long as temperature dependence of threshold field was measured in this interval.

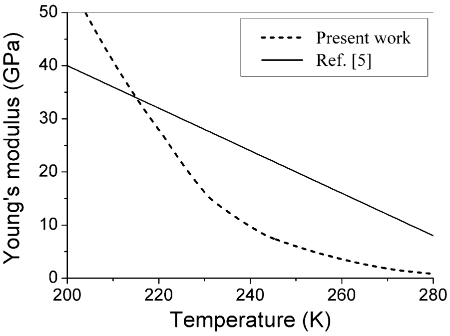

**Fig. 2** – Theoretical temperature dependence of Young's modulus extracted from experimental data (dashed line). Model function prescribing the temperature dependence of Young's modulus used in Ref. [5] (solid line)

The experimental determination of temperature dependence of the Young's modulus is a complicated task due to the instability of crystal lattice in the MT temperature range. Therefore, the estimation of this dependence from the experimental temperature dependence of the threshold magnetic field can be useful.

Figure 3 shows temperature dependence of magnetostriction computed using calculated Young's modulus and Eqs. (1) – (3). The $\varepsilon_{zz}^{(ms)}(T,H_S)$ function diverges at MT temperature because the value of Young's modulus drops to zero at this temperature. In real experiments this value is small but nonzero, and therefore, the magnetostriction is large but finite. The experimental temperature dependence of magnetostriction measured during cooling of Ni-Mn-Ga alloy is shown in the inset [12]. The measurement of magnetostriction in the martensitic phase is a complicated task, meanwhile the magnetostriction in the austenitic phase can be simply determined. Nevertheless the experimental temperature dependence of magnetostriction reaches the same values as calculated one, and a reasonable agreement between theoretical and experimental results takes place.

Knowing the temperature dependence of Young's modulus (Fig. 2) and magnetostriction (Fig. 3) one can solve an inverse problem – find the temperature dependence of the threshold magnetic field using equation (4). The solutions of this equation $H=H_{th}(T)$ are

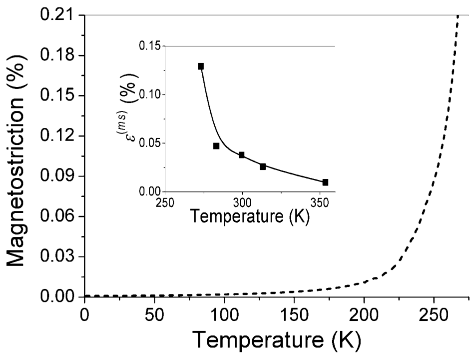

**Fig. 3** – Theoretical temperature dependence of magnetostriction computed using Young's modulus calculated in the martensitic phase (dashed line). The experimental temperature dependence of magnetostriction measured in the austenitic phase in Ref. [12] is shown in the inset

presented graphically in Fig. 1 by dashed line and it coincides with analytical fit to experimental data. This excellent coincidence illustrates only the high accuracy of the previously computed Young's modulus values. However, the resolution of the inverse problem is of significance in its own right, because it shows that the temperature dependence of the threshold magnetic field can be determined if the temperature dependence of Young's modulus is known.

## 3. SUMMARY AND CONCLUSION

The magnetically induced reorientation of twinned martensite goes by means of twin boundaries motion. Under magnetic field the crystal lattice misfit between the twin components arises due to the spatially inhomogeneous magnetostriction. The magnetostriction of FSMAs is temperature dependent as the result of the strong temperature dependence of elastic modulus. MIR starts when the magnetostrictive strain reaches a certain threshold value, which can be considered temperature independent. In the same time, the threshold magnetic field appears to be temperature dependent and the shape of theoretical $H_{th}(T)$ curve appears to be strictly related to the temperature dependence of shear elastic modulus. It can by concluded, therefore, that the careful fitting of theoretical $H_{th}(T)$ curve to experimental one results in the characterization of hardly measurable physical values of martensitic phase, such as temperature dependences of elastic modulus and magnetostriction.

## AKNOWLEDGEMENTS

The author is grateful to Victor A. L'vov for his fruitful discussions.

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