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ORIENTATION RELATIONSHIP, TEXTURE AND MICROSTRUCTURE IN ELECTROMAGNETIC PROCESSED MATERIALS (EPM)

RELACJA ORIENTACJI, TEKSTURA I MIKROSTRUKTURA MATERIAŁÓW PRZETWARZANYCH ELEKTROMAGNETYCZNIE (EPM)

In this work, some of our recent results in microstructure, texture and orientation relationship resulting from the application of an external high magnetic field during diffusional and non-diffusional phase transformation in both steel and functional metallic materials have been summarized. A 12-T magnetic field was applied to the diffusional decomposition of austenite in 0.81C-Fe alloy and martensitic transformation of a Ni-Mn-Ga magnetic shape memory alloy. For the 0.81C-Fe alloy, it was found that the magnetic field induces the formation of proeutectoid ferrite and slightly enhances the <001> fiber component in ferrite in the transverse field direction. The magnetic dipolar interaction between Fe atoms in the transverse field direction accounts for this phenomenon. The magnetic field favors the formation of pearlite with Pitsch-Petch 2 (P-P 2) and Isaichev (IS) orientation relationships (OR) between the lamellar ferrite and cementite. For the Ni-Mn-Ga magnetic shape memory alloy, the magnetic field makes the martensite lamellas to grow in some specific directions with their c-axes [001] orientated to the field direction and transverse field direction.

Keywords: Orientation relationship (OR); texture; electromagnetic processing of materials (EPM); steel; shape memory alloy

W pracy podsumowano nasze ostatnie wyniki w zakresie badania mikrostruktury, tekstury i zależności orientacji wynikających z zastosowania silnego zewnętrznego pola magnetycznego podczas przemiany fazowej dyfuzyjnej i bez-dyfuzyjnej w stali oraz funkcjonalnym materiale metalicznym. Pole magnetyczne 12-T zastosowano do dyfuzyjnego rozkładu austenitu w stopie 0.81C-Fe oraz do przemiany martenzytu w stopie Ni-Mn-Ga z magnetyczną pamięcią kształtu. Stwierdzono, że w stopie 0.81C-Fe pole magnetyczne indukuje formowanie się przedeutektoidalnego ferrytu i sprzyja formowaniu się w ferrycie dość słabej osiowej orientacji składowej <001> w kierunku poprzecznym do linii sił pola magnetycznego. Wyjaśnienie tego zjawiska tkwi w oddziaływaniu pola magnetycznego z atomami Fe w kierunku poprzecznym do linii sił pola. Pole magnetyczne sprzyja formowaniu się perlitu zgodnie z zależnościami Pitsch-Petch 2 (P-P 2) oraz Isaichev (IS) pomiędzy płytkami ferrytu i cementytu. W stopie Ni-Mn-Ga z magnetyczną pamięcią kształtu, pole magnetyczne sprawia, że płytki martenzytu wzrastają w specyficznych kierunkach, zgodnie z którymi układają się ich osie c [001], zorientowane prostopadle i równolegle do kierunku pola.

1. Introduction

In the area of solid-state phase transformation, if the parent and product phases are different in saturation magnetization and are allowed to transform under a magnetic field, the transformation behaviors can be considerably affected, as the Gibbs free energy of a phase can be lowered by an amount according to its magnetization. This effect has been first investigated in several ferro-alloys during their non-diffusional martensitic transformations mainly by Sadovsky's group in USSR in the 1950's [1] and then by Kakeshita's group in Japan in the 1980's [2]. It was revealed that magnetic field increases martensite transformation start temperature, Ms, promotes the transformation process and increases the amount of the martensite formed but it has less effect on the morphology of the product martensite. With the breakthrough of the super-conducting materials and cryocooling technique, simultaneously obtaining high magnetic field and high temperature became possible. Therefore, applying a high magnetic field to high temperature diffusion-controlled phase transformation, such as

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austenite to ferrite transformation, has aroused much interest. Research in this domain has mainly been carried out on following aspects: (1) theoretical simulation [3–5] and experimental examination [6, 7] of the effect of the magnetic field on ferrite/austenite and austenite/ferrite phase equilibrium; (2) morphological features appearing during ferrite to austenite [8] and austenite to ferrite [9, 10] transformations; (3) thermodynamic and kinetic characteristics of proeutectoid ferrite transformation under magnetic field [11–15]; (4) martensitic decomposition under a high magnetic field [16, 17]. Recently the ferromagnetic shape memory alloys (FSMAs) that display a shape memory effect actuated by an applied magnetic field have received much attention due to their strong advantages of both large output strain and short reaction time over the conventional shape memory alloys. Among such FSMAs, Ni-Mn-Ga alloys with composition close to the stoichiometric compound Ni_2MnGa have drawn much attention due to their high performance that can provide one order of magnitude higher strain induced by magnetic field than that of magnetostrictive materials. As the room temperature phase of these materials is in most cases martensite and martensite is magnetically anisotropic, introducing a magnetic field during martensitic transformation may modify the microstructure and change their shape memory effect. Thus the related study has become an interesting topic.

In the present paper, some of our recent work on the effect of a magnetic field on microstructure, texture and orientation relationships (ORs) during the diffusional decomposition of austenite in 0.81C-Fe alloy and martensitic transformation of a Ni-Mn-Ga magnetic shape memory alloy is reported.

2. Diffusional Phase Transformation

The material used is a 0.81C-Fe (wt.%) near eutectoid plain carbon steel. It was austenitized at 840°C for 42 min and cooled at a rate of 2°C/min without and with a 12-Tesla high magnetic field. During the heat treatment, the specimens were placed in the central (zero magnetic force) area.

The microstructure transformed was observed with an OLYMPUS BX61 microscope equipped with the analysis^{TM} software. Synchrotron radiation measurements were performed to measure the incomplete pole figures of ferrite of the samples cooled at 2°C/min without and with a 12-Tesla high magnetic field. The data were analyzed with *MAUD* and represented in inverse pole figures. Individual orientations of ferrite and cementite in pearlite colonies were manually measured through acquiring and indexing their electron back-scattering diffraction (EBSD) Kikuchi patterns and represented in the form of Euler angles (φ_1, ϕ, φ_2) in Bunge notation [18]. More than 30 areas were randomly selected to achieve a statistical reliability. The ORs between two adjacent phases, ferrite and cementite, were identified and represented in the form of Miller indices. The habit planes of ferrite/cementite interfaces were determined by the "indirect two-trace method" developed by our group [19].

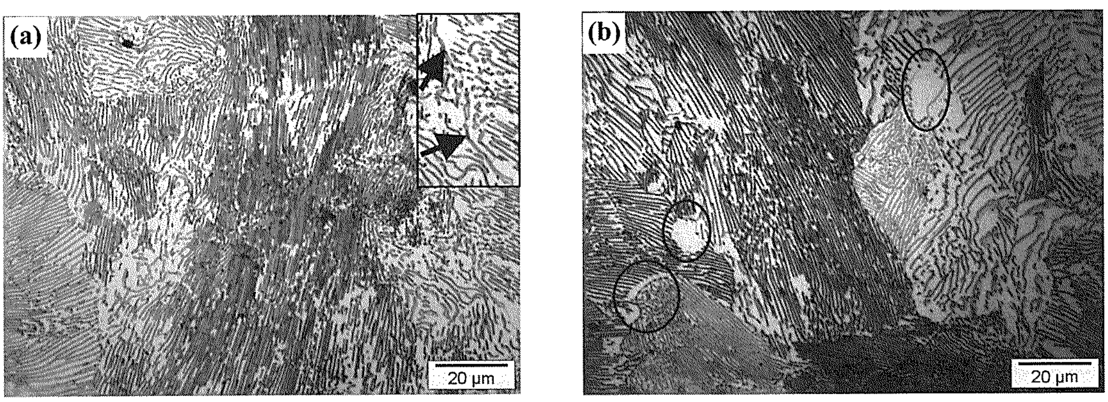

Fig. 1. Optical micrographs of samples austenitized at 840°C for 42 min and cooled at 2°C/min without (a) and with (b) a 12-T magnetic field (The field direction is horizontal). The zoom image in the right hand corner of Figure. 1 (a) shows the secondary cementite, as indicated by the arrow. The magnification is 1.5 times that of the main image. The circles in Figure 1 (b) mark out the proeutectoid ferrite between pearlite colonies

Figure 1 shows the microstructure of the specimens cooled at 2°C/min (a) without and (b) with a 12-T magnetic field. Though lamellar pearlite is the main component in both micrographs, the striking difference between the two is that, in the non-field treated specimen, we could observe a small amount of proeutectoid cementite (arrowed in the zoom image in the top right corner of Figure 1 (a)) characterizing the hypereutectoid microstructure whereas, in the field-treated specimen, we could see some bulk ferrite or proeutectoid ferrite between pearlite colonies (the white areas circled in Figure 1 (b)) and that component – rather than proeutectoid cementite – is typical of the hypoeutectoid microstructure. The presence of bulk ferrite in the field-treated specimens suggests that the magnetic field shifts the eutectoid point in the Fe-C binary system beyond the carbon content of the material tested (0.81C%wt.) [20].

Figure 2 shows the inverse pole figures of ferrite of the samples heat treated at 2°C /min without and with the 12T magnetic field and the corresponding sample coordinate system. It is seen that under the magnetic field there is slight enhancement of <001> fiber component in both the sample normal direction (ND) and the widthwise direction (TD), as seen in Figure 2 (b). This result is quite close to what we found in a medium carbon plain steel heat treated under a 12T magnetic field [21]. Actually in the present case, both ND and TD are transverse field directions. It is known that each Fe atom carries a magnetic moment. Under the applied magnetic field, these moments tend to align along the field direction. Then, there exists the dipolar interaction between neighboring Fe atoms. They attract each other along the field direction but repel each other along the transverse field direction (ND and TD in the present study). Correlatively, the distance between neighboring atoms tends to decrease along FD and increase along ND and TD to minimize the total energy of the system. For ferrite, the carbon atoms are located in the octahedral interstices. The interstices are flat in the <001> direction. The occupation of the carbon atom in this interstice exerts an expansion stress on its neighboring iron atoms along the <001> direction. This gives rise to the lattice distortion and creates distortion energy. If such a <001> direction of a grain were parallel to the transverse field direction (ND or TD), the lattice distortion energy would be reduced through increasing the atomic spacing in such <001> direction by the magnetic field. Therefore, the nucleation and growth of the grains having such <001> parallel to the ND and TD is most energetically favored by the magnetic field. In this way, the <001> component could be enhanced.

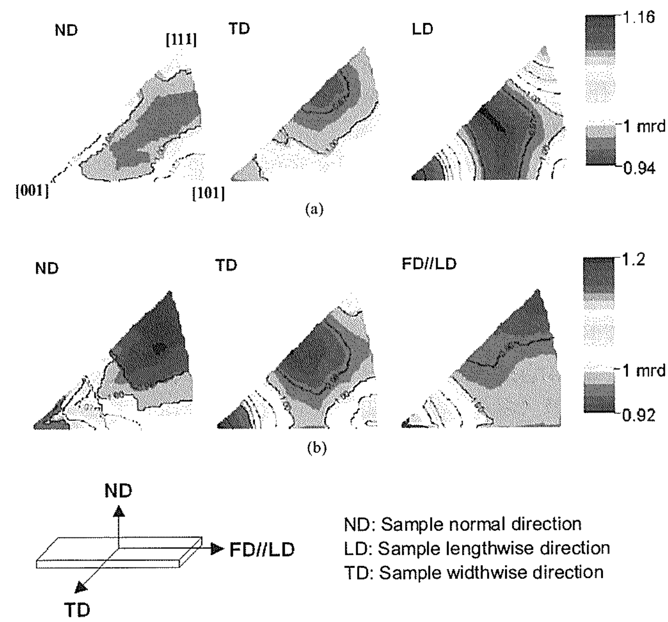

Fig. 2. Inverse pole figures of the samples austenitized at 840°C for 42 min and cooled at a rate of 2°C/min without (a) and with a 12-T magnetic field (b), and the corresponding sample coordinate system

TABLE 1

Orientation relationships (ORs) between pearlitic ferrite and pearlitic cementite in the non-field treated sample [22]

Near Bag. OR	IS OR	P-P 1	P-P 2
$(103)_C//(01\bar{1})_F$ $[010]_C//[111]_F$ Habit plane $(001)_C \sim 3°$ from $//(2\bar{1}\bar{1})_F$	$(103)_C//(01\bar{1})_F$ $[010]_C//[111]_F$ Habit plane $(101)_C//(11\bar{2})_F$	$(103)_C//(\bar{1}01)_F$ $[010]_C//[131]_F$ Habit planes $(001)_C//(\bar{2}\bar{1}5)_F$ $(103)_C//(\bar{1}01)_F$ $(101)_C 8.7°$ from $(\bar{2}15)_F$	$(103)_C//(\bar{1}01)_F$ $[31\bar{1}]_C//[111]_F$ Habit planes $(001)_C \sim 3.5°$ from $(\bar{2}\bar{1}5)_F$ Unknown

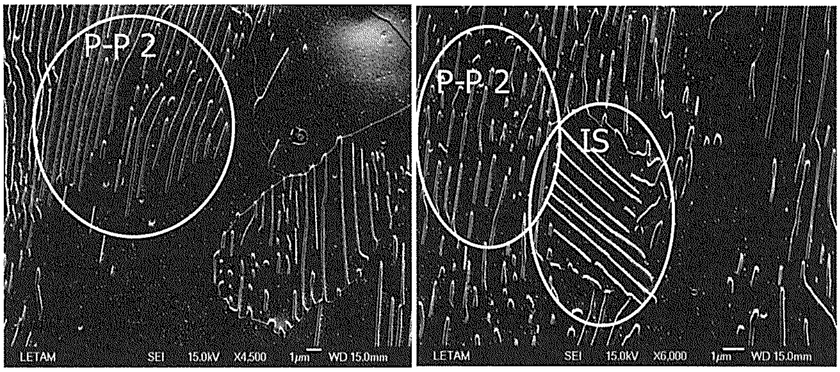

Fig. 3. Lamellar pearlite with P-P 2 and IS ORs near the proeutectoid ferrite in the sample austenitized at 840°C for 42 min and cooled at 2°C/min with a 12 T magnetic field

In our previous work [22], we have derived four different ferrite/cementite orientation relationships (ORs) with the sample cooled at 2°C/min after full austenitization without the magnetic field as shown in Table 1 [22]. It was found that all the four ORs possess a common feature of close-packed plane parallelism between ferrite and cementite. Their crystallographic compatibility with habit planes exhibit variety of possible habit plane and excludes the existence of the exact conventional Bagaryatsky and Pitsch-Petch ORs [22]. Whereas when the magnetic field was applied, the four ORs also appear but each has a different occurrence frequency from the same OR in the non-field treated sample. It is found that the frequency of appearance of P-P 2 is obviously increased under the 12 T magnetic field. Many of such oriented lamellar ferrite and cementite appear next to the proeutectoid ferrite as shown in Figure 3. It is known that the pearlitic transformation involves two structural changes. One is the transformation from fcc austenite into bcc ferrite and orthorhombic cementite and the other is the final formation of ferrite/cementite interface. The first may lead to a misfit at the austenite/ferrite and austenite/cementite interfaces due to their difference in crystal structure, resulting in the transformation strain at these interface boundaries. The second may create the interfacial energy at the habit plane between ferrite and cementite that depends on the atomic misfit on interface planes. These two energy terms are considered as the energy barriers to the pearlitic transformation. To minimize these barriers, it requires some specific ORs between the parent and product phase that finally result in specific ORs between the product phases and the coherent habit planes. It was suggested in our previous work that the four ORs well satisfy the "edge-to-edge" matching condition at the austenite/ferrite and austenite/cementite interface that helps to reduce the transformation strain [22]. However, the different ORs are correlated to different nucleation conditions. The P-P 1 OR occurs when the pearlitic ferrite and cementite nucleate simultaneously, whereas the P-P 2 OR appears when pearlitic ferrite forms before pearlitic cementite. However, the IS OR could happen either when pearlitic ferrite nucleates first or the pearlitic cementite nucleates first [22]. This derivation is quite coherent with the present observation that under a 12 T magnetic field the occurrences of P-P 2 OR is increased. Many studies have proved that the equilibrium condition between phases with different induced magnetization can be changed by the application of a magnetic field [11–15]. The phase with high-induced magnetization will become more stable or easily to nucleate than that with low-induced magnetization. As at the pearlitic transformation temperature of the present study, pearlitic ferrite is ferromagnetic with high-induced magnetization under the 12 T magnetic field and cementite is paramagnetic with low-induced magnetization, ferrite would nucleate before cementite, especially when there already exists proeutectoid ferrite. In this way, the ORs related to the nucleation of ferrite first would become more frequent.

3. Martensitic transformation of Ni-Mn-Ga shape memory alloy

In this work, a Ni-Mn-Ga alloy with chemical composition of $Ni_{53}Mn_{25}Ga_{22}$ (at.%) was prepared by repeated melting of the high-purity constituent elements Ni, Mn and Ga in an arc furnace protected under an argon atmosphere. Samples with the dimension of 3mm×6mm×10mm were cut from the ingot. They were further austenitized at 400°C for 1h and then cooled at ~10°C/min without and with a 12T magnetic field to allow austenite to transform into martensite. The microstructure characteristics of the samples were examined by means of electron backscattering diffraction (EBSD) technology in the same FEG SEM.

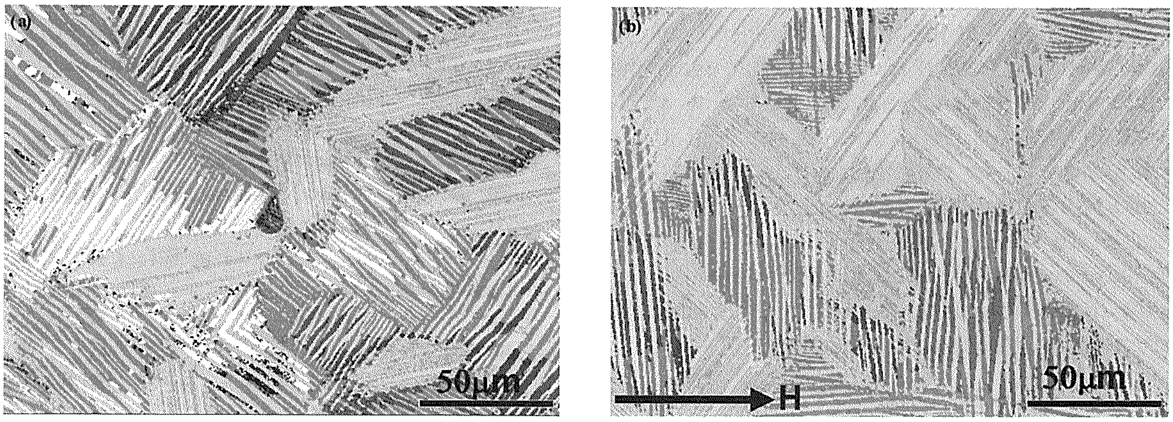

Fig. 4. Orientation maps of the Ni-Mn-Ga shape memory alloy austenitized at 400°C for 1h and then cooled at ~10°C/min (a) without and (b) with a 12T magnetic field

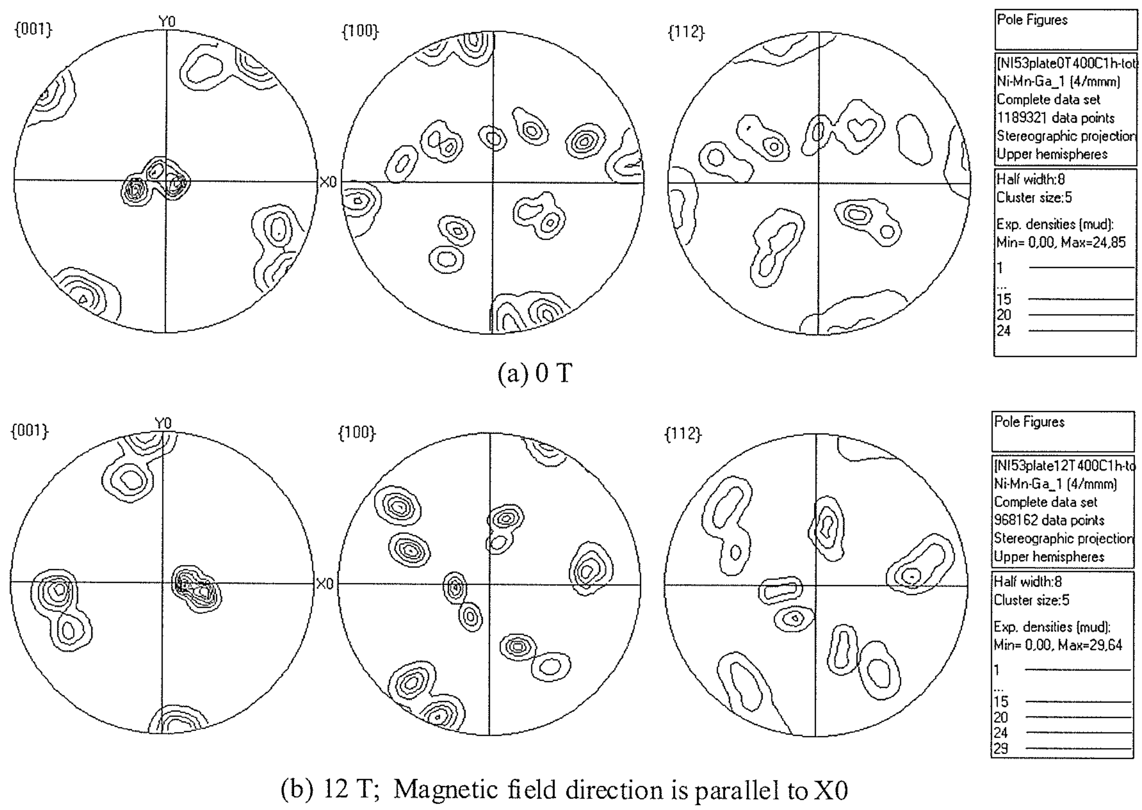

Fig. 5. Pole figures of the Ni-Mn-Ga shape memory alloy austenitized at 400°C for 1h and then cooled at ~10°C/min without (a) and with a 12T magnetic field (b)

Fig. 4 (a) and (b) display the orientation maps of the samples treated without and with a magnetic field of 12T, respectively. It can be seen that in both samples the microstructure consists of the well self-accommodated lamellar martensite. Our previous study has revealed that the martensite lamellas are twin related [23]. However, the distributions of orientation of the lamellar martensite in the non-field and field treated samples are quite different. In the non-field treated sample, the martensite lamellas are orientated relatively randomly; while in the field treated sample, the martensite lamellas run only in some specific directions, as seen in Fig. 4 (a) and (b).

Furthermore, the crystallographic orientations of the treated samples are also analyzed and expressed in the form of pole figures, as shown in Fig. 5. It is seen from the {001} pole figures that the main difference between the non-field and field treated samples is that under the magnetic field there are some martensite variants tending to orient their c-axes [001] towards the field direction (X0) and some others with their c-axes [001] to the transverse field direction (Y0). However, in the non-field treated sample, no variants have their c-axes [001] appearing in these two directions. This phenomenon may related to the magnetic anisotropy and magnetostriction of the martensite. Further study is needed.

4. Conclusions

The study of the phase transformation of the 0.81C-Fe (wt.%) near eutectoid plain carbon steel and the $Ni_{53}Mn_{25}Ga_{22}$ (at.%) under a 12 T magnetic field shows that:

1. The field applied slightly enhances the <001> fiber texture in the transverse field direction due to the dipolar interaction of the magnetic moments carried by the Fe atoms.
2. The magnetic field is in favor of the occurrence of P-P 2 OR due to the promotion of nucleation of pearlitic ferrite.
3. The magnetic field also shows influence on the lamella orientation of the martensite variants and their crystallographic orientations in the Ni-Mn-Ga shape memory alloy by inducing the martensite lamellas to grow in some specific directions with their c-axes [001] orientated to the field direction and transverse field direction.

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