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Effects of high magnetic field annealing on texture and magnetic properties of FePd

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Abstract

The effects of high magnetic field annealing on the preferred orientation distribution (texture) and magnetic anisotropy of arc-melted FePd alloy were studied by recalculated pole figure method and vibrating sample magnetometry. A rigorous texture characterization method was used to analyze the crystal orientation distribution of the annealed FePd. As compared with annealing without magnetic field, the high magnetic field annealing increases the volume fraction of crystal grains with *c*-axis aligned along the annealing magnetic field direction. A corresponding uniaxial magnetic anisotropy was also observed in the magnetically annealed FePd alloy.
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1. Introduction

It is very important to control the microstructure of the magnetic materials because textured or anisotropic magnetic materials usually show better performance in technical applications [1,2]. Among many methods to impose the desired texture and magnetic properties, magnetic field processing has been given special attention in the last few decades [3–6]. For soft magnetic materials, it is well known that a well-defined uniaxial anisotropy can be obtained due to the atomic pair anisotropy induced by the magnetic field annealing [3]. For permanent magnetic materials, the loose powders of single crystal grains can rotate so as to

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align their easy axis of magnetization along with the magnetic field direction. Further, sintering the aligned grains will produce the anisotropic permanent magnetic material [4]. It is also important to mention that the oriented permanent magnets can be obtained by solidification from the molten state in a high magnetic field [5,6].

However, up to date, only a few high magnetic field annealing experiments (in the magnetic field of several Tesla) have been done on magnetic materials, and the mechanisms through which the high magnetic annealing field plays a role on microstructures and magnetic properties are still unclear [6–11]. It was found that annealing the cold-rolled Fe-Si sheet [6] in a high magnetic field of 10 T parallel to the rolling direction enhanced the selectivity of the $\langle 0\,0\,1 \rangle$ axis alignment. High magnetic field (1.5 T) annealing in another system, Armco iron, has also been studied in detail [7]. The grains with $\langle 1\,0\,0 \rangle$ parallel to the external field would nucleate preferentially. High magnetic field annealing was also applied in FePd system by Tanaka et al. [9]. It was claimed that a so-called mono variant $L1_0$ structure was obtained by high magnetic field annealing at 780 K under 10 T. However, the crystal orientation analysis method used in their experiments was rough and incomplete, and there was no study in magnetic anisotropy. In our previous study on ferromagnetically soft FeSi alloy [10] and diamagnetic ZnAl alloy [11], it was found that the preferred orientation was improved by the high magnetic field annealing. No corresponding magnetic properties were reported in these studies.

The equilibrium phase diagram of the FePd system shows five distinguishable regions at low temperature as a function of the atomic content of Pd [12]. They are α-Fe, coexistence of α-Fe and γ_1-FePd, γ_1-FePd, γ_2-FePd and γ-FePd. The equiatomic FePd undergoes an order–disorder transition at about 923 K from a disordered FCC to an ordered $L1_0$ tetragonal structure. In tetragonal FePd, the *c*-direction is an easy axis of magnetization. In this paper, the effects of the high magnetic field annealing on the phase transition of FePd alloy and the orientation distribution of the crystals in FePd $L1_0$ phase were studied. Here a robust crystal orientation distribution methodology was used to understand the microstructure. A vibrating sample magnetometer (VSM) was also utilized to characterize the corresponding magnetic properties.

2. Experiments

The alloy ingot of the FePd was prepared by arc-melting of Fe and Pd in an argon atmosphere. FePd samples sealed in a vacuum tube of the quartz glass were annealed in a 30 T magnetic field for 6 h at 650°C. The magnetic field direction (H_A) during annealing is in the plane of the FePd sheet along the sample's longitudinal direction. As a comparison, the same as-prepared FePd samples were annealed in a similar process without the exposure to the magnetic field. Texture was measured using a Philips X'Pert PW3040 MRD X-ray diffractometer, equipped with a pole figure goniometer, operating at 40 kV and 45 mA and employing Ni filtered Cu Kα radiation, as described before [13]. Incomplete pole figures of FePd (0 0 2), (1 1 1), (1 1 3), (2 0 0), (2 0 2) were obtained from the measurements. After geometric defocusing correction and background subtraction, harmonic algorithm implemented in PopLA [14] was used to calculate the crystal orientation distribution function from which the complete recalculated pole figures were constructed. Furthermore, magnetic properties were measured by VSM.

3. Results and discussions

X-ray diffraction indicates that magnetic annealing has obvious effects on the texture of the FePd alloy, as shown in Fig. 1. The error in 2θ value is $\pm 0.002°$. It is clear that the high magnetic field annealing enhances the phase separation between α-Fe phase (Fe (1 1 0)) and FePd alloy phases (FePd (1 1 1) and (0 0 2), etc.). Moreover, the high magnetic field annealing enhances the relative intensity of FePd (0 0 2) peak to that of FePd (1 1 1) peak. The ratio increases from 9.6% in the sample annealed without magnetic field to 14.7% in the sample annealed in magnetic field.

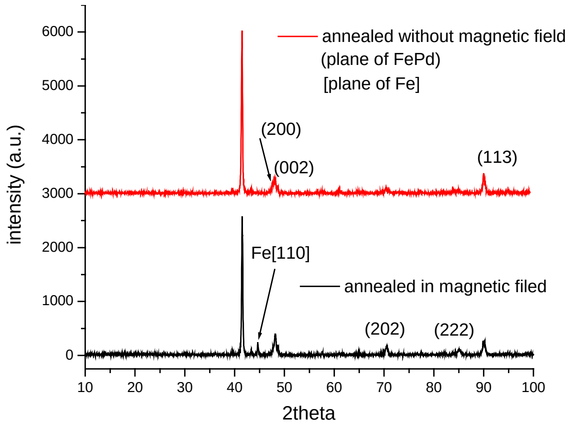

Fig. 1. X-ray diffraction patterns of FePd samples annealed without a magnetic field and in a magnetic field.

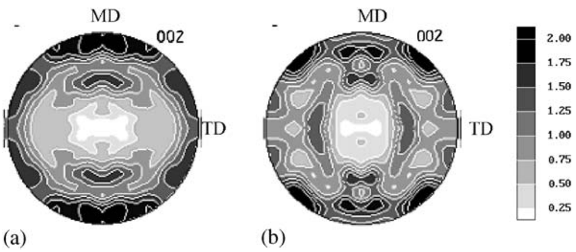

Fig. 2. (0 0 2) pole figures of FePd annealed (a) in a magnetic field and (b) without magnetic field.

Fig. 2 illustrates (0 0 2) pole figures of annealed FePd samples. MD is the longitudinal direction of the sample (also corresponds to the direction of annealing magnetic field, H_A); TD is the transverse direction, while the crosshair corresponds to the normal direction of the sample. In magnetically annealed samples the distribution density of crystals with c-axis parallel to the H_A (Fig. 2a) is 2.0 times random. The error in the intensity in Fig. 2 is smaller than 0.05 times random. This means that the high magnetic field annealing tends to align the c-axis along the direction of the annealing field. In samples annealed without magnetic field (Fig. 2b), the density of crystals with c-axis along the longitudinal direction is only 1.2 times random. This means that the FePd annealed without field has no trend to show uniaxial crystal anisotropy.

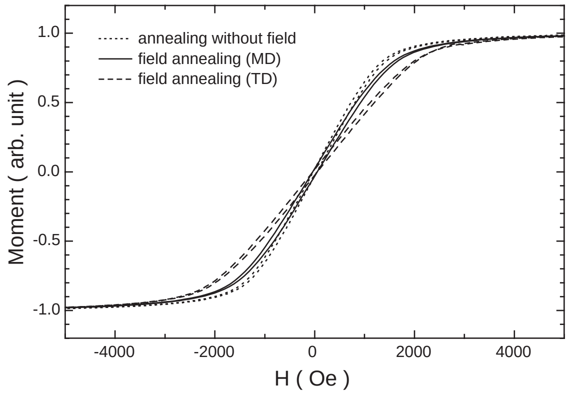

Fig. 3. The hysteresis loops of the FePd samples annealed in the magnetic field and annealed without magnetic field.

Texture analysis indicates that annealing under high magnetic field does improve the orientation distribution of crystals in the FePd samples, although far from the mono-variant structure. Since more crystal grains have their easy axis of magnetization parallel to the annealing field direction as compared with those annealed without magnetic field, the uniaxial anisotropy is expected for the magnetically annealed FePd samples. Fig. 3 shows the hysteresis loops of FePd samples of different processes, i.e., annealed without field, and annealed with field. To eliminate the influence of shape anisotropy, all of the samples used in VSM measurements were cut into circular sheets with a diameter of 3 mm, and thickness of 0.5 mm. The magnetic field used in VSM measurements was in the plane of the sheet, along MD and TD directions in the plane, respectively. In this case, the demagnetization factor is the same for all the hysteresis loops when the external field is applied in the plane of the circular sheet. Therefore, any differences in the hysteresis loops, if exist, originate from the intrinsic anisotropy. For the magnetically annealed samples, the differences (such as difference in saturation fields) in hysteresis loops of MD and TD configurations clearly show magnetic anisotropy which can be attributed to the alignment of the grains. According to the X-ray results in Fig. 2(a), the easy axis of magnetization of the grains annealed in the high field has a higher possibility to align along the

MD. Therefore, a smaller saturation field was found in MD direction than that in TD direction. By contrast, in non-magnetically annealed samples there is no detectable difference in the hysteresis loops between MD and TD in the plane of the sheet sample. Only one hysteresis loop for this annealed sample was shown in Fig. 3. This is in agreement with the pole figure in Fig. 2(b), where the distribution of easy axis of magnetization is far from the uniaxial anisotropy.

It is clear that the alignment of the grains and the magnetic anisotropy may be further enhanced if the FePd samples were annealed in the high magnetic field for a longer period of time. According to the nonmagnetic annealing process under the same annealing conditions, the equilibrium phases may be reached after about 100 h of annealing. Although the FePd samples were only annealed for 6 h in the present experiments, significant magnetic field effects have been found in two independent experiments (X-ray and VSM measurements). From the viewpoint of the free energy of the FePd system, different FePd phases and grains of magnetic crystal anisotropy may have different energy in the high magnetic field for different directions if the magnetic crystal anisotropy energy and the magnetostriction energy were taken into account. Therefore, when the FePd alloy was annealed in a high magnetic field, the FePd system may gradually evolve into different phases and show anisotropic nucleation and growth as compared with the case of the non-magnetic annealing. However, quantitative analysis on the high magnetic field annealing mechanisms still requires further research work.

4. Conclusions

In conclusion, the high magnetic field annealing can enhance the phase separation of the disorder uniform FePd alloy, and induce the microstructural and magnetic anisotropy. Since FePd system has a potential to be a candidate for the recording media and the magnetic anisotropy is highly desirable in many applications, the magnetic field induced structural and magnetic anisotropy may have great contribution to technology development.

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