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Experimental study on modulated structure in Alnico alloys under high magnetic field and comparison with phase-field simulation

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ABSTRACT

A series of magnetic isothermal heat treatment of Alnico alloys (Alnico5 and Alnico8) in a 10 T magnetic field were performed. It was found that the high magnetic field strongly influences the modulated microstructure. Our observation shows that high magnetic field can enhances the nucleation rate of spinodal decomposition in Alnico5 alloy, leads the decomposed particles finer, and also increases the volume fraction of ferromagnetic particles. The external magnetic field (H_{ext}) can also accelerate the atom diffusion and turn the diffusion direction to itself. The effect of both the E_{ext} (the external magnetic field energy) and the E_{elast} (the elastic energy) on modulated structure in a hypothetical A–B system was simulated by phase field method. The littler the E_{elast} is, the bigger the E_{ext} is, the decomposed ferromagnetic particles become smaller, and parallel along the direction of the external magnetic field.

1. Introduction

Since the Alnico alloy was firstly discovered in 1931 [1], its microstructure and magnetic properties have been the subject of a number of studies in the past several decades, and the spinodal decomposition in Alnico film that has high coercivity was studied recently [2]. Alnico alloys were widely used because of its high Curie temperature and good magnetic properties, its magnetic properties origins to the two phases of spinodal decomposition. The mechanism of spinodal decomposition in Alnico alloys is similar to that in Fe–Cr–Co alloys [3–4], a single α phase (BCC structure) was got after solution treatment at high temperature about 1250 °C, and then the α phase spinodally decomposed into α_1 phase and α_2 phase cooled furnace from 900 °C to 600 °C. The α_1 phase is a Al–Ni rich phase (weakly magnetic matrix phase) and the α_2 phase is a Fe–Co rich phase (strongly magnetic phase in the form of rod shaped precipitates embedded in the matrix). External magnetic field (H_{ext}) was applied to increase its magnetic properties during the aging [5–7], because the magnetic field increased the anisotropy of alloy. The strongly magnetic α_2 phase aligned parallel to the direction of the external magnetic field, it was confirmed in the single crystal [8,9]. When the alloy was treated without external magnetic field, the modulated structure is mainly affected by the elastic energy of the alloy, and the modulated structure arranges along the ⟨001⟩ crystal directions. High magnetic field is a very important factor that affects the microstructure and physical properties of materials, a number of studies have been subjected to the effects of high magnetic field on phase transformation in many kinds of materials [10–14], and the results suggested that high magnetic field apparently affects the thermodynamics and kinetics of the phase transformation in materials. Therefore, high magnetic field can be applied to microstructural control, as well as properties optimization. For example, a 30 T magnetic field alters the thermodynamics and transformation kinetics of austenite decomposition in 1045 steel, and the transformation temperature is increased 70–90 °C due to different cooling rates, and the ferrite volume fraction increased by 25–30% [15]. The Fe–Fe_3C phase diagram caused by a high external magnetic field was calculated on the basis of the molecular field theory [16], the phase diagram shifted upwards so that the Ac1and Ac3 temperatures increase as the magnetic field is applied.

However, these studies were concerned with structure transformation, while few were carried out on the isostructure transformation, i.e. spinodal decomposition, which is sensitive to the local environments [17–19], as well as external applied fields, such as strain field and magnetic field [20,21]. How does a high magnetic field affect the modulated structure in Alnico alloys with different elastic energies? In the present work, Alnico5 and Alnico8 alloys with different the elastic energies (E_{elast}) were chosen, which have the same chemical elements with different contents. The modulated structure in these two kinds of Alnico alloy during isothermal ageing with and without external magnetic field

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was observed by transmission electron microscope (TEM), high resolution transmission electron microscope (HRTEM) and high angle annular dark-field (HAADF), aiming to clarify the effect of the external magnetic field energy (E_{ext}) and the E_{elast} on the modulated structure in Alnico alloys. Phase-field simulation was also carried out on a hypothetical A–B system to investigate the effect of both the E_{elast} and the E_{ext} on the modulated structure in the homogeneous and in homogeneous elastic constants during isothermal ageing.

2. Experimental

The Alnico alloys in this study are Alnico5 alloy (Fe–24.7Co–16.2Ni–8.8Al–0.2Ti–3.1Cu, wt%) and Alnico8 alloy (Fe–34.2Co–14.6Ni–7Al–6.1Ti–2.7Cu, wt%), which are the same on elements, just different in the contents. The E_{elast} in Alnico8 alloy is larger than that in Alnico5 alloy [22]. Flake-like samples of $12\times10\times4$ mm^3 cut from the bulk were solid solution treated at 1250 °C for 40 min, and then quenched into iced brine. The same parameters of isothermal ageing at 830 °C for 10 min were adopted for the alloys without and with an external magnetic field up to 10 T. TEM thin foils were jet-polished and then observed on a FEI G^2 F30 transmission electron microscope at 300 kV. The model of the phase field method was described in the reference [23], the size of decomposed particles was measured by the method as that in the Ref. [24].

3. Results and discussion

3.1. Morphology of the Alnico alloys

Alnico5 alloy was isothermally treated at 830 °C for 10 min under different external magnetic field conditions, and microstructures were shown in Fig. 1. The observed crystal direction is the same as the orientation of $<001>$ and the corresponding selected area electron diffraction (SAED) pattern was shown in Fig. 1a. When the alloy was treated without an external magnetic field, the Fe–Co rich phase particles are isotropic. The decomposed particles orient along the ⟨001⟩ crystal directions, as shown in Fig. 1b. The particles are spherical and rod-shaped, and these rod-shaped particles are nearly plumb to each other. However, when Alnico5 alloy was treated with an external magnetic field, the Fe–Co rich phase particles arrange along one direction which is parallel to the direction of the external magnetic field, as shown in Fig. 1c and d. When the alloy treated in an external magnetic field of 0.4 T, the aspect ratio of the rod-shaped particles was about 1.3, and the volume fraction of them was about 30%, as shown in Fig. 1c. While the external magnetic field intensity was increased to 0.7 T, the diameter of the Fe–Co rich particles is about 40 nm, the aspect ratio was about 2.0, and the volume fraction increased to 50%. Some adjacent particles were connected together, as shown in Fig. 1d. It implied that the external magnetic field easily affects the anisotropy of the decomposed particles in Alnico5 alloy, and the E_{ext} greatly affects the thermodynamics of spinodal decomposition in Alnico5 alloy.

When the external magnetic field intensity was increased to 10 T, the morphology of the modulated structure in the Alnico5 alloy was distinctly changed, as shown in Fig. 2. All the Fe–Co rich phase particles are nearly sphere, they never arrange along the direction of the H_{ext}, and the diameter of them is about 10 nm, the volume fraction of them is more than 70%. A 10 T magnetic field makes the decomposed particles finer, indicating that the E_{ext} increased the nucleation rate of spinodal decomposition in the Alnico5 alloy. In Ref. [15], the ferrite volume fraction in 1045 steel during cooling under a 30 T magnetic field increased by 25–30%, because the transformation temperature is increased 70–90 °C. Therefore, the equilibrium phase diagram was changed by high magnetic field. In Alnico5 alloy, the H_{ext} also changed the

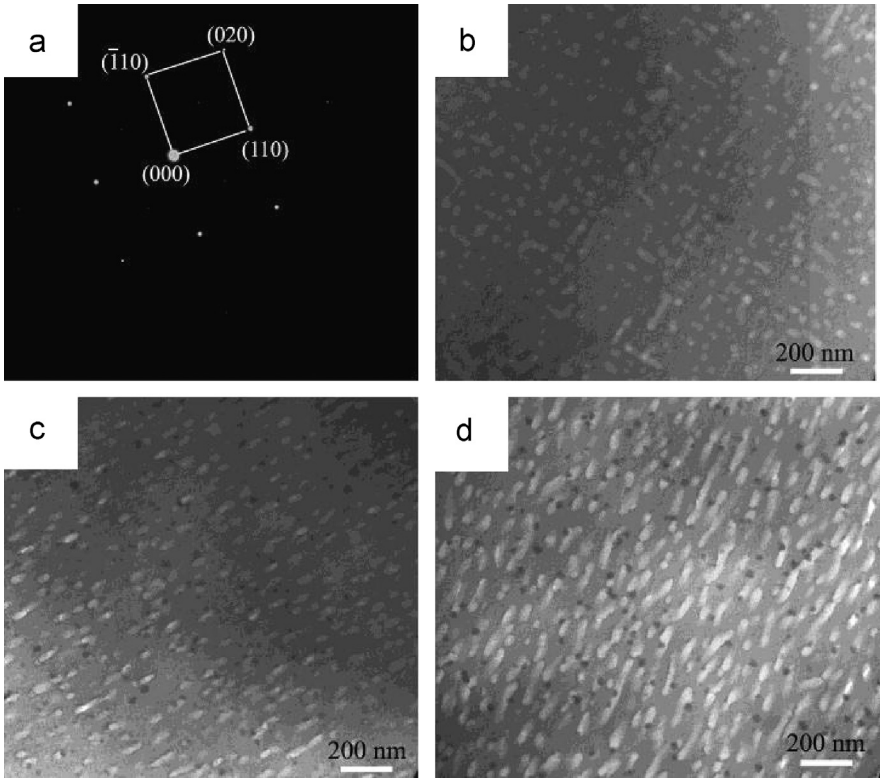

Fig. 1. TEM images showing the morphology of Alnico5 alloy treated at 830 °C for 10 min under different H_{ext} conditions. (a) SAED; (b) without H_{ext}; (c) 0.4 T, $\|H_{ext}$; (d) 0.7 T, $\|H_{ext}$.