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Research articles

Correlations of phase structure and thermal stability for Alnico 8 alloys

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ABSTRACT

The correlations of phase structure and thermal stability for Alnico 8 alloys is analyzed by three-step aging at 650 °C, 600 °C and 550 °C gradually in this paper. After three-step aging the a1 phase is a chess-like structure in transverse direction and a bamboo-like structure in longitudinal direction. Meanwhile the magnetic energy product ($(BH)_m$) increases from 9.17 MGOe to 10.59 MGOe, and the remanence temperature coefficient a(RT-180 °C) reduces from −2.31 %/°C to −1.25 %/°C. The MPMS and VSM measurements indicate that three-step aging makes the a1 phase be single domain particles and dispersed distribution, which plays an important role in optimizing the thermal stability of Alnico alloys.

1. Introduction

The recent rare-earth crisis and urgent demands for delicate instruments stimulate researchers to concentrate on Alnico alloys with excellent thermal stability and high Curie temperature (up to 550 °C) [1]. The magnetic properties of Alnico alloys results from M_s difference between the a1 phase and the a2 phase as well as the shape anisotropy of the a1 phase [2,3]. The applied field and the temperature during thermomagnetic treatment have great influences on phase structure and magnetic properties [4,5]. However, the present study reveals that during the low-temperature aging the changes of microstructure for the a1 phase and the phase structure for the a2 phase has never been observed before.

Alnico alloys are nanostructured permanent magnets and the a1 phase are single domain particles, which means the better degree alignment of the a1 phase is favorable for the thermal stability [6–8]. These researches focus on analysis orientation degree and dispersed distribution of the a1 phase with aged. In particular, they claim the aging processing is closely related to the microstructure and phase structure for the a1 phase and the a2 phase. In this paper we develop samples with grading annealing processes and characterize them for morphology, phase composition, recoiled magnetization behavior and magnetic properties at high temperature. The phase structure and magnetic properties at high temperature are investigated to clarify the correlations between the phase structure and thermal stability for Alnico alloys.

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2. Experimental

The material under investigation was a coarse grained columnar Alnico 8 alloys with 35 wt% Co, 13.8 wt% Ni, 7.2 wt% Al, 5.8 wt% Ti, 3 wt% Cu, 1.1 wt% Nb and Fe to balance. The molten ingot was cut into columnar specimens with an axis parallel to the columnar axis. After homogenizing at 1250 °C and thermomagnetic heat treatment at 827 °C with the applied field parallel to the columnar axis, the specimens were treated at 650 °C for 3 h, 600 °C for 8 h and 550 °C for 16 h gradually. The magnet in different stages of single stage aging, two-step aging and three-step aging were named A, B and C separately.

The phase and microstructure identification was performed by Transmission electron microscopy (TEM) on transverse (observation parallel to the columnar axis) and on longitudinal (observation perpendicular to the columnar axis) using a FEI Tecnai F20-XT with an acceleration voltage of 200 kv. The crystal structure was determined using powder X-ray diffractometer with Cu-Ka radiation. The magnetic properties were measured in a closed magnetic circuit with the B-H apparatus. The reverse magnetization processes was analyzed by Quantum Design Magnetic Property Measurement System (MPMS) MODEL 6000 equipped with a vibrating sample magnetometer (VSM).

3. Results and discussion

The phase and microstructure are showed in Fig. 1 by TEM images of the specimen surfaces parallel and perpendicular to the applied field. The upper row in Fig. 1 shows the a1 phase in A is a plate-like structure while that in C is a chess-board like

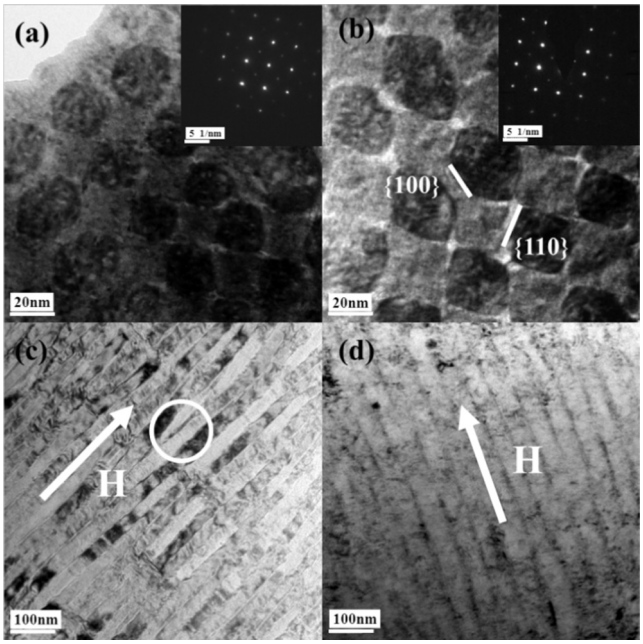

Fig. 1. TEM images of Alnico 8 alloys: (a) A, transverse; (b) C, transverse; (c) A, longitudinal; (d) C, longitudinal.

structure with {100} facets or {110} facets [1]. For one thing the size of the a1 phase from A to C increases from 20 nm to 35 nm gradually, for another the a1/a2 interface becomes more clearer. The below row in Fig. 1 shows the a1 phase changes from a needle-like structure to a bamboo-like structure. All the a1 phase elongate along with the columnar axis except for some deflected branches marked by the white circle. During the thermomagnetic treatment Spinodal decomposition occurs to form the a1 phase and the a2 phase of the nanoscale: an isolated a1 phase and a matrix a2 phase. It can be found the a1 phase is short bar with longitudinal axis parallel the applied field direction. Due to the lowest system energy in the applied field direction the aging promotes the short bar to elongate end-to-end. The length and draw ratio of the a1 phase increases step-by-step. The a1/a2 interface of C in Fig. 1 (d) is linear. Comparing with that in Fig. 1 there is a improvement in dispersed distribution and draw ratio of the a1 phase.

The average phase compositions are collected on transverse surfaces. The results are summarized in Table 1. It is evident that partitioning of Fe and Co to the a1 phase, and Al, Ni, Ti, Cu and Nb to the a2 phase. There is no Nb atom in the a1 phase and three-step aging promotes Nb to segregate in the a2 phase. In view of the similar atomic radius and chemical character, maybe Nb atoms replace the atomic site occupation of Ti. Owing to the spinodal decomposition making the phase composition of the precipitated phase be coherent, the Fe, Co elements have sharp "peak" and "valley" across the center of the a1 phase and the a2 phase [2]. In contrast, three-step aging improves the composition uniformity distributed of the a1 phase and the a2 phase respectively to clear the a1/a2 interface. The data in Table 1 shows from A to C the sum of n(Fe + Co) atoms in the a1 phase is increasing, but the ratio of nFe/nCo is reducing. In addition the value of n(Co + Ni): n(Fe + Ti + Cu + Nb): nAl in the a2 phase gets close to 2:1:1, which will improve the degree of order of the a2 phase [1,7]. So for the a1 phase the value of nFe/nCo approaches to be 1 and it shares BCC or B2 crystal lattice, and for the a2 phase the Co and Ni shares the equivalent lattice-substitution, the same situation will occur for Fe, Al, Ti, Cu and Nb, which is correspond with B2 or $L2_1$ crystal lattice.

Fig. 2 shows a typical X-ray diffraction pattern of the Alnico alloys. The (110), and (200) reflections shows Alnico alloy is a BCC structure. So Alnico alloys is a kind of special material with coexisting of spinodal decomposition and order-disorder phase transformation [10]. According to the distinction between the lattice parameters of the a1 phases and a2 phases, the (100), (110) and (200) split into two respectively [4]. In perpendicular columnar axis the applied field cannot restrain spinodal decomposition and order-disorder phase transformation to reduce the lattice parameters of the a2 phase, which makes the patterns peak of the a2 phase shift to the right (Fig. 2). The detailed lattice parameters are showed in Table 2. It is obvious the a1 phase and a2 phase are slightly square with c/a < 1 and c/a > 1 separately (Table 2). And three-step aging expands the distinction between lattice parameters of the two phases to make a1/a2 interface more clearer (Fig. 1 and Table 2).

To study the coupling effect of the different aging stages on precipitated phase, the reduced curve of reversible and irreversible are showed in Fig. 3 and Fig. 4. In Fig. 3 it is obvious all the reversible reduced curve of different annealing is similar to exponential increase and three-step aging clearly reduces the reversible loss

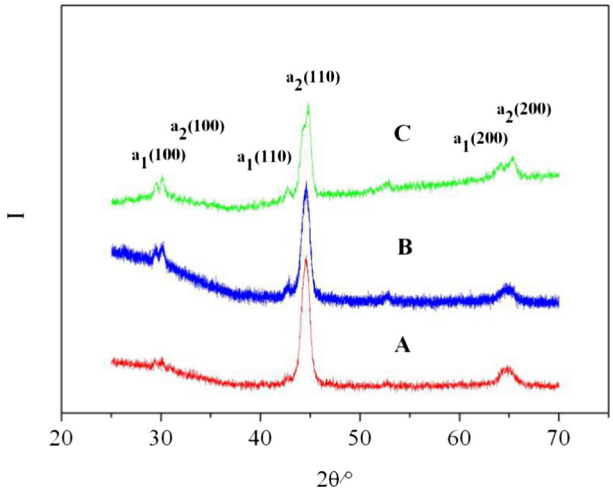

Fig. 2. The XRD patterns of Alnico 8 alloys.

Table 1
Phase compositions of the a1 and a2 phases in Alnico 8 alloys.

(at.%)	a1 phase			a2 phase		
	A	B	C	A	B	C
Fe	52.95	53.78	53.75	18.09	17.97	12.91
Co	34.78	38.27	38.57	32.49	33.10	33.19
Al	4.25	4.06	3.90	19.27	18.99	19.02
Ni	5.13	2.80	2.52	16.51	16.92	17.67
Ti	1.39	0.56	0.47	9.54	10.50	12.44
Cu	1.50	0.53	0.79	3.12	1.44	1.95
Nb	0	0	0	0.99	1.08	1.64

Table 2
Lattice parameters of the a1 and a2 phases in Alnico 8 alloys (Å).

Sample		A	B	C
a1 phase	c	2.872	2.873	2.873
	a	2.901	2.905	2.905
	c/a	0.990	0.989	0.989
a2 phase	c	2.872	2.873	2.873
	a	2.857	2.856	2.856
	c/a	1.005	1.005	1.006