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Magnetic properties of the Fe–Nd–Al alloys prepared by suction casting

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Abstract The magnetic properties of the $Fe_xNd_{90-x}Al_{10}$ (x = 30, 40, 43, 50, 53) alloys prepared by suction casting were investigated. The intrinsic coercivity ($_iH_c$) decreases significantly with the substitution of Fe for Nd. The $Fe_{53}Nd_{37}Al_{10}$ (x = 53) alloy shows soft magnetic behavior, which contains Fe-rich ($Fe_{75}Nd_{18}Al_7$) crystalline phase and Nd-rich ($Fe_{28}Nd_{59}Al_{13}$) amorphous phase. The Nd-rich amorphous phase in the $Fe_{53}Nd_{37}Al_{10}$ alloy exhibits soft magnetic behavior. However, the Nd-rich bulk amorphous alloy of the same composition prepared by suction casting shows hard magnetic behavior. The interesting phenomenon is discussed.

Introduction

During the last decade, much attention has been devoted to the development of the bulk amorphous materials. Bulk amorphous alloys have been obtained in Zr- [1], Ti- [2], Pd- [3], Mg- [4] and Ti- [5] based alloys. The bulk amorphous $Nd_{60}Fe_{30}Al_{10}$ [6] alloy has attracted much attention due to its high glass-forming ability and hard magnetic properties at room temperature, but the low saturation magnetization restricts its application. The aim of this work was to improve the magnetic properties of the alloys by replacing Nd with Fe. The effects of Fe content on the magnetic properties were discussed.

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Experimental

The button-like master alloys with compositions of $Fe_xNd_{90-x}Al_{10}$ (x = 30, 40, 43, 50, 53) were prepared by arc-melting Nd, Fe and Al with a purity of 99.9% in a titanium-gettered argon atmosphere. The ingots were remelted several times to ensure homogeneity. Specimens in the form of sheets (dimensions $1 \times 10 \times 80$ mm^3) were prepared by suction casting into a copper mold under argon atmosphere. Ribbons were obtained by melt spinning at a wheel speed of 25 m/s. The structure was characterized by D/max-2550 X-ray diffractometer (XRD) using CuKα radiation in the range of $20° \leq 2\theta \leq 90°$. The metallographic investigations were carried by a HITACHI S-570 scanning electron microscopy (SEM), equipped with an in situ energy dispersive spectroscopy (EDS). The magnetic properties were measured by a vibrating sample magnetometer (VSM) with a maximum applied field of 1.8T at room temperature.

Results and discussion

The results of the magnetic hysteresis measurements (Fig. 1) reveal that the Fe content has a large effect on the magnetic properties of the bulk $Fe_xNd_{90-x}Al_{10}$ (x = 30, 40, 43, 50, 53) alloys. The saturation magnetization (M_s) increases, while the coercivity of the alloys decreases gradually with the increasing Fe substitution. In other words, the magnetic properties of the alloys change from hard magnetic behavior to soft magnetic behavior.

To better understand and interpret the coercivity variation of the Fe–Nd–Al alloys, the $Fe_xNd_{90-x}Al_{10}$ (x = 30, 53) samples were analyzed by XRD (Fig. 2). No other obvious diffraction peaks expect Nd peaks are visible in the

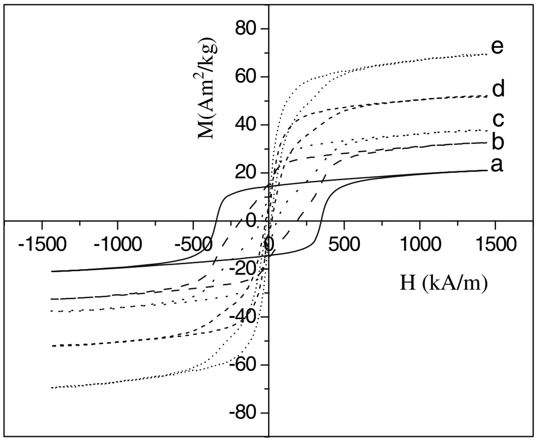

Fig. 1 Hysteresis loops of the $Fe_xNd_{90-x}Al_{10}$ alloys prepared by suction casting: (**a**) $x = 30$, (**b**) $x = 40$, (**c**) $x = 43$, (**d**) $x = 50$, (**e**) $x = 53$

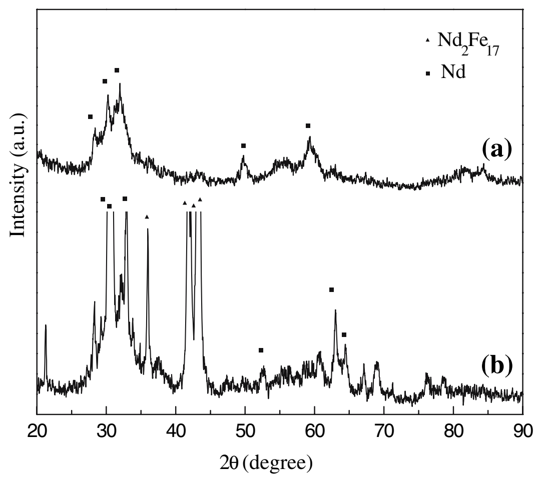

Fig. 2 XRD patterns of the $Fe_xNd_{90-x}Al_{10}$ alloys prepared by suction casting: (**a**) $x = 30$ and (**b**) $x = 53$

XRD pattern of the bulk $Fe_{30}Nd_{60}Al_{10}$ ($x = 30$) alloy (Fig. 2a), indicating that the alloy is mostly amorphous with a small amount of Nd phase. As shown in Fig. 2b, a broad halo with a maximum around $2\theta = 32°$ is found for the $Fe_{53}Nd_{37}Al_{10}$ ($x = 53$) alloy, which suggests the coexistence of amorphous and partially crystalline phases in the alloy. The crystalline phases can be identified as hexagonal Nd and Nd_2Fe_{17} phases.

Figure 3a and b are the second electron images of the $Fe_xNd_{90-x}Al_{10}$ ($x = 30, 53$) alloys made by suction casting. The local average elemental compositions were determined using EDS analysis and the calculated compositions are given in Table 1. Figure 3a shows that except for a little of dark granules (region A: Nd phase), no obvious compositional contrast can be seen in the bulk $Fe_{30}Nd_{60}Al_{10}$ ($x = 30$) alloy. It is composed of amorphous phase (marked B) and a small amount of Nd phase, which is consistent with the results of the XRD patterns. In Fig. 3b, the micrograph of the $x = 53$ alloy exhibits two different regions marked with A and B. The dark phases A are the cavities left over from etching of the crystalline phases and the grey zones (marked B) are the featureless amorphous matrix, because the amorphous state in general has a stronger resistance [7]. The region A is Fe-rich crystalline phase with the average composition of 75Fe–18Nd–7Al, embedded in the amorphous matrix. The amorphous region B has a composition around 28Fe–59Nd–13Al, which is close to $Fe_{30}Nd_{60}Al_{10}$ ($x = 30$) alloy. According to the M–H hysteresis loops shown in Fig. 1, the bulk $Fe_{53}Nd_{37}Al_{10}$ ($x = 53$) alloy shows soft magnetic behavior. Therefore, the Nd-rich amorphous phase in the $Fe_{53}Nd_{37}Al_{10}$ alloy doesn't exhibit hard magnetic properties. However, the hysteresis loop for the bulk amorphous $Fe_{30}Nd_{60}Al_{10}$ ($x = 30$) alloy (Fig. 1) has a typical shape of a hard magnet with an intrinsic coercivity ${}_iH_c = 353$ kA/m. This interesting phenomenon needs to be studied.

In order to study the magnetic properties of the Nd-rich amorphous phase ($Fe_{28}Nd_{59}Al_{13}$), the bulk specimen and ribbon of the $Fe_{28}Nd_{59}Al_{13}$ alloy were prepared by suction casting and melt spinning, respectively. The magnetic properties of the samples have been shown in Fig. 4, and they show a similar magnetization but differ in the coercivity values. The bulk specimen of the $Fe_{28}Nd_{59}Al_{13}$ alloy exhibits hard magnetic properties with a coercivity of 276 kA/m, while the ribbon shows soft magnetic properties. As mentioned above, the Nd-rich amorphous phase in the bulk $Fe_{53}Nd_{37}Al_{10}$ ($x = 53$) alloy shows soft magnetic properties. These results show that the magnetic properties of the Nd-rich amorphous phase in the bulk $Fe_{53}Nd_{37}Al_{10}$ alloy is similar with that of the Nd-rich ribbon.

According to the cluster model of the Nd–Fe magnetic system [8], it was demonstrated that the magnetic exchange coupling interaction among the magnetic clusters with large random anisotropy can cause the high coercivity of the magnetic system. The hard magnetic properties for the Nd-based bulk amorphous alloys suggest an inhomogeneous magnetic structure [9]: magnetic clusters of Fe and randomly oriented Nd spins, coupled ferromagnetically with each other. The hard magnetism in the bulk $Fe_{28}Nd_{59}Al_{13}$ alloy originates from more relaxed amorphous phase, while the soft magnetic properties of the ribbon [10] are attributed to the formation of the ideally homogeneous amorphous phase. The magnetic properties of the Nd-rich amorphous phase in the bulk $Fe_{53}Nd_{37}Al_{10}$ ($x = 53$) alloy are similar with that of the Nd-rich ribbon, indicating that they have nearly the same microstructure. The high degree of magnetic uniformity is presumed to be the reason for the soft magnetic properties of the Nd-rich amorphous phase in the bulk $Fe_{53}Nd_{37}Al_{10}$ alloy. In the bulk $Fe_{53}Nd_{37}Al_{10}$ alloy, Fe-rich ($Fe_{75}Nd_{18}Al_7$) crystalline phases precipitate

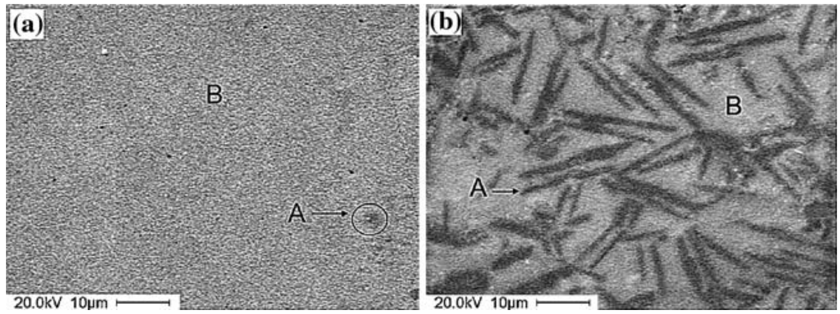

Fig. 3 SEM micrographs of the $Fe_xNd_{90-x}Al_{10}$ alloys prepared by suction casting: (**a**) $x = 30$ and (**b**) $x = 53$

Table 1 Chemical composition determined by EDS for the different phases observed in the $Fe_xNd_{90-x}Al_{10}$ alloys prepared by suction casting

x	Region	Fe (at%)	Nd (at%)	Al (at%)
30	A	2.0	98.0	0.0
	B	29.8	59.5	10.7
53	A	75.0	18.0	7.0
	B	28.0	59.0	13.0

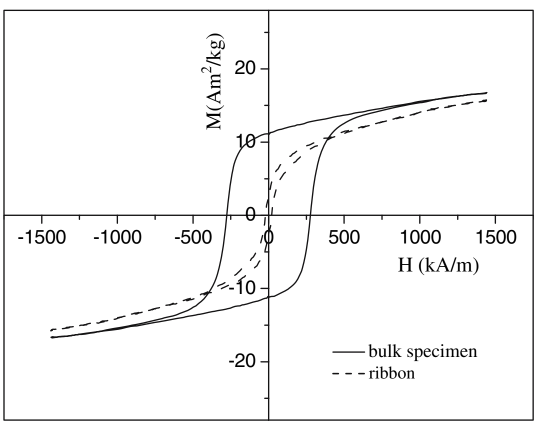

Fig. 4 Hysteresis loops of the bulk specimen and ribbon of the $Fe_{28}Nd_{59}Al_{13}$ alloy

in the matrix. The presence of the Fe-rich crystalline phase may result in the more homogeneous amorphous phase with a uniform distribution of the magnetic atoms. The number of the magnetic ordered clusters in the Nd-rich amorphous phase in the bulk $Fe_{53}Nd_{37}Al_{10}$ alloy has a smaller proportion, so it exhibits soft magnetic properties.

Conclusion

With the Fe substitution for Nd, the intrinsic coercivity of the $Fe_xNd_{90-x}Al_{10}$ alloys decreases significantly. The $Fe_{53}Nd_{37}Al_{10}$ ($x = 53$) alloy shows soft magnetic behavior, which contains Fe-rich ($Fe_{75}Nd_{18}Al_7$) crystalline phase and Nd-rich ($Fe_{28}Nd_{59}Al_{13}$) amorphous phase. The Nd-rich amorphous phase in the bulk $Fe_{53}Nd_{37}Al_{10}$ alloy exhibits soft magnetic properties, according to its ideally homogeneous amorphous structure.

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References

1. Schroeder V, Ritchie RO (2006) Acta Mater 54:1785
2. Louzguine DV, Inoue A (2000) J Mater Sci 35:4159 DOI: 10.1023/A:1004815112497
3. Saotome Y, Itoh K, Zhang T, Inoue A (2001) Scripta Mater 44:1541
4. Phyds NH (2004) Mater Sci Eng A 375–377:186
5. Zhang T, Inoue A (1998) Mater Trans JIM 39:1001
6. Inoue A, Zhang T, Zhang W, Takeuchi A (1996) Mater Trans JIM 37:99
7. Lai JKL, Shao YZ, Shek CH, Lin GM, Lan T (2002) J Magn Magn Mater 241:73
8. Siratori K, Nagayama K, Ino H (1990) J Magn Magn Mater 83:341
9. Alben R, Becker JJ, Chi MC (1978) J Appl Phys 49:1653
10. Wang XZ, Li Y, Ding J, Si L, Kong HZ (1999) J Alloys Comp 290:209