Materials Letters 217 (2018) 219–222

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/mlblue

Anisotropic bulk $Nd_2Fe_{14}B$/α-Fe nanohybrid magnets with an enhanced energy product

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ARTICLE INFO

Article history:
Received 10 November 2017
Received in revised form 3 January 2018
Accepted 17 January 2018

Keywords:
Magnets
Nanocomposites
Bulk
Anisotropy
Texture

ABSTRACT

Anisotropic bulk $Nd_2Fe_{14}B$/α-Fe nanohybrid magnets have been prepared by high-pressure thermal compression (HPTC) of the blends of 70 wt% Nd-lean $Nd_9Fe_{85.5}Cu_{1.5}B_4$ amorphous and 30 wt% Nd-rich $Nd_{13.6}Fe_{73.6}Ga_{0.6}Co_{6.6}B_{5.6}$ nanocrystalline alloys. The nanohybrid magnets have a high fraction ~24 wt% of α-Fe phase and exhibit a (00*l*) texture for $Nd_2Fe_{14}B$ nanocrystals in both Nd-lean and Nd-rich regions. The Nd-lean region contains α-Fe and $Nd_2Fe_{14}B$ nanograins with equivalent sizes of 19 nm and 27 nm and the Nd-rich region comprises $Nd_2Fe_{14}B$ phase having lath nanograins with 20–35 nm in thickness and 50–142 nm in length. This nanohybid magnet exhibits a maximum energy product of 23 MGOe and an enhanced thermal stability. The present work provides a candidate route to fabricate high-performance bulk magnets for practical applications.

1. Introduction

Nanocomposite magnets consisting of a fine mixture of nanoscale hard- and soft-magnetic phases have attracted tremendous attention for achieving high-performance magnets with less rare-earth metals [1–3]. For bulk nanocomposites, obtaining a crystallographic texture for hard-phase nanocrystals along their easy magnetization axis on the premise of a high fraction of soft phase (>20 wt%) with a small grain size (≤10 nm) and a uniform phase distribution is a great challenge [4–6]. Many techniques such as severe plastic deformation [7], hot deformation [8] and bottom-up approaches [9] etc. have been employed to achieve texture for hard magnetic nanocrystals and a substantial progress has been made [10,11], but it sill remains a challenge for Nd-Fe-B/α-Fe bulk nanocomposites with high α-Fe content ($V_{Fe} > 20\%$) [8]. For these nanocomposites, a hybridization technique, in which a R-lean R-Fe-B and a R-rich R-Fe-B alloy (R = Nd or Pr) are hybridized to form a hybrid magnet by hot pressing and subsequent die-upsetting is an effective way to induce textures for the $R_2Fe_{14}B$ phase [12]. Unfortunately, though a texture can be obtained in the host R-rich region, it is almost impossible to obtain texture in the R-lean region. Moreover, a rapid deterioration in texture and energy product with increasing the R-lean region, which leads to a low soft-phase content, and an obvious grain growth in both R-lean and R-rich regions are ineluctable [12–15]. Hence, preparing a bulk nanohybrid magnet with crystallographic texture of $R_2Fe_{14}B$ nanocrystals and fine grain size in both R-lean and R-rich regions is important to improve the energy product [4,5].

Here, we have prepared a bulk $Nd_2Fe_{14}B$/α-Fe nanohybrid magnet possessing a (00*l*) texture for $Nd_2Fe_{14}B$ nanocrystals in both Nd-lean and Nd-rich regions and a fine grain size at a high fraction of α-Fe phase ~ 24% by employing high-pressure thermal compression (HPTC) of the blends of 70 wt% Nd-lean amorphous and 30 wt% Nd-rich nanocrystalline alloys. This nanohybrid magnet exhibits a high energy product of 23 MGOe and a good thermal stability.

2. Material and methods

The Nd-rich $Nd_{13.6}Fe_{73.6}Ga_{0.6}Co_{6.6}B_{5.6}$ powders (<200 μm) were bought from Magnequench Inc. The Nd-lean $Nd_9Fe_{85.5}Cu_{1.5}B_4$ powders (<50 μm) were prepared by arc melting of pure metals and melt spinning at a wheel speed of 26 m/s and then crushing of the ribbons. The Nd-lean and Nd-rich powders were uniformly mixed with a weight ratio of 70:30. The mixtures were consolidated into circular columns with a relative density of 80% in argon atmosphere at room temperature. These bulk samples were put into a steel tube and the high-pressure thermal compression (HPTC) was carried out on the sample units in vacuum by employing Gleeble 3800 machine. The deformation temperature,

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https://doi.org/10.1016/j.matlet.2018.01.104
0167-577X/

deformation time, height reduction and maximum stress were $T = 650$ °C, $t = 45$ s, $\varepsilon = 79\%$, and $\sigma = 820$ MPa, respectively.

The microstructures of the magnets were characterized using X-ray diffractometer (XRD) with Co K_α radiation and transmission electron microscope (TEM). The weight fraction and grain size were determined from XRD patterns using the Rietveld refinement procedure with the HighScore Plus software. The room- and high-temperature magnetic properties were measured using a physical property measurement system and a vibrating sample magnetometer with a maximum magnetic field of 85 kOe and 20 kOe, respectively, and the demagnetization effect was corrected.

3. Results and discussion

Microstructure characterizations of the precursors show that the Nd-rich powders are crystalline with a grain size ~55 nm [Fig. 1(a) and inset] and the Nd-lean powders are completely amorphous (Fig. 1(b)). The deformed bulk magnet is composed of α-Fe and $Nd_2Fe_{14}B$ phases with a grain size of 22 nm and 29 nm, respectively, determined from XRD pattern (Fig. 1(c)). The weight fraction of the α-Fe phase was ~24% calculated from the XRD pattern. This demonstrates that the Nd-lean amorphous alloy transforms into α-Fe and $Nd_2Fe_{14}B$ phases during HPTC process.

XRD pattern measured on the face perpendicular to the pressure direction [Fig. 1(c)] shows an obvious (00l) texture of $Nd_2Fe_{14}B$ nanocrystals along the pressure direction, which is indicated by the enhanced intensity of (0 0 4), (1 0 5) and (0 0 8) peaks, where the intensity ratio $I_{(0\,0\,4)}/I_{(2\,2\,0)} = 368\%$ (Fig. 1(d)) is much larger than that 68% for isotropic $Nd_2Fe_{14}B$ crystals [see the standard powder diffraction file (ICSD): 067224]. This can be further confirmed by the XRD pattern measured on the face parallel to the pressure [Fig. 1(e)], in which reduced intensity of (0 0 4), (1 0 5) and (0 0 8) diffractions was obtained, where $I_{(0\,0\,4)}/I_{(2\,2\,0)} = 31\%$ (Fig. 1(f)) is lower than that 68% for isotropic $Nd_2Fe_{14}B$ crystals. These results demonstrate that a bulk nanohybrid magnet with a (00l) texture of $Nd_2Fe_{14}B$ phase has been synthesized by HPTC deformation.

TEM images show that the nanohybrid magnets are composed of two different microstructure regions. The major region comprises $Nd_2Fe_{14}B$ and α-Fe phases, which derive from the Nd-lean amorphous alloy (Figs. 2(a) and (b)). In this region, many lath-like nanocrystals (indicated by the black arrows in Fig. 2(a)) with a thickness of 15–30 nm and a length of 26–45 nm are determined to be $Nd_2Fe_{14}B$ nanocrystals (Fig. 2(b)). The equivalent sizes of α-Fe

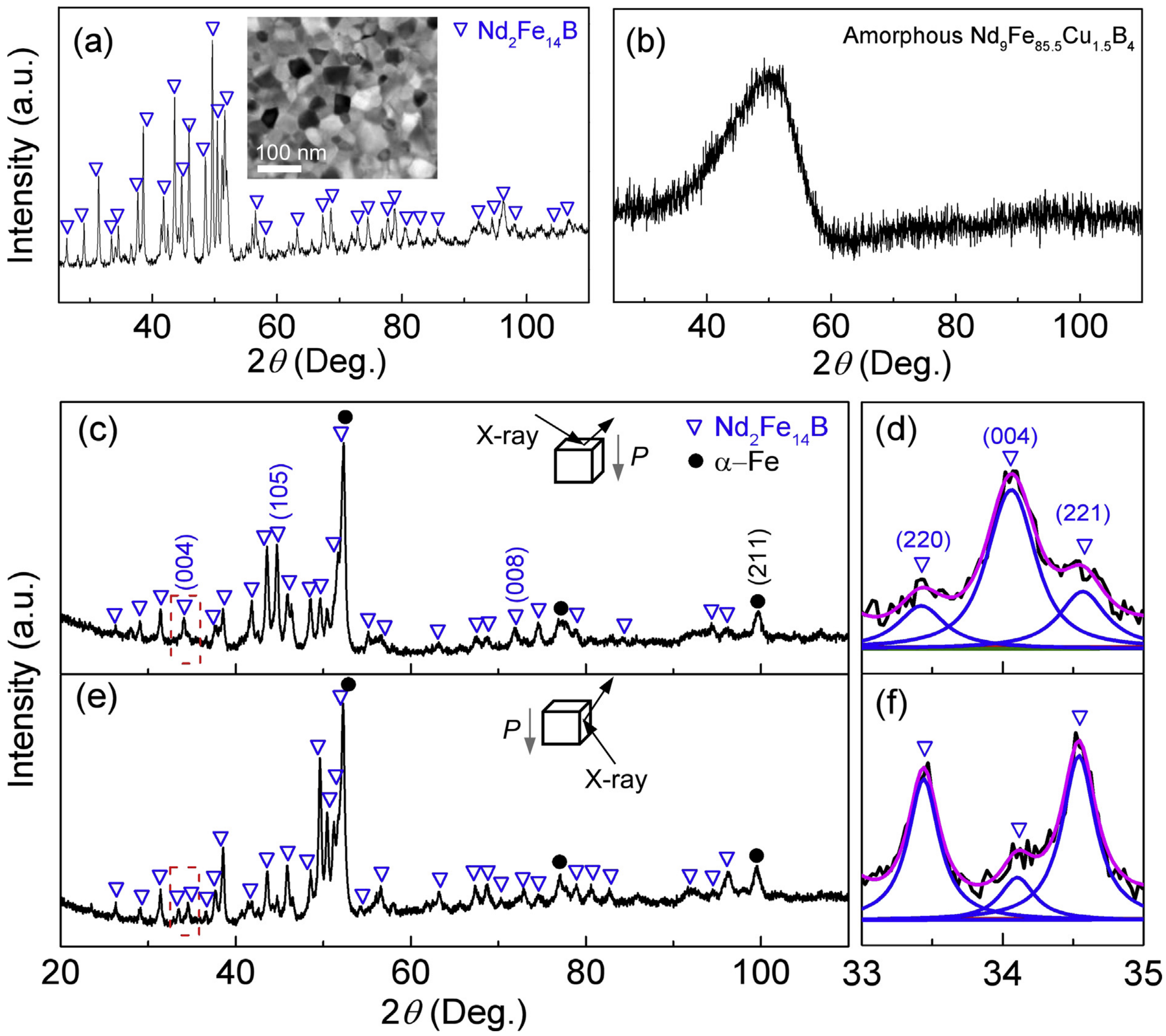

Fig. 1. XRD patterns of the precursors and deformed magnets. (a) Nd-rich powders, inset is the TEM image. (b) Nd-lean $Nd_9Fe_{85.5}Cu_{1.5}B_4$ powders. Deformed magnets measured on the face (c) perpendicular and (e) parallel to the pressure direction. (d, f) The zoomed view of the XRD patterns in plane (c) and (e).