Magnetic properties of YCo_5 (70%wt)+Y_2Co_{17} (30%wt) nanocomposite powders at low temperatures

J. T. Elizalde-Galindo, F. J. Rivera Gómez, J. A. Matutes-Aquino, C.E. Botez

Abstract

Nanostructured YCo_5 (70%wt)+Y_2Co_{17} (30%wt) composite powders were prepared by mechanical milling and subsequent annealing at 1073K for 1.5 min. The average grain size <D> of the YCo_5 and Y_2Co_{17} phases, obtained from XRD data, was 14 and 12 nm, respectively. The temperature dependence of the magnetic properties was studied by DC magnetization measurements at temperatures *T* ranging from 3 to 300 K. Hysteresis loops (H_{max} = 70 kOe) show that both the coercivity H_C and the squareness σ_r/σ_{max} are temperature dependent The coercivity increases from 12 kOe at room temperature to 18 kOe at T = 3K. The observed enhanced remanence (σ_r/σ_{max}>0.5) indicates that a strong exchange coupling is present at all temperatures used in this study. The maximum magnetization σ_{max} changes little with temperature and has a value of about 70% of the effective saturation magnetization of the title compound.

Keywords: Nanocrystalline material; Hard magnet; Nanostructured magnet; High coercivity; Permanent magnet.

Introduction

The discovery of spring exchange coupling between hard and soft magnetic grains was made in 1991 when it was shown that a mixture of $Nd_2Fe_{14}B$ and Fe_3B or α-Fe could in principle lead to energy products $(BH)_{max}$ higher than those achieved in single-phase magnets [1]. Since then many theoretical and experimental investigations

have been carried out on various exchange-coupled nanocomposite materials with the goal of enhancing their magnetic properties [2–6]. Particularly, the hexagonal $RECo_5$ system (RE=rare earth) has been mixed with α-Fe [7] and RE_2Co_{17} in order to improve the magnetization [8]. Besides the well-known temperature dependence of the $RECo_5$-phase anisotropy constant, the exchange coupling between the soft and hard phases itself might be affected by the temperature. Consequently, it is important to investigate the temperature dependence of the magnetic properties of nanocomposite powders [9].

In this work we present the low-T behavior of the magnetic properties of YCo_5 (70%wt)+Y_2Co_{17} (30%wt) nanocomposite powders prepared by mechanical milling and subsequent annealing at 1073K for 1.5 min, followed by quenching in water.

Experimental

The starting materials were Y and Co ingots with purity of 99.9% and 99.8%, respectively. Alloys with nominal composition YCo_5 and Y_2Co_{17} were prepared by arc melting pure elements in an Ar atmosphere. The ingots were turned and re-melted four times to ensure homogeneity. The as-cast ingots were then coarsely pulverized and mixed to obtain 3 g of powders containing 70%wt of YCo_5 and 30%wt of Y_2Co_{17}. Afterwards, the powders were mechanically milled for 240 min under Ar atmosphere using a SPEX 8000 ball mill with a ratio of powders to balls of 1:8. The as-milled amorphous powders were annealed at 1073K for 1.5 min in high-vacuum vycor tubes, followed by quenching in water. More details about the sample preparation can be found elsewhere [10]. Structural analysis was carried out from X-ray diffraction (XRD) patterns collected on a Siemens D5000 diffractometer with Cu-Kα radiation (λ=1.5406Å). The magnetic properties were measured on a Quantum Design physical

property measurement system (PPMS) with a maximum applied field, H_{max} = 70 kOe. Microstructural observations were carried out with a JEOL 2100 F transmission electron microscope (TEM).

Results and discussion

Fig. 1 shows the XRD pattern of YCo_5 (70%wt)+ Y_2Co_{17} (30%wt) nanocomposite powders obtained after 4 h of mechanical milling and a subsequent annealing at 1073K for 1.5 min followed by quenching in water. The hexagonal $CaCu_5$-type (PDF #17-078) and rhombohedral Th_2Zn_{17}-type (PDF #18-434) structures were used to index all the observed peaks of YCo_5 and Y_2Co_{17}, respectively. The full-width at half-maximum (FWHM) of the YCo_5 and Y_2Co_{17} peaks was used in the Scherrer equation [11] to independently estimate the average grain size <D> of the two phases that make the nanocomposite. Average grain sizes of 14 and 12nm were found for the YCo_5 and Y_2Co_{17} phases, respectively.

Fig. 2 shows the virgin magnetization curves and hysteresis loops of YCo_5 (70%wt)+Y_2Co_{17} (30%wt) nanocomposite powders annealed at 1073K for 1.5 min measured at two different temperatures, 295 and 3K. Both virgin curves indicate the same pinning-type magnetization mechanism as the one reported for single-phase YCo_5 nanostructured powders [12–14]. Magnetic saturation is not observed for the maximum applied field (H_{max}=70 - kOe) at any of the two temperatures, as expected for nanostructured magnetic materials [15]. In addition, the maximum magnetization σ_{max} values of the YCo_5 (70%wt)+Y_2Co_{17} (30%wt) nanocomposite at 3 and 295K are almost the same.

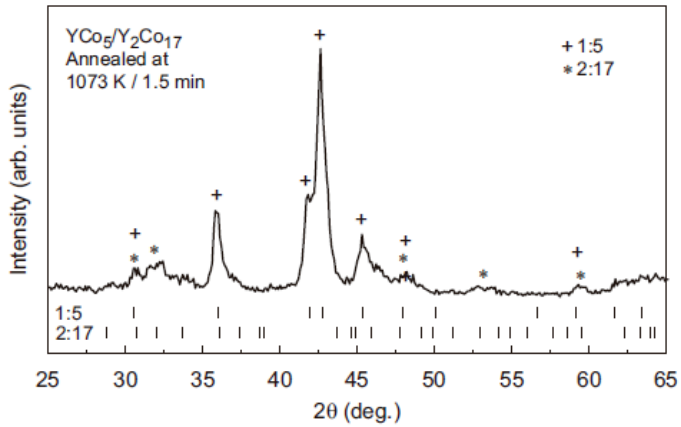

Fig. 1. X-ray diffraction pattern of (70%) YCo_5 + (30%) Y_2Co_{17} annealed in high vacuum at 1073 K for 1.5 min, followed by quenching in water.

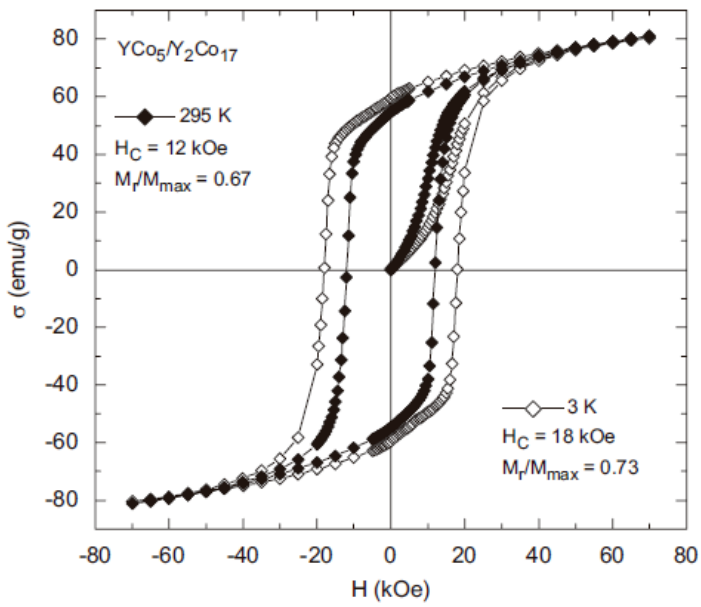

Fig. 2. Virgin magnetization curves and hysteresis loops of YCo_5 (70%) + Y_2Co_{17} (30%) nanocomposite powders annealed at 1073 K for 1.5 min measured at 3 and 295 K.

They are also very close to the roomtemperature value reported for the single-phase YCo_5 [13,14], which is most likely due to the similar saturation magnetizations of YCo_5 and Y_2Co_{17} [16]. The hysteresis loop measured at 295K reveals a high coercivity value, H_C = 12.0 kOe and an enhanced remanence, σ_r/σ_{max} = 0.67. The coercivity value

is consistent with the high anisotropy of the YCo_5 phase and the microstructure of this nanocomposite, where the grain size of both phases is in the 10–15 nm range [8,15,17]. The enhanced remanence is a fingerprint of strong exchange interactions between adjacent nanograins. The low-temperature hysteresis loop, T=3K, reveals a greater coercivity value, H_C=18 kOe, which is 50% more than its room temperature counterpart. This is most likely due to the increase of the YCo_5 anisotropy constant, K_1, at low temperatures [16]. At the same time, the increase of the squareness value at low T, σ_r/σ_{max} = 0.73, might be attributed to the reduction of the thermal effects at 3K.

Fig. 3 shows the temperature dependence of (a) the maximum magnetization σ_{max} and (b) the squareness σ_r/σ_{max} of YCo_5 (70%wt)+Y_2Co_{17} (30%wt) nanocomposite powders. The maximum magnetization curve reveals an almost temperature-independent behavior, as the σ_{max} values are within the 80–84 emu/g range. These σ_{max} values are around 70% of the effective saturation magnetization of the nanocomposite ($\sigma_{s,eff}$ = 120 emu/g). On the other hand, the squareness σ_r/σ_{max} increases as the temperature is lowered. As mentioned above, the σ_r/σ_{max} increase at lower temperatures can be attributed to the reduction of thermal effects.

A very strong temperature dependence of the coercivity was observed. This is shown in Fig. 4, which illustrates the coercivity HC behavior as a function of temperature T. The most remarkable feature of the H_C vs. T dependence is that a steeper decrease of the coercivity with increasing temperature occurs at higher temperatures (between 120 and 300 K) than in the 3–120K range. This behavior is in very good agreement with the known T-dependence of the YCo_5-phase anisotropy constant K_1 [16]. Also worthy of note are the high values of the coercivity at low

temperatures—at 3K, for example, H_C = 18 kOe, some 50% more than its room temperature counterpart.

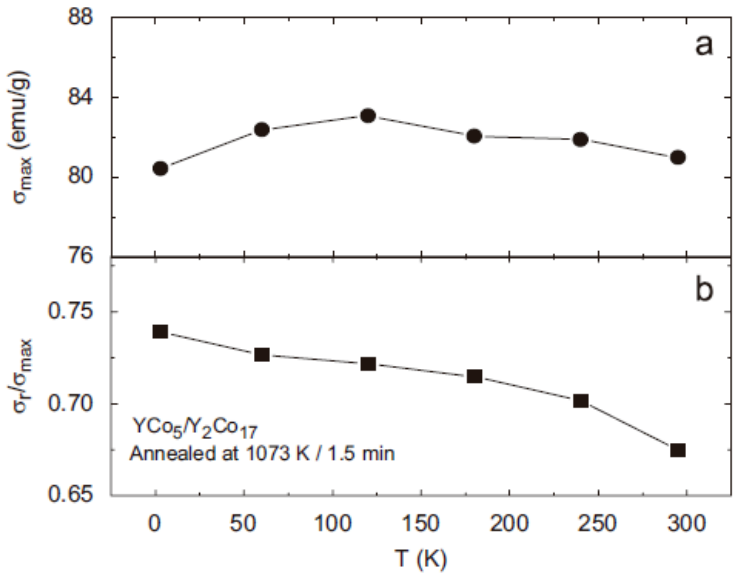

Fig. 3. (a) Maximum magnetization, σ_{max}, and (b) squareness, σ_r/σ_{max}, as a function of temperature T for (70%) YCo_5 + (30%) Y_2Co_{17} nanocomposite powders annealed at 1073 K for 1.5 min.

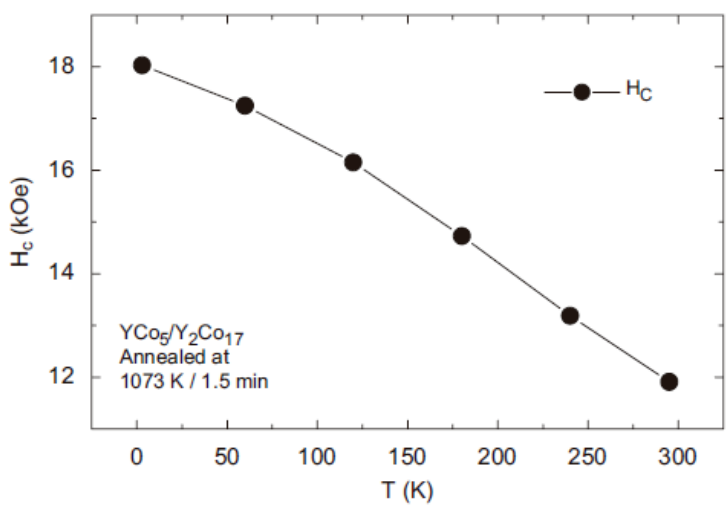

Fig. 4. Coercivity H_C as a function of temperature T for YCo_5 (70%wt) + Y_2Co_{17} (30%wt) nanocomposite powders annealed at 1073 K for 1.5 min.

Summary

Nanostructured YCo_5 (70%wt)+Y_2Co_{17} (30%wt) composite powders were prepared by mechanical milling and subsequent annealing at 1073K for 1.5 min. The average grain size <D> of the YCo_5 and Y_2Co_{17} phases was 14 and 12nm, respectively. Temperature-resolved (3–300 K) DC magnetization measurements revealed a strong temperature dependence of both the squareness, σ_r/σ_{max}, and the coercivity, H_C. High coercivity values were observed at all temperatures. The substantial increase of H_C with decreasing T is attributed to the temperature dependence of the anisotropy constant of the YCo_5 phase. The enhanced remanence (σ_r/σ_{max}>0.5) observed throughout the entire temperature range indicates a strong exchange coupling between the hard and soft phases. The maximum magnetization σmax exhibits a very weak temperature dependence. Its value is about 70% of the effective saturation magnetization of the title compound. The observed magnetic properties of the YCo_5 (70%wt)+ Y_2Co_{17} (30%wt) nanocomposite stem from the intrinsic properties of the two phases, as well as from the average grain sizes that favor an effective exchange coupling.

Acknowledgments

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