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A facile way to realize exchange coupling interaction in hard/soft magnetic composites

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ABSTRACT

$SrFe_{12}O_{19}/CoFe_2O_4$ and $SrFe_{12}O_{19}$/Fe–B hard/soft magnetic composites were obtained by using powders synthesized via a hydrothermal and a molten salt method, respectively. The exchange coupling interaction was found to exist in the composites after a facile grinding according to the results of magnetic hysteresis loops and irreversible sloping recoil loops. It can be found that different grinding time affects their magnetic properties slightly. Our study proves that the conditions of realizing exchange coupling interaction may not be so stringent.

1. Introduction

The exchange coupling interaction (ECI) between hard- and soft-magnetic nanoscaled grains is expected to enhance the maximum energy product $(BH)_{max}$ of composite hard-magnetic materials [1–8]. As is known, it was proposed that the exchange length (L_{ex}) can be used to characterize the effective range of ECI [9]. Here, L_{ex} can be quantified as:

$$L_{ex} = \sqrt{A/K_1} \quad (1)$$

Where A and K_1 denote the exchange stiffness and the mean amplitude of the random anisotropy constant, respectively. For examples, the calculated L_{ex} for Nd–Fe–B and $SrFe_{12}O_{19}$ (SrM) magnets is about 1.34 and 4.28 nm, respectively, according to the data given in Refs. [10,11]. The L_{ex} is so small that preparing nanoscale multilayers [4,5], core-shell architectures [6,8] and annealed compact composites [3,12] may be the optimal choices to realize ECI.

As reported by Kronmüller et al. [10] and Schrefl et al. [13], the soft-magnetic grains with diameters of twice the domain wall width (δ_B) of the hard-magnetic phase are required to realize fine ECI together with high saturation magnetization (M_s) and high coercivity (H_c) in nanocrystalline composites. Normally, for annealed compact bulk composites, it is difficult to control the grain growth under high temperatures, suggesting the difficulty to realize a fine ECI together with high M_s and high H_c simultaneously.

Hexagonal SrM ferrite is widely investigated due to its large uniaxial magnetocrystalline anisotropy, high cost performance and fine chemical stability [3,14]. In order to enhance its magnetic properties, the ECI in SrM ferrite has aroused much attention [3,15–17]. Previously, we have systematically studied the ECI in sintered SrM/$(Ni,Zn)Fe_2O_4$ and SrM/$CoFe_2O_4$ (CFO) systems [3,7], in which the ECI was confirmed to exist firmly. Recently, it is unexpected and interesting to find that the ECI and the single-phase magnetic behavior could also be found to exist in mixed powders of SrM and another “soft” phase only through a simple grinding by hand for tens of minutes.

2. Experimental

In this study, single-phase SrM and CFO powders were synthesized via a hydrothermal method, and the Fe–B powder was synthesized via a molten salt method. For SrM and CFO, first, the nitrates used to synthesize were dissolved in deionized water and

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coprecipitated by NaOH; then, the precipitates and aqueous solution were hydrothermally reacted in a Teflon liner for 220 °C × 5 h and 200 °C × 8 h to obtain SrM and CFO powders, respectively; finally, the obtained powders were washed by diluted hydrochloric acid (22 wt%) to ensure their phase purity. For Fe–B, a typical synthesis procedure can be described as follows: First, Fe and amorphous B powders were mixed by hand in an agate mortar, and quantitative NaCl/KCl with a mole ratio of 1:1 was added to Fe/B mixture and kept mixing for 30 min; second, the mixed Fe/B/NaCl/KCl powders were sintered at 1000 °C for 1 h; finally, after cooling down to room temperature (RT) naturally, the sintered powders were immersed in 80 °C distilled water to wash out NaCl/KCl and possible impurity B_2O_3. All the more detailed synthesis procedures can be found in Refs. [3,7]. Then the SrM powders were ground by hand in agate mortar with CFO or Fe–B powders with the mass ratio of 1:1 for 10, 20 and 30 min, respectively, to prepare the composite specimens used in this study. Then, a vibrating sample magnetometer (VSM, Quantum Design VersaLab) was used to measure the RT magnetic hysteresis loops and recoil curves of powder specimens under a maximum magnetic field of 1592 kA/m (20,000 Oe) and 1194 kA/m (15,000 Oe), respectively.

The phase composition of SrM, CFO and Fe–B have been identified and discussed systematically in Refs. [7,18] by using X-ray diffractometry (XRD), Fourier transformed infrared spectrometry (FTIR) and transmission electron microscopy (TEM/HRTEM). In this study, we are focused on the ECI and some magnetic properties of grinding composites.

3. Results and discussion

As is well-known, the magnetism of SrM, CFO and Fe–B is also crucial for the magnetic properties of resultant composites. In order to ensure the single-phase magnetic behavior of composites, the magnetic hysteresis loops of SrM, CFO and Fe–B should also exhibit a single-phase magnetic behavior. Fig. 1 gives the RT magnetic hysteresis loops of as-synthesized SrM, CFO and Fe–B specimens. In order to illustrate their single-phase magnetic behavior more clearly, we only give the magnetic hysteresis loops from −800 kA to 800 kA/m. The magnetic properties are listed in Table 1. Seen from Fig. 1, all the magnetic hysteresis loops are smooth, suggesting a typical single-phase magnetic behavior. Among the three powder specimens, the SrM exhibits the lowest M_s but the highest H_c, while the Fe–B exhibits the highest M_s but the lowest H_c. Therefore, the ECI between SrM and Fe–B or CFO is expected to enhance the magnetic properties of SrM.

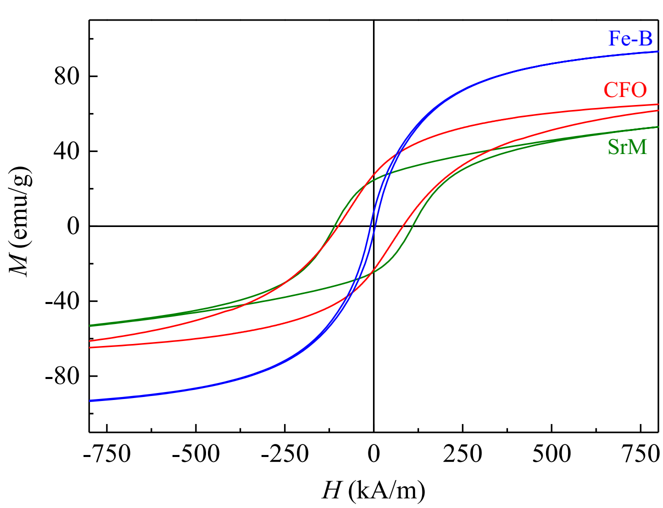

Fig. 1. RT magnetic hysteresis loops of as-synthesized SrM, CFO and Fe–B specimens.

Table 1
Magnetic properties of as-synthesized powders.

Specimen	M_s (emu/g)	H_c (kA/m)
SrM	57.2	110.0
Fe–B	99.0	6.6
CFO	69.8	90.7

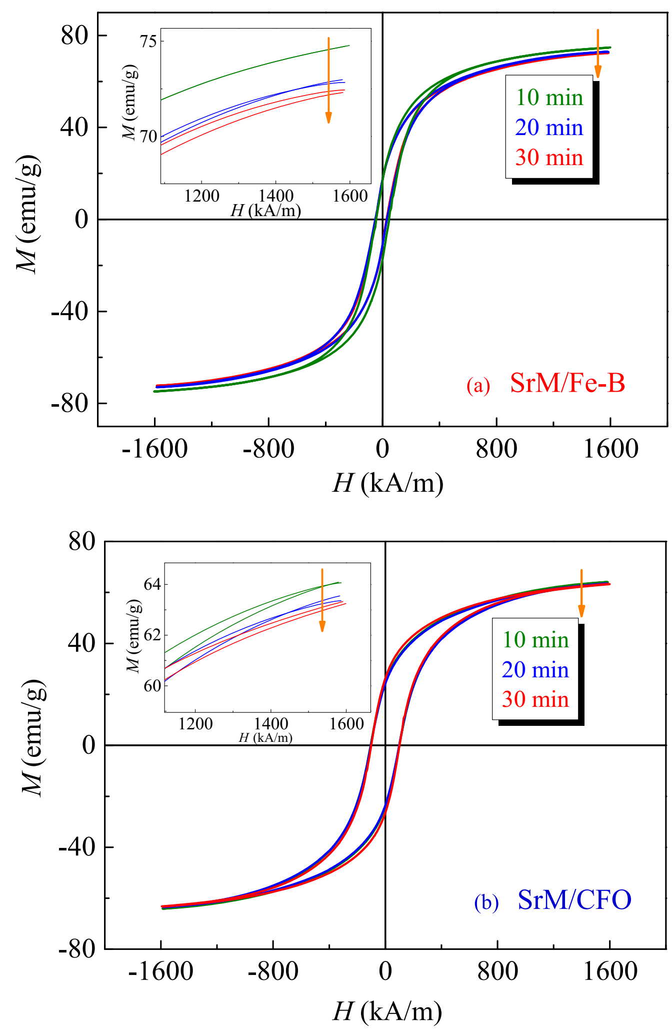

Fig. 2. RT magnetic hysteresis loops of the ground composite SrM/Fe–B (a) and SrM/CFO (b) powders with different ground time but the same mass ratio (1:1).

For the ground composite powders SrM/Fe–B and SrM/CFO with a mass ratio of 1:1, their RT magnetic hysteresis loops are given in Fig. 2. For comparison, the magnetic properties of sintered SrM/Fe–B and SrM/CFO with a mass ratio of 1:1 are given in Table 2. Fig. 2 also presents the smooth magnetic hysteresis loops, suggesting a typical single-phase behavior. In fact, in these not sintered systems, just as described above, we had thought that the

Table 2
Magnetic properties of sintered SrM/Fe–B and SrM/CFO composite powders with a mass ratio of 1:1.

Specimens	Sintered at	M_s (emu/g)	H_c (kA/m)	Ref.
SrM/CFO	700 °C × 2 h	66.9	145.9	7
SrM/Fe–B	500 °C × 2 h	61.1	49.1	18