Remanence enhancement in composite magnets of micrometre Sm-Fe-N grains and nanometre Fe particles

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Remanence enhancement in composite magnets of micrometre Sm–Fe–N grains and nanometre Fe particles

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Abstract. We report the hard magnetic behaviour of composite magnets prepared by directly mixing micrometre Sm–Fe–N grains with micrometre iron particles and nanometre iron particles, respectively. Remanence enhancement has been found in composite magnets prepared by directly mixing the micrometre Sm–Fe–N grains with nanometre iron particles. Our experimental results indicate that for remanence enhancement to occur in composite materials the size of the soft magnetic phase involved must be nanometre, while the particle size of the hard magnetic phase involved need not be limited to nanometre scales.

Recently, two-phase nanocrystalline materials consisting of a hard magnetic rare-earth-based intermetallic and an iron-based soft magnetic phase have attracted much attention [1–10]. The effect of remanence enhancement found in both melt-spun and mechanically alloyed materials is based on the principle that the hard and soft magnetic phases involved emerge from a common metastable matrix phase, such as the glass-like state, from which the very fine grains may be obtained after subsequent heat treatment. Strong magnetic exchange coupling between soft and hard phases occurs [4]. In a previous paper [12], the effect of remanence enhancement has been reported in composite magnets prepared by directly mixing iron nanoparticles and HDDR NdDy–FeCo–B powders and subsequently ball milling for 5 min. This result indicates that remanence enhancement can occur in materials consisting of soft and hard magnetic phases that have been produced separately. In the present work we report the hard magnetic behaviour of composite magnets prepared by directly mixing the micrometre Sm–Fe–N grains (about 1 μm) with micrometre iron particles (about 1 μm) and nanometre iron particles (about 20–50 nm), respectively, and then bonding with epoxy resin into the shape of a cylinder (diameter, 3 mm; length, 6 mm). The weight ratio of magnetic powders to epoxy resin is about 92 to 8. The remanence and coercivity are measured using a pulsed high magnetic field. The remanence enhancement has been found in composite magnets prepared by directly mixing the micrometre Sm–Fe–N grains (about 1 μm) with nanometre iron particles (about 20–50 nm). Our experimental results indicate that for remanence enhancement to occur in composite materials the size of the soft magnetic phase involved must be nanometre, while the particles size of the hard magnetic phase involved need not be limited to nanometre scales.

Figure 1 shows the dependence of the remanence on the atomic composition, x at room temperature for isotropic composite magnets $(\text{Sm–Fe–N})_{100-x}\text{Fe}_x$ prepared by directly mixing micrometre Sm–Fe–N grains with nanometre iron particles and micrometre iron particles, respectively. In composite magnets consisting of micrometre Sm–Fe–N and

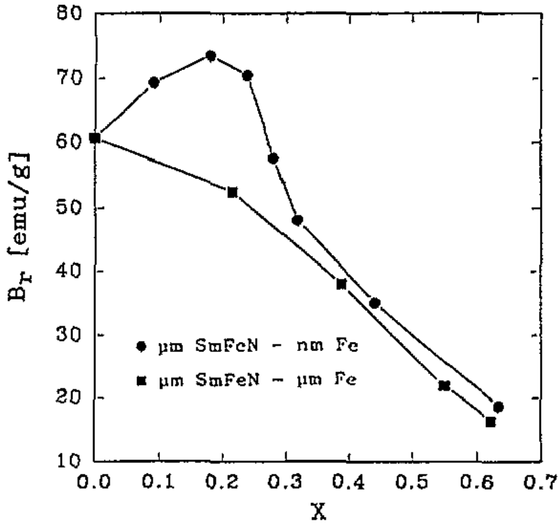

Figure 1. Dependence of the remanence on x for isotropic composite magnets (Sm–Fe–N)$_{100-x}$Fe$_x$ prepared by directly mixing micrometre Sm–Fe–N grains with nanometre Fe particles and micrometre Fe particles, respectively.

nanometre Fe particles, the remanence increases from 60.7 emu g^{-1} at $x = 0$ to 73.5 emu g^{-1} at $x = 83.6$, which clearly indicates that remanence enhancement occurs. With further increase in the Fe component, there is a decrease in remanence. However, in composite magnets consisting of micrometre Sm–Fe–N and micrometre Fe particles, the remanence decreases monotonically with increasing content of iron particles. The remanence is 57.5 emu g^{-1} at $x = 54.0$, which is smaller than that at $x = 0$. No remanence enhancement has been observed in these materials. The experimental result that the nanometre size of soft magnetic particles is the essential condition for the occurrence of remanence enhancement in composite materials agrees very well with the conclusions of theoretical analysis [4–8]. Our experimental results also indicate that the particle size of the hard magnetic phase involved need not be limited to nanometre. As we know, the exchange coupling of two grains is mainly controlled by the exchange interaction between nearest-neighbour spins on the surfaces of two grains. If a nanometre iron particle is very close to a grain of the hard magnetic phase, exchange interaction may occur and contribute to the remanence enhancement of the composite magnet observed here, which is similar to the previous case of composite materials of the iron nanoparticles and HDDR NdDy–FeCo–B powders [12]. The magnetostatic interaction may also play a role in the coupling of a soft grain and a hard grain and thus contribute to the remanence enhancement observed [9–11]. Our present experimental results confirm that remanence enhancement can occur not only in materials in which the soft and hard phases emerge from a common glass-like state after heat treatment, but also in materials consisting of soft and hard magnetic phases involved that have been produced separately. However, the extent of remanence enhancement occurring in the two kinds of material may be different. From the viewpoint of crystallographic coherence and magnetic exchange coupling or magnetostatic coupling, it seems that the extent of the remanence enhancement is larger when the soft and hard phases emerge from a common metastable matrix phase as pointed out by Kneller and Hawig [4].

Figure 2 shows the dependence of the coercivity on the atomic composition, x at

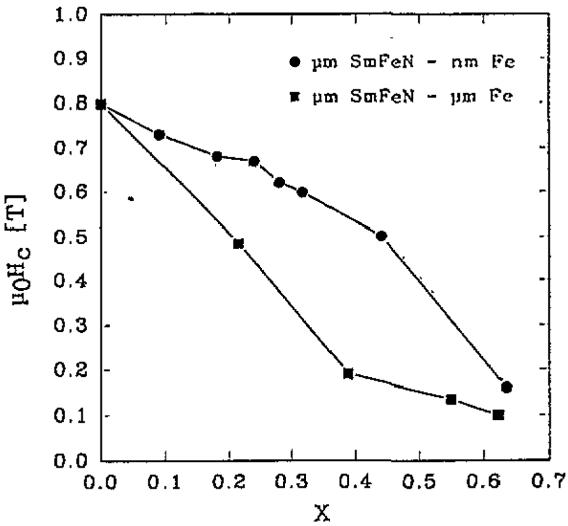

Figure 2. Dependence of the coercivity on x for isotropic composite magnets $(Sm\text{–}Fe\text{–}N)_{100-x}Fe_x$ prepared by directly mixing micrometre Sm–Fe–N grains with nanometre Fe particles and micrometre Fe particles, respectively.

room temperature for the isotropic composite magnets $(Sm\text{–}Fe\text{–}N)_{100-x}Fe_x$ prepared by directly mixing micrometre Sm–Fe–N grains with nanometre iron particles and micrometre iron particles, respectively. In both kinds of composite magnet, the coercivity decreases monotonically with increasing Fe content. Nevertheless, magnetic coupling between the hard and soft phases not only results in a large remanence but also preserves a relatively high coercivity for $x < 86$. With further increasing Fe content in composite magnets, the magnetic coupling hardening becomes weak, and both remanence and coercivity decrease sharply. It is evident that the coercivity in composite magnets consisting of micrometre Sm–Fe–N and nanometre Fe is larger than that in composite magnets consisting of micrometre Sm–Fe–N and micrometre Fe. The self-demagnetizing field causes the hard magnetic properties to deteriorate due to the magnetic reversal and the formation of the incoherent structure within the micrometre Fe particle.

In conclusion, remanence enhancement has been found in composite magnets prepared by directly mixing micrometre Sm–Fe–N grains with nanometre iron particles. Our experimental results indicate that for remanence enhancement to occur in composite materials the size of the soft magnetic phase involved must be nanometre, while the particle size of the hard magnetic phase involved need not be limited to nanometre size.

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