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# Ferromagnetic Resonance Linewidth in Powders Consisting of Core–Shell Particles

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**Abstract**—The dependence of the ferromagnetic resonance linewidth on the thickness of nonmagnetic shells in powders consisting of ferromagnetic core–nonferromagnetic shell composite particles is investigated. It is found that an increase in shell thickness reduces the ferromagnetic resonance linewidth by several times, down to values comparable to those for coatings with compositions similar to that of the particle's core. The observed effect is assumed to result from suppression of the inhomogeneity of demagnetizing fields in a powder consisting of magnetic particles.

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## INTRODUCTION

The ferromagnetic resonance (FMR) linewidth for the powders consisting of 3*d* metal particles can be as high as several kilooersteds. For cubic phases in Fe-, Co-, and Ni-based alloys, this is not only much larger than the linewidth for single crystals, but also exceeds by many times the expected linewidth for polycrystalline samples [1]. Dipole–dipole interaction between neighboring particles does substantially affect both the magnetization vector orientation and the work of magnetization of an individual particle. In addition, dipole–dipole interaction leads to particle agglomeration with the formation of clusters with different shapes and sizes. The effective magnetic field acting on a powder particle is largely determined by the demagnetizing field, which depends on the size and shape of a particle cluster and the position the particles inside it. The inhomogeneity of the local effective fields eventually leads to very great FMR linewidths. When measuring the resonance absorption of electromagnetic waves in a powder, this inhomogeneity is hard to control, which sharply reduces the utility of FMR in studying magnetic powders. The structure of the mutual arrangement of particles in magnetic powders is poorly understood and depends on many factors, including the prehistory of different effects on a powder. It is therefore nearly impossible to theoretically consider such inhomogeneities in FMR linewidth precisely. In this work, we isolated magnetic particles of a powder using a nonmagnetic shell to weaken the dipole–dipole interaction between them to the level at which the influence of the effective field inhomogeneity in a particle ensemble is weaker than that of the inhomogeneity inside particles. The aim of this work was to establish the influence a particle shell has on FMR linewidth.

## EXPERIMENTAL

We investigated two particle coating techniques: the chemical deposition of a nonmagnetic shell on particles of a magnetic powder poured into a solution (series *A*), and chemical deposition on particles of a magnetic powder prepared in a solution according to the homogeneous nucleation scenario (series *B*). The formation of clusters of individual particles can fundamentally differ for the different sample coating techniques we used.

To prepare samples of series *A*, we used a finished Co–P powder with a known mass, which was ground in a mortar, mixed in a solution to form a homogeneous suspension, and then coated with a copper shell from a solution containing $CuSO_4$ (12 g/L), trilon B (25 g/L), formalin (25 mL/L), and NaOH (pH 12) via chemical deposition. Knowing the weight of the powder and the mass of blue copper in the solution, we calculated the ratio between the two phases.

To prepare samples of series *B*, we first synthesized powder (Co(P), CoNi(P), CoFe(P), or Fe(P)) from a solution containing $NiSO_4$ (5 g/L), $CoSO_4$ (25 g/L by the example of CoNi(P) particles), $Na_3C_6H_5O_7$ (40 g/L), and $NaH_2PO_2$ (200 g/L). When the reaction

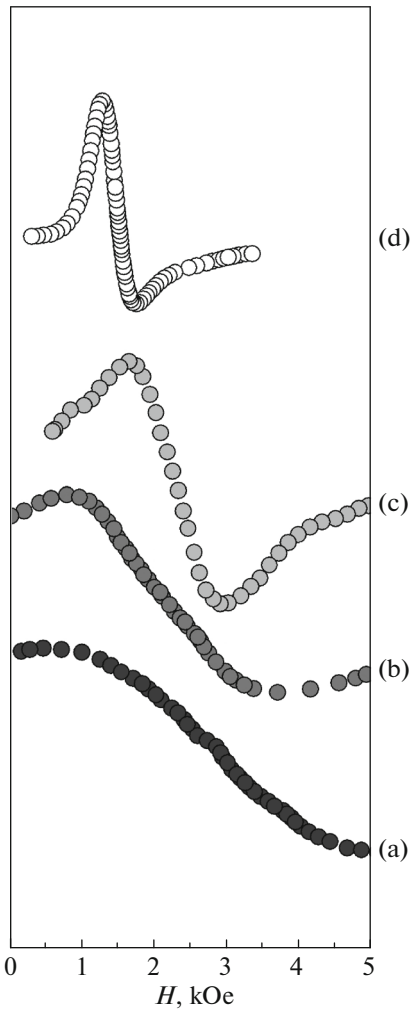


**Fig. 1.** Variation in FMR linewidth using the example of Co–Ni–P powders with nonmagnetic Ni(P) shell weight fractions of (a) 0, (b) 46, (c) 68, and (d) 93%.

was complete, the solution was left to settle for several minutes to remove coarse particles. A second solution containing $NiSO_4$ (30 g/L), $(NH_4)_2SO_4$ (30 g/L), and $NaH_2PO_2$ (200 g/L) was then added to form nonmagnetic Ni(P) shell particles dispersed in the solution on the surface. The obtained Ni(P) coating was amorphous, contained about 20 at % of phosphorous, and was nonmagnetic [2, 3]. To prepare powders with different shell thicknesses, we changed the volume ratio between the two solutions. The phase ratio was calculated from the saturation magnetization determined by measurements made with a vibrating sample magnetometer. The obtained samples had different weight fractions of the nonmagnetic Ni(P) shell.

The morphology, chemical composition, phase composition, and structure of the investigated powders used as our magnetic core were described in [4]. Particles of the Co(P), CoNi(P), CoFe(P), and Fe(P) powders were spherical and characterized by a lognormal size distribution with an average value of 1 μm and a deviation of 0.53 [4]. The morphology and chemical composition of the powders consisting of core–shell particles were studied on a S5500 Hitachi scanning electron microscope and a TM 3000 energy dispersive spectrometer. Ferromagnetic resonance was measured at a frequency of 9.2 GHz, using a standard EPA-2M FMR spectrometer. The investigated powder was poured into a cylindrical cuvette and placed in a resonator. The magnetization measurements needed for quantitative control of the nonmagnetic phase weight fraction were performed on a vibrating sample magnetometer at room temperature.

## RESULTS AND DISCUSSION

Our scanning electron microscopy investigations of several samples showed that the investigated particles did indeed have a core–shell structure with core and shell chemical compositions corresponding to technical standards. However, since a core's coating can be inhomogeneous over its thickness, we talk below about the weight fraction of the nonmagnetic phase. The estimated volume fraction of a nonmagnetic shell (or nonmagnetic phase) was consistent with the one obtained using the vibrating sample magnetometer (the saturation magnetization).

Our study of the FMR spectra of the Co(P), CoNi(P), CoFe(P), and Fe(P) powders with different thicknesses of the nonmagnetic shell showed that as nonmagnetic shell thickness (the weight fraction of the nonmagnetic phase) grew, the resonance curve narrowed strongly (the linewidth was reduced many times) and the resonance shifted toward weaker fields (Fig. 1). For the powders with the shell deposited immediately after the formation of a magnetic core from the same solution (series *B*), the linewidth shrank monotonically with as the thickness of the nonmagnetic coating grew (Fig. 2). We observed the threshold dependence for particles prepared by coating with the magnetic powder mixed in the solution: the linewidth remained invariable to a certain mass fraction of the nonmagnetic shell (~60%) and then narrowed sharply.

The observed FMR line narrowing as the fraction of the nonmagnetic phase grew can be explained by the switching off of dipole–dipole interaction between individual magnetic powder particles upon an increase in the distance between them. As this distance grows, the effective field acting on a particle weakens and the inhomogeneity of the local fields on each particle is reduced. In the limit of absolutely no inhomogeneity associated with interparticle coupling, the linewidth should be determined by only the structural inhomogeneities of the material of an individual particle. This limit situation is observed in, e.g., the FMRs of polycrystalline Co(P), CoNi(P), CoFe(P), and Fe(P) coatings; for comparison, we therefore prepared coatings with compositions analogous to those of magnetic particles via chemical deposition. In the resulting dia-

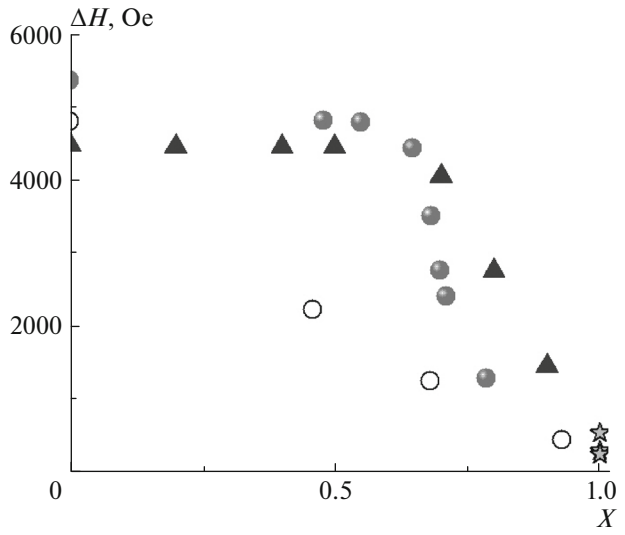


**Fig. 2.** FMR linewidth in powders consisting of composite particles versus weight fraction $x$ of the nonmagnetic phase. White dots represent CoNiP@NiP; black dots, CoFeP@NiP; triangles, CoP@Cu. The stars mark the reference linewidths measured on the coatings with compositions analogous to those of magnetic particles.

gram, the FMR linewidth of the coatings is positioned at the point with the coordinate corresponding to a 100% nonmagnetic phase fraction ($x$). We should emphasize that the diagram is valid only for core–shell particles, and the FMR linewidth of coatings is given for the proposed interpretation as a reference linewidth with no contribution from the dipole field inhomogeneity, which is achieved for particles in the limit of the 100% nonmagnetic phase fraction.

The film linewidth agrees fairly well with the estimate obtained by extrapolating the experimental data on the powder to the 100% nonmagnetic phase. This means that coating particles with nonmagnetic shells can be used to study the FMR linewidth of a material composed of powder particles. Different behaviors of the linewidth for series *A* and *B* could be due to different mechanisms of cluster formation in these two cases or to, e.g., different degrees of homogeneity of the nonmagnetic coating of particles. Coating with the amorphous Ni(P) solution (series *B*) in particular is usually homogeneous over the thickness. The linewidth behavior, like the one illustrated in Fig. 2 for series *A*, resembles the occurrence of a percolation point where the coupling between magnetic clusters is interrupted upon transitioning through the critical concentration of the nonmagnetic phase.

## CONCLUSIONS

We investigated the dependence of the ferromagnetic resonance linewidth in powders of ferromagnetic core–nonferromagnetic shell composite particles with different thicknesses of the latter. Using chemical reduction from metal salts, we prepared powders with Co(P), CoNi(P), CoFe(P), and Fe(P) cores in the crystalline and amorphous states with sizes ranging from tenths of a micron to several microns. The deposited nonmagnetic shells were formed from amorphous Ni(P) alloy and Cu (for Co(P) particles). An increase in shell thickness reduced the ferromagnetic resonance linewidth many times, to values comparable to the linewidth for coatings with compositions analogous to that of a particle core. The observed effect was attributed to the suppression of demagnetizing field inhomogeneity in a powder consisting of magnetic particles.

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