MICROMAGNETISM AND THE MICROSTRUCTURE OF MODERN MAGNETIC MATERIALS

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1. Introduction

During the last decades a large number of outstanding magnetic materials have been developed covering a wide range of coercivities and permeabilities. The development of high-tech magnetic materials is based on the tailoring of suitable microstructures and the development of alloys and intermetallic compounds with extreme values of intrinsic magnetic properties [1, 2, 3, 4]. In most types of magnetic materials a large spontaneous magnetization is required. As shown in Fig. 1 the development of magnetic materials requires besides the theoretical background the combination of three different fields of research: i) Materials synthesis and analysis of alloys. ii) Microstructural characterization of alloys. iii) Magnetic properties and microstructure relations.

There are at least two additional fields which have influenced the development of magnetic materials: Alloys and intermetallic compounds of rare earth metals and transition metals have opened a wide field of outstanding ferromagnetic alloys [5, 6, 7, 8, 9, 10]. New preparation techniques as liquid phase sintering, melt-spinning, mechanical alloying, multilayer sputtering and molecular beam epitaxy allow to develop artificial microstructures.

It is very surprising that the characteristic properties of the hysteresis loops may be related to only a few intrinsic properties: Spontaneous polarization, \( J_S = \mu_0 M_S \) (\( M_S \) = spontaneous magnetization), magnetic crystalline anisotropy constants, \( K_i \), magnetostriction, \( \lambda_S \), and Curie temperature \( T_C \). The main properties of the hysteresis loop are the coercive field, \( H_C \), the remanence, \( J_R = \mu_0 M_R \), and the Rayleigh law of the initial magnetization curve

\[
M(H) = \chi_0 H + \alpha_R H^2 ,
\]

(1)

with the initial susceptibility, $\chi_0$, and the Rayleigh constant, $\alpha_R$. $\chi_0$ and $H_C$ are among of the most exciting properties because their values may vary over 6 orders of magnitude. E.g., the coercive field, $H_C$, may vary from a fracture of an A/m up to $7 \cdot 10^6$ A/m. This tremendous variety of a physical property is due to the variation of intrinsic properties but also to the role of the microstructure. Considering the dependence of $H_C$ on the anisotropy constant, $K_1$, the general trend is shown in Fig. 2. Comparing different groups of materials as, e.g., soft materials and hard magnetic materials, it turns out that $H_C$ is well described by a universal relation [11, 12, 13]

$$H_C = \frac{2K_1}{\mu_0M_S} \alpha - N_{eff}M_S. \quad (2)$$

The first and second term in eq. (2) represent modified magnetocrystalline and demagnetization fields, where $\alpha$ and $N_{eff}$ correspond to microstructural parameters which describe the effect of the microstructure on the crystal field and the local internal dipolar field which in turn depend on the intrinsic material parameters. It is of interest that nucleation as well as pinning hardened materials in many cases may be described by eq. (2).

Fig. 3 shows the development of the superhard magnetic materials ranging from the Alnicos and the ferrites up to the rare earth metal intermetallic compounds. There has been a continuous improvement of the coercive field by the discovery of alloys with large anisotropy constants. It is, however, of interest that during five decades the experimental values of $H_C$ are in general a factor of 4–5 smaller (Brown's paradoxon) than the theoretically