Anhysteretic Magnetization for NiFeMo Soft Magnetic Compacted Powder

D. OLEKŠÁKOVÁ*a, P. KOLLÁRb, M. JAKUBČINb, P. SLOVENSKYb, Z. BIRCÁKOVÁc, J. FÜZERb, M. FÁBEROVÁc AND R. BUREŠc

aInstitute of Manufacturing Management, Faculty of Manufacturing Technologies with the seat in Prešov, Technical University of Košice, Bayerova 1, 080 01 Prešov, Slovakia
bInstitute of Physics, Faculty of Science, P.J. Šafárik University, Park Angelinum 9, 041 54 Košice, Slovakia
cInstitute of Materials Research, Slovak Academy of Sciences, Watsonova 47, 043 53 Košice, Slovakia

Experimentally obtained anhysteretic curves, which characterize NiFeMo soft magnetic compacted powders were measured by modified DC hysteresisgraph. Two anhysteretic curves of two properly prepared samples were compared. First sample was compacted from powder obtained by milling of small chips with particle size between 100 µm and 300 µm. Then, the surface particles were mechanically smoothed. Second sample was prepared in the same way as first one, only that after compaction the sample was annealed at 1100 °C. Numerical analysis of anhysteretic curves showed that the origin of the improvement of the soft magnetic properties of the bulk is due to annealing.

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1. Introduction

Nickel iron alloys (permalloys) are important in many areas of science from material research and engineering [1] to the planetary sciences (founded in most meteorite classes) [2]. High permeability and low magnetostrictive properties of permalloys are widely used in magnetic cores for electrical equipment applications. They are also useful as magnetic shielding materials [3]. Nickel iron alloys are still attractive systems to study because their applications being one of the primary concerns in science and technology of materials [4, 5].

In the present work, we study Ni-rich Mo substituted permalloys. Generally, Mo enhances material permeability even if a small amount is added [6]. High permeability can be also achieved by reducing the amount of Ni. In turn, Mo increases the electrical resistivity of permalloys, and reduces eddy current losses at the same time. Iron nickel molybdenum alloys (called supermalloy) show excellent high frequency characteristics [6, 7].

The appropriate structure of the supermalloy (produced usually in the form of thin sheet) with initial permeability much larger than that of pure iron arises after proper heat treatment. For some applications the form of a sheet is not suitable, therefore it is logical to try to prepare such material in another form, for example in a form of a ring. This shape would be more convenient for construction of some type components for electronic devices [6]. One of the methods of preparing 3D samples is the compaction of powder obtained by the mechanical milling, or mechanical alloying [8].

In this paper, we demonstrate the matching to the anhysteretic curve of experimental data for compacted Ni80Fe15Mo5 (wt. %) based on the Jiles-Atherton model with an additional parameter. The influence of annealing on parameters from the Jiles-Atherton model is also examined.

2. Experimental

Small chips Ni80Fe15Mo5 (wt. %) with size of 2 mm were prepared from the sheet by a rotary drill grinder mounted in a lathe. The chips were milled in a planetary ball mill Retch PM100 in steel vial with steel balls for 10 min with BPR ratio 10:1. The morphology of the chips and the milled chips (powder) was scanned by optical microscope (Nikon Epiphot 200), and scanning electron microscope (TESCAN VEGA3), displayed in Fig. 1. The milled powder was sieved to obtain size fraction from 100 µm to 300 µm. The powder particles were mechanically smoothed [9], and compacted by uniaxial pressure of 700 MPa at the temperature of 410 °C with durability of 10 min, sample A. The B sample was prepared by the same way, only after compaction the sample was annealed at 1100 °C for 10 hours in hydrogen atmosphere. The dimensions of resulted bulk samples were: height of 2.9 mm, outer diameter of 24 mm, and inner diameter of 18 mm. The detailed samples parameters including density are given in [9].

3. Anhysteretic curves

The anhysteretic magnetization curve (also called “ideal magnetization” [10]) is a concept used extensively in the characterization of magnetic materials. Anhysteretic magnetization is defined as the “thermal equilibrium” curve measured by the cooling the sample from
Before the annealing

After the annealing

The demagnetization factor was determined by the linear part of anhysteretic curve for $H_{\text{ext}} \to 0$. Demagnetization field in the sample depends on numerous parameters, such as shape and size of particles, and porosity [13]. To determine the demagnetization factor one can use formula [13]

$$N_d = \left( \frac{B}{\mu_0 H_{\text{ext}}} - 1 \right)^{-1},$$

where $B$ is the magnetic induction, and $B/H_{\text{ext}}$ is the slope of the linear part of anhysteretic curve. The values of demagnetization factor of compacted Ni$_{80}$Fe$_{15}$Mo$_{5}$ (wt%), before the annealing and after the annealing at 1100 °C, are in Table I. The value of the demagnetization factor for annealed sample is significantly lower than that for non-annealed sample due to the paths creation between powder elements for magnetic induction.

5. Jiles-Atherton model

Nowadays, the anhysteretic magnetization curves are often processed with the Jiles-Atherton model of magnetic hysteresis [15]. This one of most popular magnetic models is suitable for design and simulations of electrotechnical and electronic components with soft magnetic cores [16]. The model itself is based on the anhysteretic curves, which are derived using a mean field approach, and where the magnetization of any domain is coupled to the magnetic field $H_{\text{int}}$ and the bulk magnetization $M$ [15, 17].

According to Jiles-Atherton model [15] the energy $E$ of a domain with the magnetic moment $m$ of ferromagnetic material in the presence of the magnetic field $H_{\text{int}}$ is:

$$E = \mu_0 m H_E = \mu_0 m (H_I + H_{\text{int}}),$$

where $\mu_0$ is permeability of vacuum, $H_E$ is the effective magnetic field, and $H_I$ is the magnetic field representing inter domain coupling. Typically, $H_I$ determines the shape of the anhysteretic magnetic curve, and according to the Jiles–Atherton model [15] it is

$$H_I = f(M), \quad H_I(M) = \alpha M, \quad \alpha = \alpha(M),$$

where $\alpha$ is a constant mean field parameter. Now, (3) can be rewritten as

$$E = \mu_0 m (\alpha M + H_{\text{int}}).$$

### Table I

| Coefficient | Before the annealing | After the annealing |
|-------------|----------------------|---------------------|
| $N_d$ [1] | $6.69 \times 10^{-4}$ | $3.14 \times 10^{-6}$ |
| $K_1$ [m/A] | $94 \times 10^{-4}$ | $10.385 \times 10^{-4}$ |
| $K_2$ [m/A] | $5.07 \times 10^{-6}$ | $6.295 \times 10^{-6}$ |
| $m$ [A/m] | $3049.36 \times 10^{-10}$ | $336.89 \times 10^{-10}$ |
| $\alpha$ [-] | $53.94 \times 10^{-3}$ | $6.06 \times 10^{-3}$ |

The significance of inner demagnetization factor lies in the possibility of creating coplanar and copolarized magnetic layers using the methods of electroplating, sputtering, or magnetron cathode deposition [2, 3]. It is especially important to mention that the presence of an internal field in the recording media is often required to provide adequate values of the magnetic moment in the domain walls. To determine the demagnetization factor one can use formula [13]

$$N_d = \left( \frac{B}{\mu_0 H_{\text{ext}}} - 1 \right)^{-1},$$

where $B$ is the magnetic induction, and $B/H_{\text{ext}}$ is the slope of the linear part of anhysteretic curve. The values of demagnetization factor of compacted Ni$_{80}$Fe$_{15}$Mo$_{5}$ (wt%), before the annealing and after the annealing at 1100 °C, are in Table I. The value of the demagnetization factor for annealed sample is significantly lower than that for non-annealed sample due to the paths creation between powder elements for magnetic induction.

### 4. Inner demagnetization factor

Since the samples used for measurements were prepared by compaction of powder, then each powder element as a source of demagnetizing field reduces the value of internal magnetic field $H_{\text{int}}$. It is expressed as follows:

$$H_{\text{int}} = H_{\text{ext}} - H_d = H_{\text{ext}} - N_d M,$$

where $H_d$ is demagnetization field, $N_d$ is inner demagnetization factor, and $M$ is the magnetization.
According to the Jiles-Atherton model, which is based on the idea of anhysteretic magnetization $M$ of ferromagnetic material, after applying Maxwell-Boltzman statistics (distribution of magnetization vectors of domains) and introducing the modified Langevin function $L$, we can write:

$$M = M_s L \left( \frac{E}{k_B T} \right) = M_s L \left( \frac{\mu_0 m}{k_B T} (\alpha M + H_{int}) \right)$$

$$K_1 = \frac{\mu_0 m}{k_B T}, \quad K_2 = K_1 \alpha,$$

$$M = M_s \left( K_1 H_{int} + K_2 M \right),$$

where $k_B$ is Boltzmann constant, $M_s$ is the saturation magnetization, and $K_1$, $K_2$ are parameters, which can be fitted according to (7) based on experimental data of anhysteretic curves for two compacted Ni$_{80}$Fe$_{15}$Mo$_5$ samples (wt%) before the annealing and after the annealing at 1100 °C. Parameter $K_1$ depends on the room temperature $T$, and the average magnetic moment of an effective domain $m$. Definition of $K_1$ includes the Boltzmann constant $k_B$, as well as the magnetic constant $\mu_0$. Parameter $K_2$ is consistent with a constant mean field parameter $\alpha$ in (4).

The fitted parameters $K_1$, $K_2$, and calculated parameters $m$, $\alpha$ can be find in Table I. The values of $m$ are unexpectedly low, which is explained in [18]. The comparison between measured anhysteretic curves for both samples with theoretical ones obtained with $m$ and $\alpha$ parameters, is depicted in Fig. 3.

5. Conclusions

Experimental data of anhysteretic curves (before the annealing and after the annealing at 1100°C) of the compacted powder Ni$_{80}$Fe$_{15}$Mo$_5$ sample with particle size from 100 µm to 300 µm, were compared with Jiles-Atherton model for ferromagnetic material. At first, however, the parameters of Langevin function were determined. The annealing causes a significant decrease of the parameter $m$ (the average magnetic moment of an effective domain), and a slight decrease of the parameter $\alpha$ (the mean field parameter). It is treated as a consequence of the creation of the paths for magnetic flux between powder elements in the compacted material. The decrease of parameters values leads to stronger coupling, and denser effective domains after annealing. We can summarize that the presented model matches the experimental data with very good accuracy.

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