Low Frequency Core Losses Components of FeNiMo Powder Compacted Materials

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The relations of core losses with the frequency of FeNiMo alloys were investigated. The core energy losses were determined by the measurements of dc and ac hysteresis loops as functions of frequency (1 Hz–50 Hz). The usual three-component concept of separation of core losses consisting of hysteresis, eddy current and anomalous losses was used to explain the influence of the powder particle size on core loss frequency dependences.

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1. Introduction

Most remarkable permalloys are the alloys with composition close to Fe₂₀Ni₈₀, where both anisotropy and magnetostriction fall to zero at almost the same composition. A tendency towards unfavourable Ni₃Fe-type L1₂ atomic ordering can be suppressed by Mo addition, i.e., in supermalloy FeNiMo [1].

The appropriate structure of the supermalloys (produced usually in the form of thin sheet) having initial permeability much larger than that of pure iron arises after proper heat treatment. The form of a sheet is not suitable for some applications and therefore it is logical to attempt to prepare such material in another form, for example as a cylinder or a ring, which would be more convenient for construction of some type components for electronic devices. One of the suitable methods for preparation of 3-D samples is compaction of the powder prepared by mechanical milling or mechanical alloying [2]. Mechanical milling is a useful powder processing technique that can produce a variety of equilibrium and non-equilibrium alloy phases [2 - 5]. Some researchers reported results concerning FeNiMo powders system produced by mechanical milling in [6, 7].

In addition to our previous study on Fe–Ni [8] and on Fe–Ni–Mo [3], now we focused the interest on low frequency losses components of FeNiMo powder compacts.

2. Experimental

The Fe₁₆Ni₇₉Mo₅ (wt.%) swarfs were prepared from the ingot of the same chemical composition using a lathe (while it was not possible to prepare the thin ribbon by melt spinning in contrast with binary Fe₁₉Ni₈₁ (wt. %) alloy, which was successfully prepared by melt spinning

in the form of thin ribbon as described in [7, 9]). The swarfs were milled using a RETSCH PM4000 planetary ball mill with hardened steel vials for 1 and 100 hours. To make the alloy more brittle (and thus more suitable for milling), the bowl together with milled material was cooled before grinding by diving in liquid nitrogen. The rotational speed of main mill's disk was 180 rpm and ball to powder ratio was of 6:1.

The powder samples were compacted at a pressure of 800 MPa, the temperature of 600°C (causing the best magnetic properties when annealed in the range from 400°C to 600°C) was stabilized for 5 min. The resulting cylinders have following parameters: diameter of 10 mm, height of approx. 2.5 mm. To prepare the ring samples we drilled an axial hole with a diameter of 5 mm into the centre the cylinders.

- FeNiMo 1 – a bulk sample prepared by the warm consolidation of the swarfs milled for 1 h.
- FeNiMo 100 – a bulk sample prepared by the warm consolidation of the swarfs milled for 100 h.

More details concerning the milling and compaction process of FeNiMo alloy and its magnetic characteristics have been already reported in our previous articles [9, 10].

The dc hysteresis loops were obtained by a hysteresisgraph based on the fluxmeter at maximum induction of 0.2 T, by the point-by-point (ballistic) method, with 4s delays between two measured points. The ac hysteresis loops were measured in the frequency range from 1 Hz to 50 Hz. We have determined the hysteresis losses W_{dc} , core losses W_t and coercive field directly from the measured hysteresis loops.

3. Coercivity

As proved earlier, the coercivity H_c decreases with increasing annealing temperature (from 800°C to 1100°C), reaching a minimum value of 11.2 A/m for FeNiMo bulk sample annealed at 1100°C [7, 9] and it is comparable to

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those for the material of the same composition produced by casting in the form of a thin sheet [11].

The coercive field (determined from hysteresis loops with $B_m = 0.2$ T) as a function of the frequency for bulk samples prepared by the compaction the powder milled for 1 and 100 hours is shown the Fig. 1 a). We can see that the bulk sample prepared by the powder milled longer time reaches higher values of the coercive field in whole measured frequency range. In first part of the frequency range approx. from 1 Hz to 5 Hz the most significant effect for higher coercive field of sample FeNiMo 100 is the influence of more defects introduced to the powder sample during mechanical milling acting as pinning centres for domain wall displacement. Moreover, the influence of particle size and shape may be a reason of the shape of dc hysteresis loops (measured at $B_m = 0.2$ T) in Fig. 2a) and b). The tendency to saturate the dc hysteresis loop (measured at maximum magnetic field of 4800 A/m) for the sample FeNiMo 1 is significantly stronger (Fig. 2 c)) than that for the sample FeNiMo 100 (Fig. 2 d)) what confirms the assumption of the influence of the defects introduced during the milling process.

Fig. 1. Coercive field a) and core losses b) as a function of frequency measured for bulk FeNiMo prepared by the compaction of the powder milled for 1 h and 100 h.

Fig. 2. The dc hysteresis loops of samples a) FeNiMo 1, b) FeNiMo 100 measured at $B_m = 0.2$ T and dc hysteresis loops of samples c) FeNiMo 1, d) FeNiMo 100 measured at $H_c = 4800$ A/m.

In the second part of the frequency range 5–50 Hz, the function of the coercive field versus frequency (Fig. 1a)) has the slope of coercivity for the FeNiMo 100 sample

higher value than that for FeNiMo 1 sample. It can be explained by the prevalence of magnetization vector rotation as a dominant magnetization process in smaller powder elements (sample FeNiMo 100) leading to the larger increase of the hysteresis loop area (core losses).

4. Core losses

The tendency for the frequency dependence of the total losses qualitatively follows the coercive field function for both samples.

The specific energy core losses W_t [J/m³] can be expressed as

$$W_t = W_{dc} + W_{cl} + W_a, \quad (1)$$

where W_{dc} - hysteresis losses, W_{cl} - classical eddy current losses and W_a - anomalous losses [11, 12]. Hysteresis losses W_{dc} can be calculated as an area of dc hysteresis loops and is described as coefficient C_{dc} , $W_{dc} = C_{dc}$.

For eddy current losses W_{cl} is usually taken into account is the expression [12]

$$W_{cl} = \frac{\pi^2 B_{\max}^2 d^2}{\beta} \sigma f = C_{cl} f, \quad (2)$$

where $C_{cl} = \frac{\pi^2 B_{\max}^2 d^2}{\beta} \sigma$ is frequency proportionality coefficient, which include material parameters (d - thickness of the sample and σ - conductivity of the ferromagnetic material) and measurements conditions (B_m - maximum induction and β - geometrical coefficient of the cross section sample perpendicular to the magnetic induction). For the geometrical coefficient β of the sample with the width w and the height h of the rectangle is valid [12]:

$$\beta = \frac{6}{1 - 0.633 \left(\frac{w}{h}\right) \tanh\left(1.58 \frac{h}{w}\right)}. \quad (3)$$

For the anomalous losses coming from damping of domain walls displacement of local eddy we can write the expression [12]

$$W_a = \frac{8.8 \sqrt{SB_{\max}^3 G \sigma V_0}}{\rho} = C_a \sqrt{f}, \quad (4)$$

where $C_a = \frac{8.8 \sqrt{SB_{\max}^3 G \sigma V_0}}{\rho}$ is frequency proportionality coefficient, which includes parameters of the material and measurements conditions (S - the cross section of the material perpendicular to the magnetic induction, G - parameter depending on the material, V_0 - parameter that depend on the magnetisation and the material).

According to the formulas (1), (2) and (3) we can suppose that the frequency dependences of the core losses for all samples is

$$W_t = W_{dc} + W_{cl} + W_a = C_{dc} + C_{cl} f + C_a f^{\frac{1}{2}}. \quad (5)$$

Fig. 1 b) shows the core losses as a function of frequency of both samples in the frequency range from 1 Hz to 50 Hz measured at $B_m = 0.2$ T.

We suppose the presence of all three contributions to the total losses: hysteresis, eddy current and anomalous. The size of the contributors to the total losses was performed by the fitting the experimental results according to the Eq. 5, which allowed to calculate the coefficients

C_{dc} , C_{cl} and C_a , and specific conductivity σ according to Eq. 2. and Table I.

TABLE I

Measured and calculated parameters of FeNiMo samples.

Sample	FeNiMo 1	FeNiMo 100
powder milling time [h]	1	100
exp. values of W_{dc} [J/m ³]	3.5	38.6
C_{dc} [J/m ³]	3.4	38.4
C_{cl} [J/(m ³ s)]	0.12	0.46
C_a [J/m ³ s ^{1/2}]	0.49	1.57
σ [S/m]	4.55×10^5	1.07×10^6

The values of hysteresis losses W_{dc} calculated from frequency dependences of core energy losses W_t are close to the values W_{dc} obtained by measuring of dc hysteresis loops.

Fig. 3. The frequency dependence of the contributions to the core losses from dc to 50 Hz at B_m at 0.2 T calculated by fitting according to Eq. (4), compared with experimental results a) for sample FeNiMo 1 and b) for sample FeNiMo 100.

All components to the total losses are higher for the sample FeNiMo 100 prepared by compaction of powder milled for a significantly longer time than that for the sample FeNiMo 1, Fig. 3. The larger value of hysteresis loss is caused by introduction of defects at milling (similar as for coercivity and coercive field). The sample FeNiMo 100 exhibits larger value of specific conductivity (smaller particles fit very well to each other after compaction and are responsible for better electric contact) leading to the steeper frequency dependence of eddy current losses. The restoring the magnetic “contact” between two particles (confirmed by the increase of specific conductivity) causes the increase of the anomalous component of losses in FeNiMo 100 more significant. The higher influence of anomalous losses in FeNiMo 100 is probably caused by lower number of movable domains, performing Barkhausen jumps on longer distances overtaking attractive forces of pinning centres created as a consequence of longer milling process walls in comparison with FeNiMo 1.

5. Conclusions

The bulk sample FeNiMo1 prepared by the compaction of powder milled for 1 hour exhibits lower values of core losses and all their contributions (hysteresis losses, eddy current losses, anomalous losses) in comparison with the sample prepared by compaction of FeNiMo 100 hours milled powder. For lower value of hysteresis loss is responsible easier movement of domain walls in ferromagnet with lower concentration of defects. Lower specific conductivity of bulk material consisting of larger better insulated particles (FeNiMo 1) leads to the lower values of eddy current and anomalous losses than in sample consisting of compaction longer milled powder (FeNiMo 100).

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