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Reducing the losses in sintered permalloy by addition of ferrite

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Abstract

The reduction of the magnetic losses in soft magnetic materials is crucial for the inductive devices market. For high-frequency applications, ferromagnetic metals show high eddy current losses that can be avoided by adding isolating particles to them. In this work, we show that the addition of 3% by weight of ferrite in permalloy considerably reduces the eddy current losses. We also present a phenomenological model that explains the power losses reduction by increasing the resistivity.

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Keywords: Permalloy; Eddy currents; Quality factor

1. Introduction

One of the most important markets for the soft magnetic materials is the market of inductive systems, which includes transport and transformation of electric energy and also low-field magnetic sensing. In these inductive systems, the alternating magnetization of the ferromagnetic core produces power losses due to two different phenomena: the eddy currents induced in conductive materials due to the variation in magnetization versus time and the hysteresis losses due to the coercivity of the core [1]. Therefore, total power losses can be presented as

$$P = \alpha_1 f^2 + \alpha_2 f, \tag{1}$$

where α_1 is related to the eddy current losses and α_2 to the hysteresis losses [2,3]. Eddy current losses are the main drawback for the use of metallic systems in high-frequency devices due to their low resistivity, which leads to high eddy currents induced in the material. To avoid this, metallic materials are normally alloyed with non-magnetic isolating ones (P, Si...), although this addition of non-magnetic elements reduces the saturation magnetization, and also the magnetic flux produced by the cores, which can be unsuitable for several applications [4]. For high-frequency applications, non-metallic ferrite-based cores are normally used in spite of their lower saturation magnetization ($\mu_0 M_s < 0.5\,\mathrm{T}$).

In spite of being metallic, Ni–Fe alloys in general, and permalloy ($Ni_{80}Fe_{20}$) in particular, are among the most used soft magnetic materials in inductive applications due to their low coercivity ($H_c \simeq 1\,\mathrm{Oe}$) and their relatively high saturation magnetization ($\mu_0 M_s = 1\,\mathrm{T}$) [5]. In a previous work [6], we showed that the introduction of a small amount of non-conductive ferromagnetic particles in sintered permalloy reduces the eddy currents losses in a great amount without decreasing the saturation magnetization too much. However, this addition of non-conductive particles produces a considerable increase in the coercivity of permalloy and, therefore, in the hysteresis losses. This increment was attributed to a high porosity.

In this work, we show that the hysteresis losses of these permalloy–ferrite alloys can be controlled and reduced. By using different mixing procedures in the sintering processes we have fabricated samples with low eddy currents and low hysteresis losses.

2. Experimental

Permalloy–ferrite samples were produced by mixing, pressing and sintering powders. In order to reduce the

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porosity of the samples [6], we decided to use a permalloy powder alloy. The samples were made from permalloy powder—supplied by GoodFellow—mixed with 3% in weight of 4A15 Ni–Zn ferrite—supplied by Ferroxcube. It is important to note that the amount of ferrite is smaller than in our previous work.

The powders were mixed in three different ways:

(1) mixed manually;
(2) mixed in acetone and stirred until the acetone evaporates;
(3) mixed in a mill (with and without ball) at 100 r.p.m. for 20 min. The low energy involved in this milling procedure is enough for mixing but prevents any other reaction or decomposition.

After the mixing procedure, the samples were compacted at a pressure of 600 MPa and sintered at high temperature.

Thermal treatments were carried out in two different steps. First, 1 h at 400 °C to evaporate the binder used to compact the ferrite, and then 1 h at 800 °C. The first step is mandatory to avoid the formation of microcracks due to the ignition of the binder. Both pressure and thermal treatments were carried out in Ar atmosphere to prevent oxidation.

To compare, pure permalloy and ferrite samples were produced mixing the pure powders in a mill and following the same sintering procedure that we used for the other samples.

Sample homogeneity has been studied by scanning electron microscopy (SEM) and magnetic properties by a conventional inductive method up to 15 mT. The total power losses have been estimated by numerical integration of the hysteresis loops area. Permeability values were also calculated from the hysteresis loops, as the highest slope of the curve. For these measurements, we used a rod-shaped samples of 50 mm × 6 mm × 0.5 mm in size.

Saturation magnetization has been measured by a vibrating sample magnetometer (VSM) up to 1 T. In order to measure the samples with the VSM, they were cut in pieces of 6 mm × 6 mm × 0.5 mm. Density was estimated from the values of mass and volume. The latter was obtained by using the Archimede method. The resistivity was measured by the Van der Pauw method.

3. Results and discussion

A study of the cross-section of the samples by SEM reveals big differences in homogeneity between the samples mixed using the mill and the ones mixed by the other methods.

Fig. 1a shows a typical image obtained for the cross-section of a sample in which the powders have been mixed using the mill—micrographs for samples mixed with and without balls in the mill look very similar—and Fig. 1b a typical image obtained for the cross-section for one mixed manually—micrographs of samples mixed in acetone (not shown here) show the same kinds of agglomerates. In the latter, agglomerates of ferrite particles in the permalloy matrix can be easily observed whereas the former is very much homogeneous. Therefore, the use of the mill produces a more homogeneous distribution of the ferrite in the sample.

Taking into account that we have not found significant differences in the properties of the samples milled with and without balls, in the following we consider only the samples milled without balls assuming that the results are the same than the others within the experimental error.

Saturation magnetization, density, electrical resistivity and others important parameters are shown in Table 1. It can be observed that saturation magnetization of permalloy–ferrite is about 10% lower than the one of permalloy. We have not found differences among the different samples of permalloy–ferrite.

Fig. 2 shows the variation with the frequency of the magnetic permeability for ferrite, permalloy and permalloy–ferrite (mixed in a mill). Permalloy–ferrite behaves like permalloy for low frequencies whereas for high frequency it tends to the behavior of ferrite.

It can be noticed that the values of permeability are lower than expected (i.e. $\mu_i = 1200$ for 4A15 ferrite [7]) mainly because of the effect of the demagnetizing field due to the shape of the samples. Nevertheless, the analysis of the behavior versus frequency is still, qualitatively, valid.

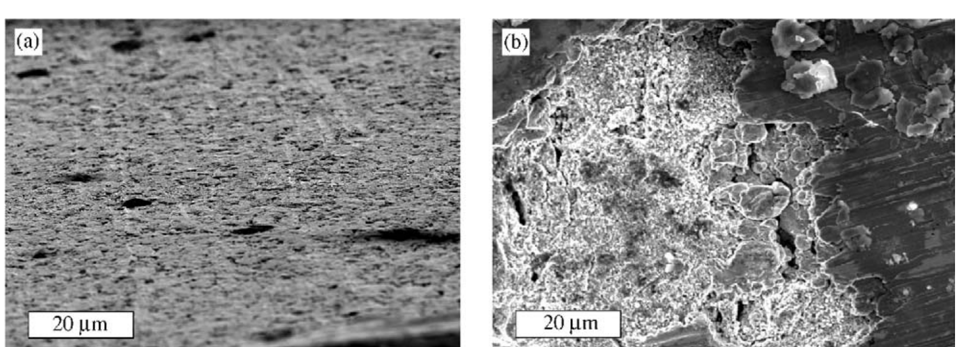

Fig. 1. SEM images of the cross-section of samples in which the powders have been mixed using the mill (a), and mixed by manually (b).