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MICROSTRUCTURAL ENGINEERING OF POWER FERRITES

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ABSTRACT: The correlation between the high frequency power loss of MnZn ferrites and microstructure was considered. It was shown that when the grain boundaries in MnZn ferrites are permeable to eddy currents during the ferrite core operation in the MHz range, the power loss is proportional to the average grain size. From this interpretation it follows that the most effective way to decrease the power loss of MnZn ferrites is to reduce the average grain size during sintering. A nanosized MnZn ferrite powder would be promising for the preparation of dense and fine grained ferrite cores.

Krmiljenje mikrostrukture močnostnih feritov

KLJUČNE BESEDE: materiali magnetni, Mn-Zn feriti, izgube močnostne, tok vrtinčni, mikrostrukture materialov, velikost zrn, prahovi feritni, sinteza prahov feritnih

POVZETEK: Proučevali smo odvisnost močnostnih izgub v MnZn feritih v odvisnosti od mikrostrukture. V primeru, ko so meje med zrni ferita propustne za električne tokove pri frekvencah okoli 1 MHz, je možno pokazati, da so močnostne izgube sorazmerne povprečni zrnavosti MnZn ferita.

Introduction

The use of MnZn ferrites in power electronics is constantly increasing. Particularly the growth of the commercial market for Switch Mode Power Supplies (SMPS) places demands on the ferrite industry to produce high performance ferrite cores capable of operating at increasingly higher frequencies(1). In SMPS the switching frequency is related to power output, making It possible for smaller core volumes to transform the same amount of power as a larger core would at lower frequencies. This is a direct challenge for the miniaturisation of SMPS(2) and related power devices.

MnZn ferrites exhibit a relatively high electrical resistivity in comparison to alloys, and a saturation magnetisation which is the highest among ferrites. These properties make MnZn ferrite very suitable for use in power applications(3).

Power loss and intrinsic properties

The main core characteristics are core losses which contribute the major part of the total electrical loss. In general the core loss can be divided into residual loss, hysteresis loss and eddy current loss. The residual loss is important only at low induction levels and can be ignored in power application of MnZn ferrites. The hysteresis loss $P_H = W_Hf$, where $W_H = \int HdB$ is the energy represented by the area of the hysteresis loop measured under the maximum flux density, depends on many parameters; however, the hindernice to the domain wall displacements(4), which takes part at high induction levels(5), play the major role.

The factors governing the hysteresis loss are the magnetocrystalline anisotropy K_1, magnetostriction λ, stress σ, porosity p and saturation magnetisation M_S. For low hysteresis loss K_1, λ, σ, and p should be low. These parameters are composition dependent and can be controlled by the chemical formulation; however, the porosity (p) and mechanical stress (σ) are controlled mostly by the microstructure and impurities. The ferrous content, which is essential in MnZn ferrites for achieving low magnetocrystalline anisotropy and magnetostriction and thus low hysteresis loss, give rise to a high electrical conductivity due to the thermally activated hopping mechanism between Fe^{2+} and Fe^{3+} in spinel ferrites. The relatively low electrical resistivity, ρ_{bulk}, influences the eddy current loss, $P_E = d^2B_{m2f2}/\rho_{bulk}$ where d^2 is the core cross section, B_m is the maximal flux density, and f is the frequency. In the case of very pure MnZn ferrites where the grain boundary resistivity is low, the resistivity of the bulk ρ_{bulk} is roughly equal to the grain resistivity. The most effective way to suppress electron hopping and thus the electric conductivity inside the ferrite grains, is by the substitution of Ti^{4+}, which occupies the B site adjacent to Fe^{2+} (6).

At higher operating frequencies the contribution of the eddy current loss to the total loss strongly increases and above 500 kHz it dominates all other losses. Therefore in order to increase the performance of MnZn ferrites for power applications at high frequencies, the eddy current losses must be suppressed to the greatest possible extent.

However, in considering the eddy current loss, the extent of the eddy current in the magnetic core must be considered and correlated to the microstructure.

In general, two extreme cases regarding the eddy current in the magnetic core can be considered. In the first case, when the magnetic grains are isolated and the eddy current in this hypothetical case is localized inside the grains, Fig. 1, the core behaves as an assembly of individual magnetic grains in which each grain contributes to the eddy current loss.

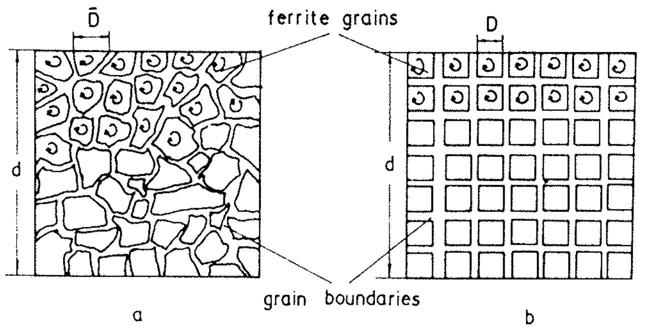

Fig. 1: *Schematic picture of a real (a) and an ideal (b) microstructure of a material with isolated magnetic grains exposed to micro eddy currents.*

In this case the parameter d loses its original meaning of the core dimension, and stands rather for the "size" of the micro eddy current in individual grains, representing their average diameter $\bar{D}$. Thus, using these arguments the core cross section, d^2 in the Eq. for P_E, becomes the average grain cross section of an individual grain and written $\bar{D}^2$. In the limiting case when the grain boundaries are thick enough to substantially decrease the electric capacity of the grain boundaries and eliminate the frequency dispersion of the electrical resistivity, the bulk electrical resistivity ρ_{bulk} becomes the pure ohmic resistivity and does not depend on the material's microstructure, i.e. $\rho_{bulk} = \rho_{grain}$. In this case the total power loss at higher frequencies is proportional to the square of the average grain size;

$$P \approx P_E = \bar{D}^2 f^2 B^2_m / \rho_{grain}.$$

Such a dependence was indeed observed when Fe-based soft magnetic particles were separated by insulating layers of metal oxides(7).

A different dependence between the total loss and the microstructure holds when the grain boundaries are permeable to the eddy current.

In MnZn ferrites the grain boundary shows different chemical and physical properties from the ferrite grains. The segregation of impurities and partial reoxidation of Fe^{2+} during cooling on the grain boundaries makes the MnZn ferrite grain boundaries highly insulating in comparison to the grain interior. These insulating layers are in practice very thin and therefore exhibit a relatively high electrical capacity (C).

For such a ferrite core the equivalent electrical circuit of the semiconducting grain and the insulating grain boundaries are a parallelly connected resistance and capacitance whose impedance is proportional to $1/\Omega C$. This property causes a dispersion of the electrical resistivity with respect to the frequency(8).

In order to elucidate the dependence of power loss (P) on the average grain size $\bar{D}$, we will divide the ferrite material into small cubes. In this hypothetical model the grain boundaries will lie in directions perpendicular and parallel to the principal axis, i.e. to the electric field direction. The grain boundaries which are parallel to the principal axis will be electrically bypassed by the bulk material. Therefore the small cubes can be approximated by bulk material separated by high ohmic layers - the grain boundaries - which are perpendicular to the principal axis. Each layer can be represented by a resistance-capacitance (r - c) lumped circuit of high ohmic layers. When the resistivity of the bulk is much lower in comparison to the grain boundary layers, the equivalent circuit of the ferrite can be represented by a series of lumped r - c circuits of the grain boundary layers. The resistivity of the ferrite material is in this simplified approach proportional to the number of grain boundaries per unit length. In ferrite core with the dimension d the bulk resistivity is then given by $\rho_{bulk} = d/\bar{D}\,(\rho_{grain} + \rho_{gr.boudary})$. In MnZn ferrites where $\rho_{gr.bound.} > \rho_{gr.}$ we obtain for bulk resistivity $\rho_{bulk} \approx d/\bar{D}\ \rho_{gr.bound.}$

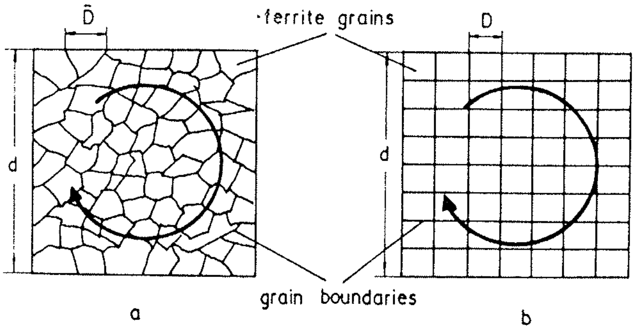

Fig. 2: *A sketch of an actual (a) and an idealised (b) ferrite microstructure with grain boundaries permeable to the eddy current.*

In a real material, Fig. 2, the grains have the shapes of irregular polyhedra. In this case only the components of the grain boundaries which are perpendicular to the principal axis can effectively block the electric current.

At higher frequencies where the eddy current loss predominates the total loss is proportional to the average grain size $\bar{D}$;

$$P \approx P_E = \bar{D} d f^2 B_m^2 / \rho_{gr.bound.}.$$

At frequencies where the grain boundaries are not short circuited by a high displacement current, the power loss can be effectively suppressed by a decrease in the average grain size.

To achieve a fine grained, homogeneous and dense microstructure, a small grained and equisized MnZn ferrite powder must be used. There are several non-conventional methods for producing a powder which exceeds the performance of conventionally prepared powders(9).

When engineering MnZn ferrites ceramics with the objective of forming fine grained, homogeneous and dense ceramics, one must proceed from a nonconventionally prepared ferrite powder. Among chemically prepared ferrite powders, those, prepared by the hydrothermal method offer enough advantages to realize this objective.

With ever increasing energy costs, the hydrothermal method could possibly become very attractive for the preparation of fine powders because of the low temperature involved during synthesis and their good sinterability. During hydrothermal syntheses equisized nanosized powders with a narrow grain size distribution can be achieved(10,11). These samples sinter to a relative high density. In order to engineer the MnZn ferrite microstructure from the nanosized ferrite powder with an average grain size of 10 nm and a green density of 55% T.D., and prepare a ferrite core with an average grain size of around one µm, the average grain size should increase during sintering by a factor 10^2 and the density by 40%. So if we assume that the typical power loss of a ferrite core with an average size of 10 µm and 95 % T.G. at 50 mT, 80°C and 1MHz is about 10^3 mW/cm^3, then a ferrite core with an order of magnitude smaller average grain size and with all other parameters of similar magnitude, will have a power loss of an order of magnitude lower as well. By using hydrothermally prepared powder a fine grained ferrite core ($\bar{d} \approx 1$ µm) can be prepared by conventional sintering (12). Such a microstructure can drastically decrease the high frequency power loss of MnZn ferrites.

Conclusions

- The power loss in MnZn ferrites at higher frequencies close to 1 MHz is mostly due to the eddy current loss, P_E.
- The average grain size is the most important microstructural parameter governing the power loss, P.
- The relationship between the eddy current loss and the average grain size is dependent on the extent of the eddy current and is governed by the microstructure of the ferrite.
- The most effective way to decrease the power loss in MnZn ferrites is to decrease the average grain size, provided that all other intrinsic properties stay constant.
- In order to prepare a fine grained and dense microstructure, a nanosized ferrite powder should be used. This offers the possibility of finding a compromise between a fine grained microstructure and a high density during sintering.

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