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Development of low loss Mn–Zn ferrite working at frequency higher than 3 MHz

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ABSTRACT

With the advance of modern electronic technology, there has been a critical need for Mn–Zn ferrites with even higher permeability and even lower power loss at higher frequencies. In this study, ferrite with extremely low losses than conventional ferrite materials at high frequency was developed employing a conventional ceramic powder processing technique. As a result, the core loss at 3 MHz, 10 mT and 100 °C is around 300 kW/m^3, and its cutoff frequency is 4 MHz. Furthermore, the electromagnetic characteristics and the microstructure of this new DMR50 material are also discussed.

1. Introduction

In keeping with the advance of more compact and more power-saving electronic equipment, the demand is increasing for smaller and more efficient switching power supplies. Now, the driving frequency of power supplies has been raised from tens of kHz to about 1 MHz; thus, there is an urgent need for the reduction of power losses of Mn–Zn ferrites in this high-frequency range [1,2]. The power loss (P_C) can be expressed as a function of frequency (f) and magnetic flux density (B):

$$P_C = kB^x f^y \tag{1}$$

where x and y are called Steinmetz coefficients [2,3].

Theoretically, the power loss in ferrites is generally split up into three contributions with quite different physical origins [3–6]:

$$P_C = P_h + P_e + P_r = K_H B^3 f + K_E B^2 f^2/\rho + P_r \tag{2}$$

where P_C is the total power loss, P_h, P_e and P_r are the hysteresis loss, eddy current loss and residual loss, respectively, K_H and K_E are constants, B is the magnetic flux density, f is the frequency and ρ is the electrical resistivity. The justification for this subdivision resides in part in differences in the frequency response of each loss contribution. Apart from the contributions to the eddy current loss, the understanding of ferrite dissipation is mainly phenomenological [1,6]. As a basic approach for development of the low loss materials, research and analysis have been conducted to unravel the mechanism of loss generation in Mn–Zn ferrites [7,8].

The relative importance of the different loss contributions to the total loss P_C depends on frequency and on induction level. P_h corresponds to the dissipation already present in the DC measurement, and is considered to be caused by hindrances to domain wall movements when irreversible jumps of domain walls occur between pinning points, such as grain boundaries, internal pores or inclusions [5,6]. Hysteresis losses can be minimized if one reduces hindrances to domain wall movements by reducing their concentration and their individual influence. This requires a low volume fraction of pores, impurities and dislocations, but also a low level of stresses, a small magneto-crystalline anisotropy, a small magneto-striction and a high saturation magnetization. The latter three are determined by the chemical composition of the ferrite and the others by its microstructure [5].

Currently, the approach to lower P_h is to facilitate domain wall movement by using ferrites in which the coercivity Hc is minimized through selecting compositions with a minimal magneto-crystalline anisotropy constant K_1 [6], making the anisotropy compensation an important concept in manufacturing these materials. In Mn–Zn ferrite, the magneto-crystalline anisotropy can be described as the sum of two contributions, one from Fe^{2+} ion with a large positive contribution and the other from the “host” with a negative one. It is characterized by the

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compensation temperature T_{min}, at which temperature K_1 passes through zero. It coincides with the secondary maximum temperature of the magnetic permeability versus temperature and also with the temperature where the power losses exhibit a minimum. In application, usually, K_1 is minimized by anisotropy compensation due to the Fe^{2+} ions, which ideally have their anisotropy compensation point at the operating temperature of a transformer of 80–100 °C, because the transformer core is usually operated at these intended working temperatures [5]. In addition, compositions having a low magneto-striction constant λ are taken. As for the microstructure, the inner part of the grains should be homogeneous and free of impurities, pores and other defects.

As can be seen from Eq. (2), eddy current loss $P_e \propto f^2$. Hence the eddy current loss becomes progressively more important at higher frequencies. Eddy current loss can be reduced by providing a high electrical resistivity, that is, to increase the resistivity of polycrystalline ferrites by increasing the grain boundary resistivity either by careful control of the processing conditions or by adding glass-forming dopants, and to increase the resistivity inside the grains [5,6]. As spinel ferrites are semiconductors, electrical conductivity in Mn–Zn ferrite has been attributed to electron hopping between the two valence states of iron, $Fe^{2+} \leftrightarrow Fe^{3+}$, on octahedral sites. Maintaining the 3+ valence state of octahedral Fe ions is thus a prerequisite for achieving high resistivity. There are types of additions increasing the grain boundary electrical resistivity, and multivalent ions can increase grain resistivity.

At high frequencies, perhaps the most widely practiced method of suppressing the enlarged P_e is the use of a composite $CaO–SiO_2$ additives that diffuse towards grain boundaries during the cooling part of the firing cycle and create a high-resistive insulating layer in the grain boundary region [5,6]. A way to increase the resistivity inside the grains is to substitute multivalent ions, such as Ti^{4+} and Sn^{4+}, in the spinel lattice of the ferrite. They may form pairs with Fe^{2+} ions and thus may reduce electron hopping [5].

With regard to P_r, recent studies have indicated that P_r claims over 80% of the total core loss at frequencies above 500 kHz [7], so P_r plays an important role in reducing power loss in the MHz range. Residual loss P_r is associated with magnetic relaxations and resonances in the ferrite [5]. Magnetic relaxations contributing to these losses are due to domain wall excitations by the driving AC magnetic field. Magnetic resonance may occur in two ways, viz. as rotational resonance and as domain wall resonance. To reduce P_r, the complex permeability has to be made to peak at the frequency as high as possible, and this can be achieved by using fine-grained ferrites [5–7]. Small grains can be realized by applying finer powders, enabling sintering at lower temperatures during shorter periods. Also applying sinter acids, such as Bi_2O_3, may lower the sintering temperature and thus yield small grains [5]. Because of their low melting point, these oxides melt at grain boundaries and initially act as a grain growth inhibitor, but special attention should then be paid to homogeneous distribution of the additives, since otherwise secondary grain growth may deteriorate the ferrite.

As we can see that, the electromagnetic characteristics of an Mn–Zn ferrite are dependent not only on the composition of main elements but also on its microstructure, efforts have been exerted to improve their loss characteristics by controlling the size of grains and the distribution of small amounts of additives in the grain boundary region. Through analyzing the relations between the core loss and the microstructure of Mn–Zn ferrites for power supplies, and examining the effect of small quantity additives of many different additive elements such as $CaO–SiO_2$ on the microstructure and core loss, Mn–Zn ferrite material DMR50 with extremely low losses than conventional ferrite materials at rather high frequency and high magnetic flux density levels were successfully developed. In addition, taking fully into account the mass production conditions of the company, a conventional ceramic powder processing technique is employed. Furthermore, the electromagnetic characteristics and the microstructure of this new material are also discussed.

2. Experimental procedure

We employed a conventional ceramic processing technique, and the chemical composition of Mn–Zn ferrite is $Mn_{0.745}Zn_{0.173}Fe_{2.082}O_4$, suited for power applications. The prescribed quantities of Fe_2O_3, Mn_3O_4 and ZnO were mixed in a ball mill. This mixture was calcinated at 900–980 °C for 2 h. The calcinated powder was mixed and milled with various combinations of CaO, SiO_2 and other additives such as Nb_2O_5, ZrO_2 and TiO_2 in ball mill. The obtained ferrite powder, after mixing with PVA (a binder agent), was granulated and pressed into toroidal shapes with 25 mm in outer diameter, 15 mm in inner diameter and 8 mm in height.

These cores were sintered between 1200 and 1300 °C in oxygen partial pressure that was carefully controlled. The relation between the cooling temperature and oxygen partial pressure was maintained according to the following equation [7]:

$$\log P_{O_2} = -14540/T[K] + a \qquad (3)$$

where atmospheric parameter "a" is a constant.

Power losses were measured using an Iwatsu BH analyzer (SY8232). An RF Impedance/Material Analyzer (Agilent 4291B) was used to measure the magnetic spectrum and the temperature dependence properties of permeability. A Hewlett–Packard impedance analyzer (4284A Precision LCR Meter) was used to measure the DC-Bias properties, and the DC magnetic properties of the samples were measured by a MATS-2000 Magnetic Material Automatic Meter. X-ray diffraction (XRD) measurements are carried out with an X-ray powder diffraction (Rigaku D/Max-3B). The crystalline phases were identified, the Bragg peaks were indexed and the lattice parameter was calculated. Images of microstructure are obtained by means of a scanning electron microscope (SEM) (Hitachi S-570).

3. Results and discussion

In Fig. 1 the XRD pattern of the DMR50 material is shown. XRD analysis clearly exhibits that all the observed diffraction peaks and

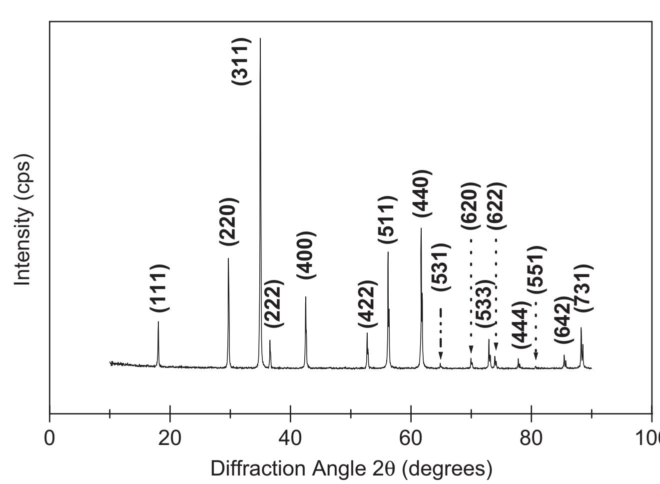

Fig. 1. XRD pattern of DMR50 material.