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SOFT MAGNETIC FERRITE MATERIALS

MEHKOMAGNETNI FERITNI MATERIALI

Andrej Žnidaršič[1], Miha Drofenik[2]
[1]Iskra feriti, Stegne 29, 1000 Ljubljana, Slovenia
[2]Institut Jožef Stefan, Jamova 39, 1000 Ljubljana, Slovenia
andrej.znidarsic@iskra-feriti.si

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MnZn ferrites are ceramics with special magnetic properties which are widely used as core materials for inductive components in electronics. For special applications, MnZn ferrites with the following properties are required: low power losses in the frequency range of 500 kHz and a high magnetic saturation flux density. This paper describes the differences in the electromagnetic characteristics of a standard ISKRA material, A, and a new material, B, together with the results of a structural analysis.

Key words: magnetic ceramic, MnZn ferrites, magnetic properties, grain boundaries, eddy current, ferrite grains, electrical properties

MnZn-feriti so keramični materiali, ki so zaradi svojih specifičnih magnetnih lastnosti pomembni gradniki v elektroniki. Nizke izgube v frekvenčnem območju do 500 kHz in visoka nasičenjska gostota sta pomembni lastnosti pri posebnih aplikacijah. V članku je predstavljena razlika elektromagnetnih lastnosti med obstoječim materialom A in novim materialom B ter analizni pregled rezultatov.

Ključne besede: magnetna keramika, MnZn-feriti, magnetne lastnosti, meje med zrni, vrtinčne izgube, feritna zrna, električne lastnosti

1 INTRODUCTION

The development and continued success of switch-mode power supplies is constantly challenging the ferrite industry to produce new, high-quality ferrite cores capable of operating at increasingly higher frequencies [1,2]. For this reason it is important to reduce the power losses of MnZn ferrites that are used as transformer cores.

The electromagnetic characteristics of MnZn ferrite are not only dependent on the composition of the main elements but also on the material's microstructure [3]. As a consequence of this, efforts have been made to improve their loss characteristics by controlling the size of the grains and the distribution of the small amounts of additives in the grain-boundary region [4]. In MnZn ferrites the grain boundaries exhibit different chemical and physical properties than the ferrite grains. The segregation of impurities and the partial reoxidation of the Fe^{2+} on the grain boundaries during cooling make 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.

Core loss can be divided into three components: hysteresis loss (P_h), eddy-current loss (P_e) and residual loss (P_r). The proportions of these components in the total loss can vary widely, depending on the measurement conditions such as frequency and magnetic flux density.

At low frequencies P_h losses are dominant, and in order to reduce these losses it is important to form a uniform microstructure that is free from lattice defects and pores. At high frequencies the proportion of P_e losses increases, but this can be reduced by increasing the resistance of the cores. Eddy-current loss can be decreased by having grain boundaries with a high electrical resistance and by having a ceramic microstructure with small grains. The resistance of the grain boundaries is determined by additives, which are enriched at the grain boundaries during the sintering process, forming an insulating phase. Small grains can be achieved by applying sintering conditions that suppress the grain growth and by choosing additives that act as grain-growth inhibitors. The sintering parameters must lead to a suppression of the grain growth. So the choice of raw materials, as well as the technological parameters, influences the power losses.

In general, two extreme cases regarding the eddy current in the magnetic core of MnZn ferrites can be identified by applying the brick-wall model [5]. In the first case, when the magnetic grains are isolated and the eddy current in this hypothetical case is localised inside the grains, **Figure 1a**, the core behaves as an assembly of individual magnetic grains in which each grain contributes to the eddy-current loss. A different dependence between the total loss and the microstructure holds when the grain boundaries are permeable to the eddy current, **Figure 1b**.

According to this model the bulk material can be approximated by a group of small cubes of size D, separated by high-resistance layers of thickness $\delta_{g.b.}$ and resistance $R_{g.b.}$. Using this model [5] we obtain, at low frequencies ($\omega cR < 1$), the relation $P_e = cB_m^2 f^2 \cdot \frac{D}{R_{g.b.}^{(mic)}}$, while for high frequencies ($\omega cR > 1$), the equivalent relation is $P_E \approx \propto \varepsilon_{g.b.} \cdot \frac{D}{\delta_{g.b.}}$. Thus, the eddy-current power loss P_e, which prevails in the frequency range above 500 kHz, can be effectively suppressed by decreasing the average grain size ($\bar{D}$), by increasing the grain-boundary resistance $R_{g.b.}^{(mic)}$ and by increasing the grain-boundary width $\delta_{g.b.}$.

The saturation B_s of a material mainly depends on the composition of the ferrite. The maximum saturation for MnZn ferrites is in the region 55 mol % Fe_2O_3, 35 mol % MnO and 10 mol % ZnO. However, this saturation can be enhanced by increasing the density of the sintered material. Concerning the initial permeability, it must be stressed that a high μ_i and low core losses at high frequencies are in contradiction when it comes to the microstructure because small grains lead to an internal shearing and so to a lower initial permeability. This means that the composition has to be chosen as a compromise between the saturation B_s, the initial permeability μ_i, and the SMP (minimum of power loss).

There are many contradictory requirements for low-core-loss ferrites. To achieve the lowest possible core losses, both compromise and novel processing techniques are required. The development process must ensure that the required characteristics of the core are achieved. In high-frequency power ferrites the minimisation of the eddy-current losses is the most important factor in determining the optimum core characteristics. When developing a process for the production of ferrites, the problem should not be approached by trying to optimise each magnetic property. Because of the interdependency of the magnetic properties, improving one property may lead to the degradation of several others. The way to approach the problem is to find the compromise that best fits the design requirements. When designing the process, reproducibility must also be taken into account, as must the cost. The two main factors governing the reproducibility of a process are control of the processing variables and the chemical homogeneity. The number of uncontrollable processing variables is reduced by switching to more sophisticated equipment (DTA, TGA, X-ray). Chemical homogeneity is achieved mainly through good-quality starting powders and intensive mixing procedures.

Major improvements in material properties through processing usually occur as a result of the following: a careful choice of composition; the selection of raw materials and processes that introduce the minimum amount of impurities and produce a homogeneous product; proper and improved control; and an understanding of the firing process.

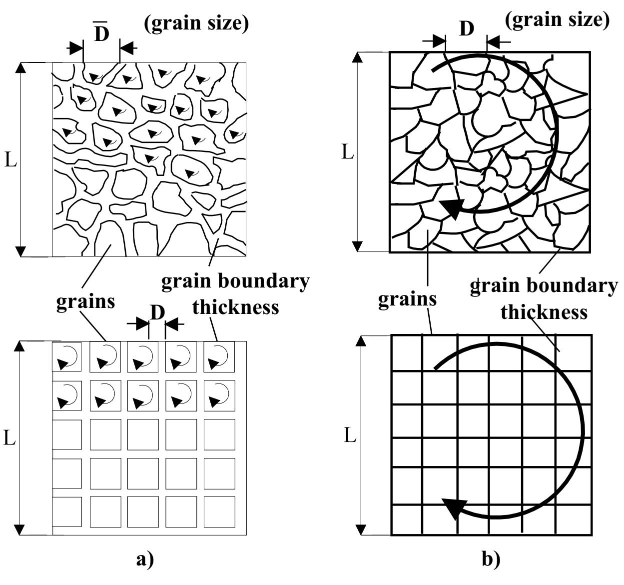

Figure 1: Brick-wall-microstructure model: (a) schematic picture of a real and an ideal microstructure of a material with isolated magnetic grains exposed to micro-eddy currents. (b) a sketch of an actual and an idealised ferrite microstructure with grain boundaries permeable to the eddy current.

Slika 1: Model opečne strukture: (a) Shema dejanske in idealne strukture materiala z izoliranimi magnetnimi zrni, (b) Shema dejanske in idealne strukture materiala, prevodnega za vrtinčne tokove

2 EXPERIMENTAL

The weighed raw materials, Fe_2O_3, Mn_3O_4 and ZnO, were mixed and then pelletized with a small amount of water. The red pellets were calcinated in a rotary kiln. After that the black pellets, together with water and the additives, were fine milled in an attritor. The average grain size of the ferrite powder after milling was 0.8 µm. The slurry was spray dried with a PVA and PEG binder combination. Toroids were pressed and sintered in order to measure the magnetic properties. For the determination of inductance (L/L_0) vs. maximum flux density, air-gapped toroids were made.

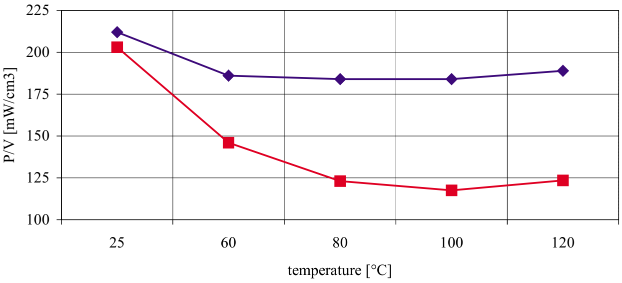

Figure 2: Core loss as a function of temperature at 400 kHz and 50 mT (measured for toroids of dimensions: d_0 = 22 mm, d_i = 14 mm, h = 7 mm) for the standard material A and the new design B

Slika 2: Izgube jedra v odvisnosti od temperature pri 400 kHz in 50 mT (merjeno na toroidnem jedru d_0 = 22 mm, d_i = 14 mm, h = 7 mm) za standardni material A in novi material B

Tabela 1: Comparison of the sintered density, initial permeability μ_i (25 °C), power losses and the B_S saturation for A and B
Tabela 1: Primerjava sintrane gostote, začetne permeabilnosti μ_i (25 °C), močnostnih izgub in nasičenjske gostote za A in B

Initial permeability μ_i		A	B
		2000	1800
Flux density Bmax (m T)			
10kHz; 250A/m	100°C	340	380
	120°C	280	360
10kHz; 1200A/m	100°C	370	420
	120°C	300	390
Curie temperature T_C (°C)		200	230
Relative loss factor P/V (mW/cm^3)			
f = 300kHz; B = 100mT	25°C	700	700
	100°C	530	390
	120°C	550	400
f = 400kHz; B = 50mT	25°C	200	200
	100°C	180	120
	120°C	180	125

3 RESULTS

Figure 2 shows the power loss of the standard high-frequency power-transformer material, A, compared with the new material, B. By introducing the design principles described above, the power loss could be decreased from 180 mW/cm^3 to 120 mW/cm^3 at 400 kHz, 50 mT, 100 °C (**Figure 3**). **Table 1** summarises the sintered density, the initial permeability and the saturation of A and the new B. For the upgraded version of B, the density was increased by 0.1 g/cm^3 and the saturation from 300 mT to 390 mT (at 1200 A/m) at 120 °C.

The average grain size during sintering can be decreased when a suitable sintering profile is applied [6], **Figure 4**. This program is a combination of an initially high oxygen concentration and then, above 900 °C, a low oxygen concentration. For an oxygen concentration of above 20 vol % the microstructural development in MnZn ferrites is dominated by exaggerated pore growth, while at lower oxygen concentrations, below about 20 vol %, the grain-boundary mobility in MnZn ferrites during sintering is promoted because of the increase in the concentration of oxygen vacancies, which are the slowest moving species and hence promote volume diffusion.

On the other hand, grain growth in ferrites is largely determined by the attachment or separation of pores from the grain boundaries, which depends on the ratio of pore size to grain size. Thus, a combination of an initially high oxygen partial pressure, which promotes exaggerated pore growth, and a subsequent low oxygen partial pressure, which enhances volume diffusion, can inhibit grain growth and consequently decrease the average grain size in MnZn ferrites, and so increase the final sintered density. The increase of the grain-boundary width and the resistance can be achieved by the segregation of Ca^{2+} during sintering and subsequent cooling of the MnZn-ferrite cores [7].

The distinction between usable flux density and saturation flux density is critical for magnetic materials such as MnZn ferrites that exhibit hard saturation. Hard saturation is a sharp decrease of the magnetic permeability as the excitation results in flux-density values located in the non-linear region of the hysteresis loop [8,9].

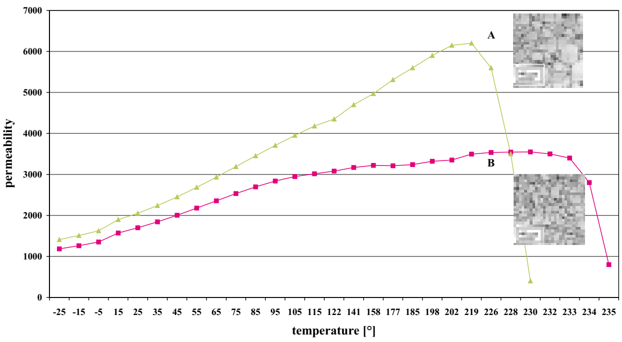

Figure 3: Initial permeability vs. temperature for the standard material A and the new design B
Slika 3: Začetna permeabilnost v odvisnosti od temperature za standardni material A in novi material B

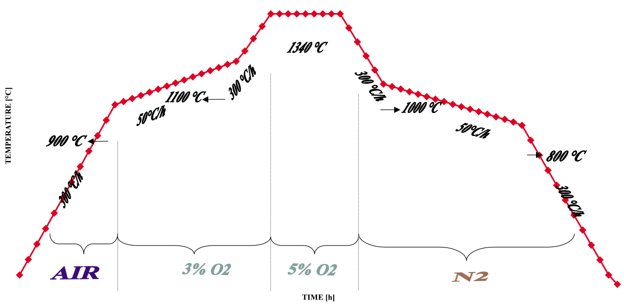

Figure 4: Typical firing scheme for the sintering of high-performance power ferrites
Slika 4: Optimalne razmere pri sintranju visokokvalitetnih močnostnih feritov

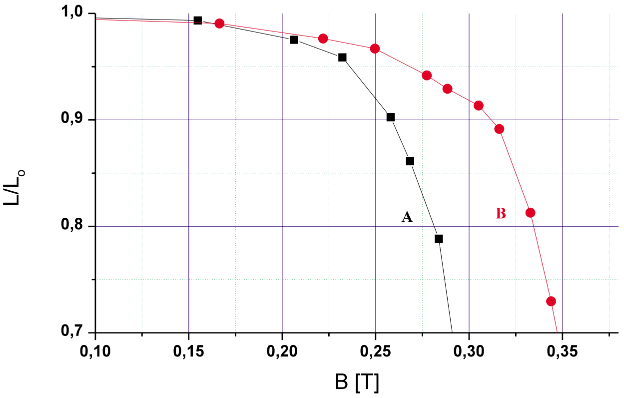

Figure 5: Inductance of toroid cores with an air-gap, made from the standard material, A, and the new design, B, as a function of B_{PK_MAX} at 120 °C

Slika 5: Primerjava induktivnosti toroidnih feritnih jeder z zračno režo materialov A in B v odvisnosti od točkovne nasičenjske gostote pri T = 120 °C

Useable flux density is defined as the calculated flux density at the point of minimum cross-sectional area (A_{min}) in the magnetic core that corresponds to the dc bias condition. A dc current (I_{DC}) equivalent to the peak current is typically used to measure the inductance for a specific peak-current condition and the maximum peak-flux density in the core (B_{PK_MAX}) is established as (**Figure 5**): L is the inductance at 0 ADC, I is the specified test current, A_{min} is the minimum cross-sectional area, and N_p is the number of turns.

4 CONCLUSIONS

The new material, B, is very appropriate for the high-frequency region up to 500 kHz. Compared with the standard material, A, the power losses can be decreased by 40 %. This was achieved mainly by creating a microstructure with smaller grains and a higher electrical resistance of the grain boundaries. At the same time the saturation was increased by choosing an appropriate composition and by enhancing the density. With these properties, B, the upgraded version of A, is very suitable for DC-DC applications.

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