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Theoretical and experimental demonstration of the relationship between microstructure and the DC-bias-superposition characteristic of ferrite materials

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ABSTRACT

DC-bias superposition is important for ferrite materials used in power components. However, methods of improving this characteristic of ferrites have not yet been clearly established. In this study, we theoretically prove that a ferrite with high intrinsic permeability composition and thick grain-boundary microstructure provides better DC-bias superposition than a ferrite with low intrinsic-permeability composition and thin grain-boundary microstructure given the same permeability. We then validate the theoretical results by experiments. Results can guide the development of ferrite materials while considering permeability and stability for the improvement of DC-bias superposition.

1. Introduction

Ferrites are important electronic ceramic materials used in many magnetic components, such as inductors, transformers, anti-EMI (electromagnetic interference) filters and converters [1–7]. Portable devices have continued to develop towards being low-profile, miniaturised and multifunctional in recent years. Consequently, an increasing number of magnetic components need to function under DC-bias conditions to improve the power density of devices [8–15]. DC-bias conditions significantly influence the magnetic properties of ferrite cores, especially their permeability. Permeability under the DC-bias-superposition condition is also called incremental permeability. In power field applications, we aim to obtain high permeability and high incremental permeability under DC-bias-superposition conditions or withstand a high-bias magnetic field when permeability decreases at the same ratio [16]. However, increasing permeability reduces the DC-bias superposition characteristic because the magnetic materials saturate at low current [14]. Given the great demand for high-performance (i.e. high inductance and superior DC-bias-superposition characteristic) magnetic components, further efforts must focus on developing new materials for power applications. Recently, H. Hsiang investigated copper-rich phase segregation effects on the DC-bias-superposition characteristic of NiCuZn ferrites. The nonmagnetic copper-rich secondary phase at the grain boundaries was found to reduce the effective magnetic field applied on the ferrite grain, enhancing the DC-superposition characteristic [16]. L. Huan investigated the effects of SnO_2 additive on the DC-bias-superposition characteristic of low-temperature-fired NiCuZn ferrites. 0.75 wt% SnO_2 additive can be well-balanced with high permeability and high DC-bias-superposition characteristic [17]. X. Tang and S. Yan investigated the effect of microstructure on the DC-bias superposition characteristic of NiCuZn ferrites and determined that a uniform and dense microstructure with a relatively small average grain size was favourable for obtaining good DC-bias-superposition characteristic [11,15]. The improvement of coercive field is suggested to be an important factor for enhancing the DC-bias-superposition characteristic of ferrite materials because a high coercive field indicates that ferrites are not easily magnetised to saturation [17,18]. High saturation magnetisation is speculated to be favourable to obtain a good DC-bias-superposition characteristic. For a ferrite with high saturation magnetisation, a linear relationship between magnetisation and DC-bias-superposition characteristic can be maintained under the DC bias magnetic field, leading to high incremental permeability [13,19]. However, previous investigations were based on experimental results and lacked clear theoretical support. The DC-bias-superposition characteristic of ferrite materials was also compared in samples with different permeability, indicating that differences in permeability exert great influence on the DC-bias-superposition characteristic. For example, high permeability is inclined towards a poor DC-bias-superposition characteristic; thus, results of previous comparisons were not very fair. The DC-bias-superposition characteristic of ferrite materials should be improved while

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obtaining the same permeability.

2. Theoretical derivation

The magnetic properties of ferrite materials are strongly influenced by their chemical composition and microstructure, and the latter is sensitive to the manufacturing process and additives [20]. In this study, we constructed a coherent model and theoretically deduced the relationship between the microstructure and the DC-bias-superposition characteristic of ferrite materials. The conclusion was experimentally verified. The results of this investigation can guide the development of ferrite materials while considering permeability and stability for the improvement of DC-bias superposition characteristic.

Polycrystalline ferrite materials are formed by magnetic grains and nonmagnetic grain boundaries, which continuously surround the grains. The permeability of grains can be regarded as an intrinsic permeability (i.e. grain permeability), whereas the permeability of nonmagnetic grain boundaries is similar to an air gap, which is equal to 1. The tested permeability of ferrite materials is equal to the combined action of the effective permeability of both magnetic grains and nonmagnetic grain boundaries. The intrinsic permeability of ferrites can be enhanced by improving the Zn ratio in the ferrite composition to some extent. Nevertheless, an increasing thickness of grain boundaries decreases the effective permeability of ferrites. Thus, a ferrite with high intrinsic permeability and a thick grain-boundary microstructure may obtain an equally effective permeability with a ferrite with low intrinsic permeability and thin grain-boundary microstructure. As shown in Fig. 1, we assumed that sample 1 has high intrinsic permeability μ_1, a thick average grain boundary δ_1 and an average grain size D_1. Sample 2 has low intrinsic permeability μ_2, a thin average grain boundary δ_2 and an average grain size D_2. The crystal phase structure of the two samples is the same. If the two samples can obtain the same effective permeability, then we first theoretically deduce which type of sample is more advantageous to obtain a superior DC-bias-superposition characteristic.

The polycrystalline ferrite samples can be regarded as a matrix of grains surrounded by nonmagnetic grain boundaries. Given an applied magnetic field H applied on the matrix, flux B will flow in the direction of H, with B being continuous across the grain–grain boundary interface [21]. Ampere's law presents the following formula:

$$\oint H.\,dl = NI \tag{1}$$

where H is the internal field in the sample, l is the length through the internal magnetic field and NI is the number of Ampere turns. Given a single period in our regular polycrystal with length $D + \delta$, Eq. (1) can be expressed in the two following ways [21]:

$$\frac{B\delta}{\mu_0} + \frac{BD}{\mu_i\mu_0} = NI = \frac{B(D+\delta)}{\mu_e\mu_0} \tag{2}$$

where μ_0 is the air permeability, μ_i is the intrinsic permeability of grains and μ_e is the effective permeability of the ferrite materials. D and δ are the average grain size and the thickness of grain boundary, respectively. As a result, we can obtain the following equation:

$$\frac{\delta}{\mu_0} + \frac{D}{\mu_i\mu_0} = \frac{D+\delta}{\mu_e\mu_0} \tag{3}$$

The tested effective permeability of polycrystalline ferrite materials can then be written as the following equation:

$$\mu_e = \frac{D+\delta}{\delta + \frac{D}{\mu_i}} = \frac{1+\frac{\delta}{D}}{\frac{\delta}{D}+\frac{1}{\mu_i}} \quad \text{and} \quad \mu_i = \frac{1}{\frac{1+\frac{\delta}{D}}{\mu_e} - \frac{\delta}{D}}. \tag{4}$$

Therefore, the following formula is derived:

$$1 - \frac{\delta}{D+\delta} = \frac{\mu_i(\mu_e - 1)}{\mu_e(\mu_i - 1)} \tag{5}$$

In Eq. (4), given μ_i derivatives of μ_e, the following formula is derived:

$$\frac{d\mu_e}{d\mu_i} = \frac{\mu_e^2}{\mu_i^2}\left(1 - \frac{\delta}{D+\delta}\right) \tag{6}$$

Introducing Eq. (5) into Eq. (6) can generate the following formula:

$$\frac{d\mu_e}{\mu_e} = \frac{d\mu_i}{\mu_i}\left(\frac{\mu_e - 1}{\mu_i - 1}\right) \tag{7}$$

Considering that $\mu_e < \mu_i$, Eq. (7) indicates that the variation ratio of effective permeability is small given any factor that causes variation in intrinsic permeability of ferrite materials. The factors leading to variation in permeability also include the influence of DC-bias-superposition on permeability.

To analyse the difference between samples 1 and 2, the following formula for sample 1 was used:

$$\frac{d\mu_{e1}}{\mu_{e1}} = \frac{d\mu_1}{\mu_1}\left(\frac{\mu_{e1} - 1}{\mu_1 - 1}\right) \tag{8}$$

where μ_{e1} and μ_1 are the effective permeability and the intrinsic permeability of sample 1, respectively. For sample 2, the following formula was used:

$$\frac{d\mu_{e2}}{\mu_{e2}} = \frac{d\mu_2}{\mu_2}\left(\frac{\mu_{e2} - 1}{\mu_2 - 1}\right) \tag{9}$$

where μ_{e2} and μ_2 are the effective permeability and the intrinsic permeability of sample 2. When $\mu_{e1} = \mu_{e2} = \mu_e$, under the same influence of external factors, we divided Eq. (9) by Eq. (8) and arrive at the following equation:

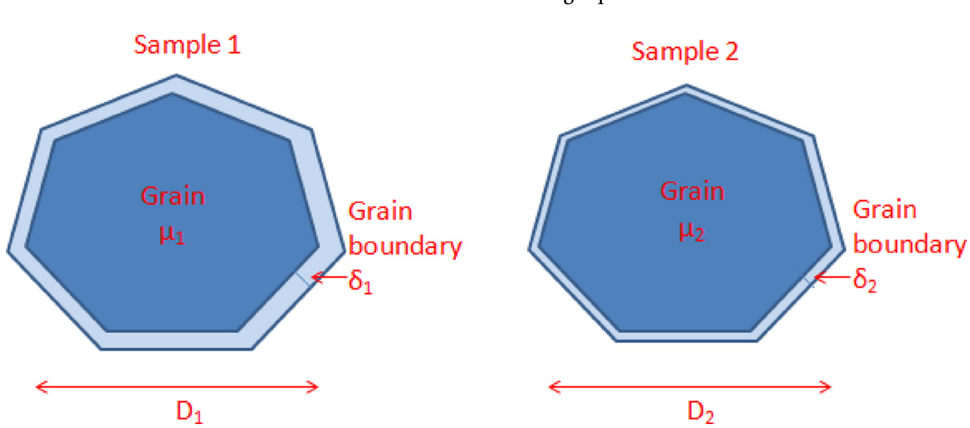

Fig. 1. Schematic representation of the polycrystalline ferrite samples 1 and 2.