MnZn Ferrites with Low Loss and High Flux Density for Power Supply Transformer†

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Abstract:

New MnZn ferrite with high saturation flux density, B_s was developed as a material suitable for transformer cores built into fly-back mode power supplies. Addition of NiO into the ternary Mn-Zn-Fe-O system requires higher Fe content to keep the temperature of minimum iron loss at around 100°C, compared to the original composition. This modification results in enhancement of B_s at 100°C. The new product "MB1H" was realized by choosing optimal composition so that B_s becomes high and iron loss is moderate. The transformer made with MB1H, designed to generate the same output power as ones with conventional materials, has proved to increase saturation flux density 20% at 100°C and to reduce 30% in volume.

1. Introduction

Switching power supplies are widely used in home electric appliances, OA equipment, and industrial machinery. Their main role is to transform commercial electricity (50/60 Hz) into DC voltage which drives the electronic components. Requirements for magnetic cores used in switching power supply transformers include soft magnetism, easy magnetization with a small external magnetic field, and low loss. Magnetic materials are classified into two groups, metallic materials and oxidic materials. Because the electric resistance of the metallic materials is generally lower, driving the transformer of a switching power supply causes large eddy current loss at high frequencies, typically from several ten hertz to several hundred hertz. In order to suppress loss, oxidic materials, especially MnZn ferrites, are used in the transformer rather than metallic materials. JFE Ferrite, a member of the JFE Steel Group, manufactures MnZn ferrite cores suitable for transformers.

The drawback of MnZn ferrites is their saturation magnetic flux density, which is lower than those in metallic soft materials. This means that a larger volume of ferrite core is required to produce the same amount of magnetic flux as metallic cores produce. Furthermore, the Curie temperature of MnZn ferrite is also lower, being typically less than 250°C. Magnetic flux density decreases as temperature increases and vanishes at the Curie temperature. This means that magnetic flux density is lower at the operating temperature of transformers, from 80 to 100°C, than at the room temperature. In an attempt to enhance magnetic flux density at around 100°C, the authors examined the main composition of this material, including introduction of NiO into the ternary MnO-ZnO-Fe_2O_3 system.

In chapter 2 of this paper, the authors describe several properties required for switching power supplies. Possible factors that can influence the most important properties, core loss and magnetic flux density, are discussed in chapter 3. The authors present the main results of the matrix components that make it possible to secure higher magnetic flux in chapter 4, and finally, the authors verify the effect of using the new material in an actual transformer.

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2. Requisites of Ferrite Core for Switching Power Supplies

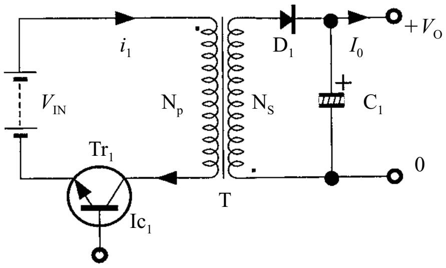
When soft magnetic materials, including soft ferrites, are used as cores in transformers, the magnetic function is realized under the condition that the core is wound with wire and an electric current is passed through it. Soft magnetic materials are utilized in various manners in comparison with hard magnetic materials, for example, as a magnet, which can create a magnetic field by itself. Therefore, various kinds of properties are required in this type of core, depending on the situation in which the core is used. For example, electric circuits in switching power supplies with AC 100 V inlet power are classified into two types, insulated and non-insulated, and the consumption wattage also varies. Transformer cores of different sizes and shapes are also adopted as required by the system. Generally, larger cores are used for larger outputs. In this paper, we focus on the switching power supply of a flyback mode converter, which has an output wattage of is less than 50–60 W, and is typically used in power adapters of laptop personal computers.

The basic configuration of the flyback mode converter is shown in **Fig. 1**[1]. When transistor Tr_1 is on, the primary winding stores electric power in the transformer. After Tr_1 is turned off, the stored energy is transferred to output through an electric current along the secondary winding. Switching on and off repeatedly produces a stable electric voltage.

The electric current along the primary winding corresponds to a magnetic field applied to the core. The *B*-*H* curves of ferrite cores with different saturation magnetic flux density, B_s, in **Fig. 2** show that the actual range of ΔB in the core with high B_s (plotted as bold line) is larger than that in the core with lower B_s (thin line). In the fly back mode, where energy is stored in the transformer temporarily, a core with higher B_s is advantageous because the energy density in the core can be higher. On the other hand, the ΔB value also becomes larger as the intercept across the ordinate is lower. This value is a parameter showing how much magnetic flux remains when the applied field is removed, and is called residual magnetic flux density, B_r. A large B_r value means a large area surrounded by the *B*-*H* loop, hysteresis, and also large loss in the core. When the maximum magnetic flux of the core produced by an electric current is defined as B_m, ΔB is expressed as $B_m - B_r$.

The number of primary windings, N_p, is related to ΔB (T) by Eq. (1)[1].

$$N_p = \frac{V_{IN} \cdot t_{OK}}{\Delta B \cdot A_e} \quad \cdots\cdots (1)$$



Tr_1: Transistor, T: Transformer, D_1: Diode, C_1: Capacitor, V_{IN}: Input voltage, N_p: Primary winding, N_s: Secondary winding

Fig. 1 Schematic diagram of electric circuit for flyback converter

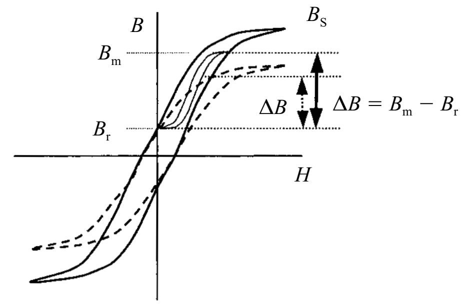


Fig. 2 *B*-*H* curves of Mn-Zn ferrite cores (Small curve in the first quadrant refers to the curve in practical drive.)

Where V_{IN}, t_{ON}, A_e denote input voltage (V), time while transistor is switched on (s), and cross-sectional area of core (m^2), respectively. Under the condition that N_p and input voltage are constant. A_e decreases as ΔB in the denominator increases; otherwise t_{ON} is short. Short t_{ON} means that the transformer is driven at high frequency. However, the upper limit in flyback mode converters is between 50 and 100 kHz. Adopting a core with large ΔB is a realistic way of downsizing transformers. When A_e is constant, N_p decreases as ΔB increases. Decreasing number of windings is another way of downsizing.

Temperature rise of the transformer originates from the core itself (iron loss) and from the Joule heat of the winding wires (copper loss). If the core is minimized without changing the cross-sectional area, it is necessary to wind thin wires in a limited space, resulting in temperature rise due to Joule heat in the wires. Increase in ΔB results in a reduction in the number and space for winding regardless of diameter of the wire. In spite of the large ΔB, the increase in the intrinsic loss of the core causes heat generation due to iron loss. Iron loss is roughly proportional to the square of the driving frequency and is therefore considered to be less serious in this type of converter than in other types because the flyback mode converter is used only at frequencies up to 100 kHz, as mentioned above. However, it is desirable to minimize this loss.

The requisite properties for the MnZn ferrite core in fly back mode converters are summarized as two, large B_s and low iron loss.

3. Development Policy

Possible measures to increase saturation magnetic flux density, B_s include (1) increasing the density of the sintered body of the core, (2) increasing the total of the magnetic moments of the constituent ions in the spinel matrix phase, and (3) raising the Curie temperature, T_c, among others.

It is clear that enhancing the density of the core will result in an increase in B_s. For this purpose, optimizing the sintering conditions and the kinds and amounts of additive trace elements is very important.

The spinel structure, which is the main phase of MnZn ferrite, is composed of Mn, Zn, and Fe ions occupying crystallographic equivalent sites, A and B, with oxygen surrounding these metallic ions, as shown in **Fig. 3**. The magnetic moments assigned to ions at the A and B sites are arranged in parallel in opposite directions by a superexchange interaction through oxygen. In this configuration, some moments are canceled, which reduces the total compared to that in soft metallic materials, where the magnetic moments are arranged in parallel in the same direction. Therefore, how the constituent elements occupy the A and B sites determines the total of the magnetic moments, namely B_s.

The B_s of spinel compounds, like that of common metallic materials, decreases as temperature increases. Comparing B_s at 25°C to that at 100°C, the decrement is smaller in cores with higher T_c. T_c can be considered to represent the strength of the superexchange interaction against thermal energy, and is determined mainly by the composition of the matrix phase. Therefore, it is very important to choose the optimal composition for increasing B_s.

On the other hand, the requirement of low loss is also related to the main composition. There are some ideal compositions that exhibit a low magnetocrystalline anisotropy constant, K_1, and low saturation magneto striction constant, λ_s[2].

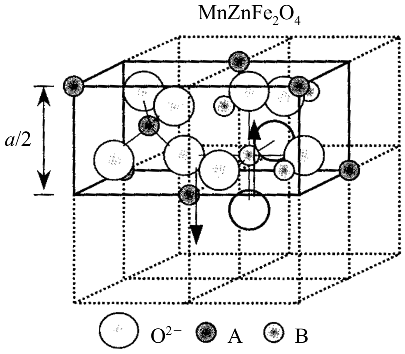


Fig. 3 Crystal structure of spinel

Both parameters, especially K_1, vary with temperature. A composition in which K_1 is almost zero at 100°C and lambda is low, typically Fe_2O_3 = 52–54 mol%, ZnO = 12–14 mol%, and MnO is the balance, is selected for conventional MnZn ferrites used in power supplies. Generally, iron loss varies remarkably with temperature, reflecting the temperature dependence of K_1. Increasing Fe_2O_3 in the main composition tends to enhance B_s and also lowers the minimum temperature, Tp, at which iron loss shows its minimum. A similar effect is seen when the ZnO content is varied. If Tp is considerably different from 100°C, iron loss becomes larger at 100°C, which is the operating temperature of transformers. Thus, it is necessary to secure Tp near the operating temperature, and at the same time, to increase the Fe_2O_3 content for higher B_s.

The ternary system of MnO-ZnO-Fe_2O_3 has been discussed so far. Magnetic properties are expected to change with the introduction of new magnetic ions. For example, a small addition of Co^{2+} to the main composition greatly reduced the temperature dependence of iron loss[3]. However, in this case, addition of the Co^{2+} ion had almost no effect on enhancing B_s. Therefore, another magnetic ion, Ni^{2+}, was examined for its effects on B_s and loss.

4. Effect of Main Composition on Temperature Dependence of Loss and Saturation Magnetic Flux Density

4.1 Experimental Procedure

MnZn ferrite cores were fabricated by a conventional powder metallurgy process. The raw materials, Fe_2O_3, Mn_3O_4, ZnO, and NiO if necessary, were mixed, calcined, and pulverized with trace additives. The obtained powders were pressed into a toroidal shape, followed by sintering. The sintered cores were 31 mm in outer diameter, 19 mm in inner diameter, and 7 mm in thickness.

The main compositions were selected as shown below; the balance is MnO in all cases.

(1) ZnO: 10 mol%, Fe_2O_3: 53–56 mol%
(2) ZnO: 4–16 mol%, Fe_2O_3 adjusted so that minimum temperature of iron loss is 90–100°C
(3) ZnO: 9.4 mol%, NiO: 0.0–0.8 mol%, where the total amount of NiO and Fe_2O_3 is 53.6 mol%
(4) ZnO: 10 mol%, Fe_2O_3: 53.5 and 54.9 mol%, NiO: 3 mol%
(5) ZnO: 10 mol%, NiO: 0–8 mol%, Fe_2O_3 adjusted so that minimum temperature of iron loss is around 90°C

Measurement of iron loss per unit volume, P_{cv}, was performed using a BH analyzer (Iwatsu Electric Co., Ltd.: SY-8216) from −30 to 140°C, under the condition that the cores were driven by a sinewave of 100 kHz and maximum flux is 200 mT.

Saturation magnetic flux density was determined using a DC BH loop tracer (Riken Denshi Co., Ltd.) from the room temperature to 140°C. Specimens were wound with 20 turns primary and 40 turns secondary and applied under a magnetic field of 1 200 A/m.

4.2 Results and Discussion

4.2.1 Influence of composition on saturation magnetic flux density and temperature dependence of iron loss in ternary system

When Fe_2O_3 is increased in a MnZn ternary system, B_s at 100°C increases linearly, as shown in **Fig. 4**, and the minimum temperatures Tp shifts toward lower temperature. **Figure 5** clearly shows that the core with 55.6 mol% of Fe_2O_3 has high B_s while iron loss is as large as over 1 000 kW/m^3 at the operating temperature of transformers, 100°C. It is considered that the temperature of a transformer using this core increases due to increased iron loss, and this is followed by a further increase at elevated temperature.

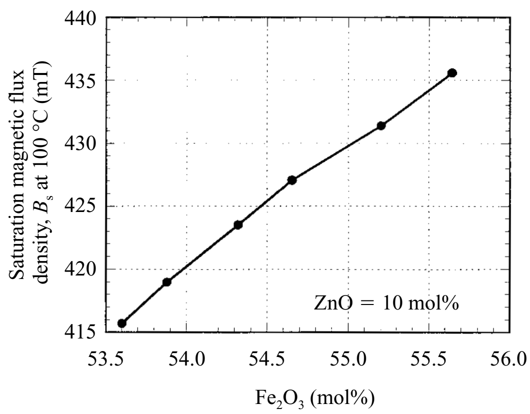


Fig. 4 Saturation magnetic flux density, B_s at 100°C in MnZn ferrites with 10 mol% of ZnO

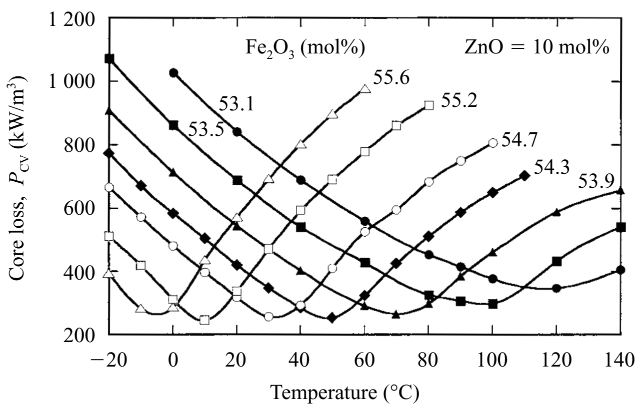


Fig. 5 Temperature dependence of core loss in MnZn ferrites with various Fe_2O_3 contents at 100 kHz and 200 mT

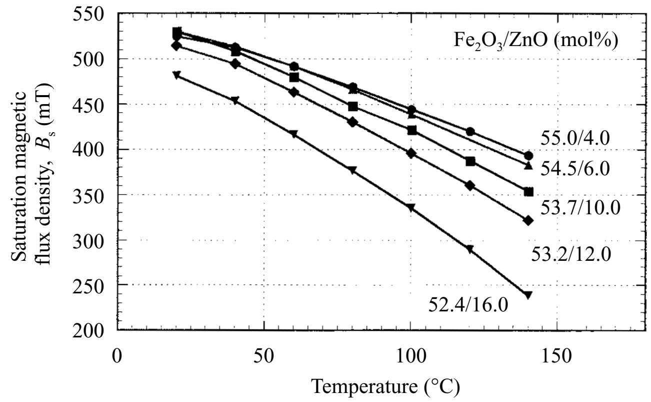


Fig. 6 Temperature dependence of saturation magnetic flux density in MnZn ferrites with various Fe_2O_3 and ZnO contents

On the other hand, increasing the ZnO content also shifts Tp toward lower temperatures. It is possible to maintain Tp by properly selecting the contents of Fe_2O_3 and ZnO. In **Fig. 6**, the temperature dependence of B_s of samples that exhibit almost constant Tp with various Fe_2O_3 and ZnO are compared. The cores with higher Fe_2O_3 and lower ZnO contents show higher B_s in the temperature range up to 140°C. B_s can be enhanced to about 450 mT by reducing the ZnO content to 4 mol%; however, the increment of B_s becomes smaller, which implies that further increases of B_s cannot be expected only by reducing the ZnO content. Another problem of cores with lower ZnO is more remarkable temperature dependence of iron loss.

4.2.2 Effect of introduction of NiO

In an attempt to increase B_s further, NiO addition to the main composition was examined. Because Ni is assumed to be a +2 ion in spinel compounds, first, the composition was determined in such a manner that Ni^{2+} replaces Fe^{2+}, which affects magnetocrystalline anisotropy, K_1, and also the temperature dependence of loss. Substitution of Ni for Fe proved that Tp shifts toward higher temperatures as the NiO content increases, as shown in **Fig. 7**, and iron loss at 100°C increases. In order to maintain Tp, it is necessary to increase the Fe content, which is expected to lead to enhanced B_s. **Figure 8** shows that increasing Fe_2O_3 from 53.5 to 54.9 mol% cause Tp to shift to 20°C, but addition of 3.0 mol% of NiO increases Tp back to 100°C. This change in temperature dependence partially shares common characteristics with Co addition originating from the change of K_1. In MnZn ferrite, K_1 has a large minus value at lower temperatures, increases as the temperature increases, and approaches zero at a certain temperature which corresponds to Tp. Increasing the in Fe_2O_3 con-

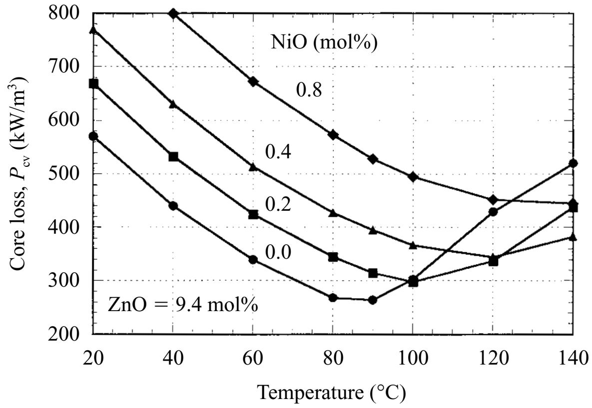


Fig. 7 Temperature dependence of core loss in MnZn ferrites with various NiO contents at 100 kHz, 200 mT

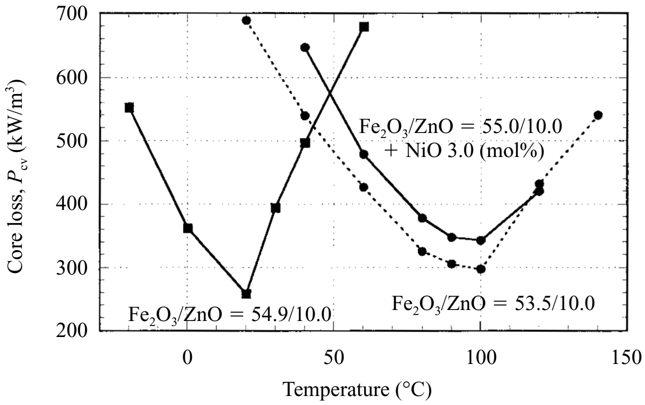


Fig. 8 Temperature dependence of core loss in MnZn ferrites with various Fe_2O_3 and NiO contents at 100 kHz and 200 mT

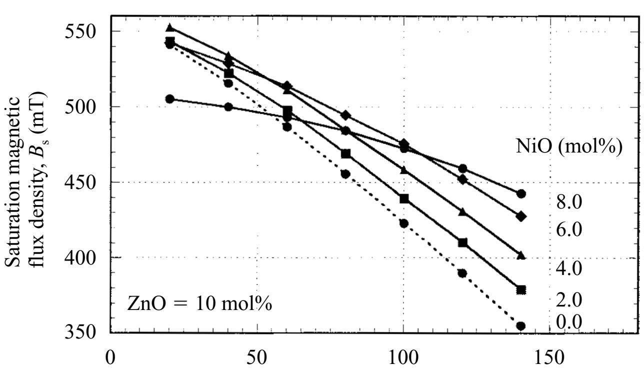


Fig. 9 Temperature dependence of saturation magnetic flux density in MnZn ferrites with various NiO contents

tent reduces Tp because Fe^{2+} contributes to increasing K_1. Ni^{2+} is considered to contribute in the opposite manner, that is by reducing K_1. Therefore, it is possible to maintain Tp at 100°C by properly selecting the contents of Fe_2O_3 and NiO.

On the basis of these results, the temperature dependence of a four-element system including NiO was investigated adjusting Tp to around 100°C. The results are shown in **Fig. 9**, where B_s at 100°C exceeds 450 mT

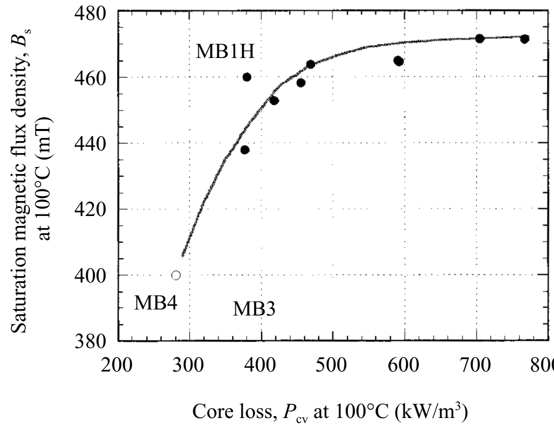


Fig. 10 Plots of core loss at 100 kHz and 200 mT and saturation magnetic flux density at 100°C in MnZn ferrites

Table 1 Comparison of properties of MB3 and MB1H

Material		MB3	MB1H
Saturation magnetic flux density at 1 200 A/m (mT)	23°C	510	540
	100°C	390	460
Core loss* (kW/m^3)	23°C	650	980
	60°C	440	600
	100°C	350	380
Curie temperature (°C)		215	300

* 100 kHz and 200 mT

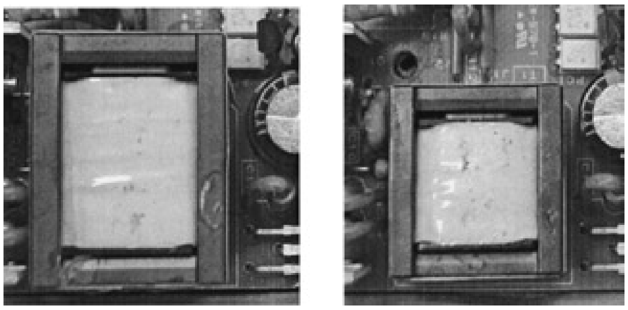
when NiO = 4 mol% and higher contents result in higher B_s, but with a slight decrease at room temperature. In the higher temperature range, the decrement with temperature is smaller as the NiO content increases. This change implies that T_c increases. Plotting B_s values against iron losses at 100°C shows that a core with a composition that enhances B_s also exhibits higher iron loss, and vice versa, as shown in **Fig. 10**. The increase in iron loss is considered to be due to larger magnetostriction, λ_s. Judging from the results in Fig. 10, the optimal composition gives higher B_s than in conventional cores and moderate iron loss, 460 mT and 400 kW/m^3, respectively. A new material, "MB1H," showing these properties has been commercialized by optimizing sintering conditions to enable lower loss and enhanced density of the sintered body with the new composition including NiO. Representative properties of MB1H are listed in **Table 1**.

5. Trial Products Using MB1H

The performance of a flyback mode switching power supply using MB1H with high B_s was compared to that using the conventional material, MB3. The transformers in commercially-available power supplies were replaced with parts assembled using MB1H and MB3, respectively. The Core size and number of windings of each

Table 2 Shape and dimension of cores, incremental magnetic flux density, and winding condition of transformers

Material	Core type	Cross sectional area (mm^2)	Volume (mm^3)	ΔB (mT)	Primary winding	Secondary winding
MB1H	EEPC-25D	41.5	2 340	340	$\phi 0.30 \times 2$: 70 turns	$\phi 0.60 \times 2$: 7 turns
MB3	EEPC-27D	48.9	3 480	270	$\phi 0.35 \times 2$: 75 turns	$\phi 0.80 \times 2$: 8 turns



(1) MB3 EEPC-27D (19.2 g) (2) MB1H EEPC-25D (13.7 g)

Photo 1 Transformer using MB3 (1) and MB1H (2) designed to show the same output power

transformer were determined as shown in **Table 2**, and the gap length in the center pole was determined so that inductance would be same.

The ΔB of MB1H was 350 mT, 30% larger than that of MB3, 270 mT because of the 20% increment in B_s in MB1H in comparison with MB3. From Eq. (1), it is possible to reduce the cross-sectional area from that of an EEPC-27D core with MB3 to that of an EEPC-25D core with MB1H, as shown in **Photo 1**, while producing the same output voltage. The decrement in core size is 20% in cross sectional area and 30% in volume, and the number of windings also decreases compared to MB3. A temperature rise test revealed that heat generation in the two transformers was almost the same (less than 2°C) in both the core part and wire part. Furthermore, conversion efficiency improved from 69.9% to 70.2% by replacing the core.

This result confirms that higher efficiency can be realized in the transformer of the flyback mode converter while also downsizing the transformer, without increasing heat generation, by using a core with higher B_s. Low temperature rise in spite of moderate loss was attributed to increment of ΔB.

6. Conclusions

(1) The saturation magnetic flux density, B_s, of ternary MnZn ferrite is increased by increasing the Fe_2O_3 content; however, at the same time, the minimum temperature of iron loss, Tp, shifts toward lower temperatures, which gives rise to increased loss at 100°C. The minimum temperature can be adjusted by properly selecting a main composition including ZnO. The maximum value of B_s at 100°C is about 440 mT.

(2) Introduction of NiO to the main composition increases Tp. The increment of Fe_2O_3 content which cancels the increased Tp results in enhanced B_s at 100°C.

(3) A new material, MB1H, was developed on the basis of these results, and exhibits 20% higher B_s compared to that of the conventional material, MB3. A trial transformer of a flyback mode switching power supply using MB1H instead of MB3 revealed that the transformer can be downsized while conversion efficiency is improved due to the increment of Bs. Temperature rise is similar in both transformers.

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