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High Performance MnZn Ferrites for Transformer Core Used in Forward Mode Switching Power Supply†

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Abstract:

Low loss MnZn ferrites which have been developed until now for transformer cores in switching power supplies were introduced with future development trends. In addition to the improvement on core loss and saturation-magnetic flux density, the temperature and frequency dependence of the core loss have been particularly improved in new materials, MBT3 and MBF4, respectively. The most suitable material for enhancing the power supply efficiency of a commercial forward mode switching power supply was evaluated in comparison with the current materials, MB3 and MB4. The efficiency increased in the order of MB3≤MB4<MBT3≤MBF4. Although MBT3 shows the lowest loss under the sinusoidal flux condition, the highest efficiency can be obtained as using MBF4, which shows lower harmonic losses derived from the rectangular wave voltage in the actual power supply due to the excellent frequency dependence of the core loss.

1. Introduction

Soft magnetic materials are used in a wide range of applications, including power conversion, signal conversion, etc., as stationary electrical machinery and rotating machines from static magnetic fields up to higher gigahertz frequency ranges. Of these materials, companies in the JFE Steel Group manufacture and market grain-oriented and non-oriented electrical steel sheets, iron powder, and soft ferrite. Among these products, soft ferrite possesses dramatically higher specific resistance in comparison with metallic soft magnetic materials and displays an excellent soft magnetic property between several kilohertzs and several hundred megahertzs, and therefore is widely used in cores for high frequency power supply transformers, choke coils, noise filters, and similar applications. Demand for soft ferrite cores is currently expanding in response to the rapid popularization of consumer electronic equipment such as digital home electrical appliances, personal computers, and cellular phones. In this field, the requirements placed on ferrite cores are compact size and thinner shapes, in combination with higher performance as defined by higher frequencies, lower loss, higher permeability, and higher magnetic flux density in comparison with conventional materials.

Among these soft ferrites, MnZn ferrites are widely used in power supply transformer cores of the switching power supplies installed in various types of electronic equipment. In MnZn ferrites, low loss is the most important item for improving power supply efficiency. To date, JFE Ferrite, which is a member of the JFE Chemical Group, has manufactured and marketed MB3 as a general-purpose low loss material and MB4 as a product with lower loss. However, recent years have seen heightened requirements from electronic equipment manufacturers and power supply transformer manufacturers, not only for this type of general-purpose low loss material,

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but also for new materials suited to each user's design and manufacturing processes. Further development and commercialization products with higher properties and higher added value suited to the distinctive features and needs of the user's products, and response to more compact or thinner designs of transformers, which account for a comparatively large volume in the power supply section, have become urgent matters.

In these circumstances, JFE Ferrite developed MB1H as the optimum soft ferrite material for flyback mode switching power supplies, which are used in large quantities in alternating current (AC) adapters and similar products[1,2]. Among switching power supplies, AC adapters with a comparatively low power capacity are driven at the order of 50 kHz to 100 kHz. This material has substantially the same core loss at 100°C as the general-purpose material MB3, but offers 20% higher saturation magnetic flux density, and thus is a suitable material for transformer downsizing, which is possible by adopting a higher magnetic flux density design. This product has earned a high evaluation in the marketplace.

On the other hand, MB3 and MB4 continue to be the main stream in materials suitable for forward mode switching power supplies with comparatively large power capacities and are driven at frequencies on the order of 100 kHz to 300 kHz. MB3 and MB4 are considered to be excellent materials with low loss under conditions of 100 kHz and 100°C[3]. However, there are various differences in the transformer design policies of power supply manufacturers, and diverse shapes and driving conditions are used in transformer cores. Methods of use which are significantly different from conventional designs have also begun to appear. These include devices in which the operating magnetic flux density is increased to near magnetic saturation, devices in which the temperature rise to more than 100°C is expected, and the like.

In this paper, first, newly-developed low loss materials for power supplies for various applications are introduced. Next, the results of an investigation of the packaging characteristics of transformer cores made of various materials using a commercial forward mode power supply and an evaluation and study of the optimum material are described.

2. Development of Various Low Loss Materials

2.1 Development Trends

Taking advantage of the strength of the JFE Chemical Group as a corporate group with an integrated production system from iron oxide to ferrite cores, JFE Chemical, jointly with JFE Ferrite, developed materials with outstanding properties, including energy loss, permeability, etc., and developed a roller hearth kiln that enables precise atmosphere control and is capable of satisfying both high property requirements and high productivity. **Figure 1** shows the materials for power supplies developed to date, together with future trends. Using the general-purpose material MB3 as the starting material, development is advancing in the directions of improving core loss and saturation magnetic flux density from the viewpoints of temperature and frequency, which have large respective effects on those properties. In Fig. 1, the materials enclosed in circles are products which are in the mass production stage, those in squares have completed laboratory development and are in the small sample stage, and those in diamonds are under development. As shown in this figure, the four directions of development are (1) improvement of core loss at 100 kHz, 200 mT, 100°C, (2) improvement of the temperature dependence of core loss, (3) improvement of core loss in the high frequency range, and (4) improvement of saturation magnetic flux density.

MB4, which is a low loss material for power supplies, has a core loss value of 270 kW/m^3 (100 kHz, 200 mT, 100°C) and achieves an energy loss improvement of approximately 20% in comparison with the general-purpose power supply material MB3. Thus, this is a material that can respond to the social need for energy saving. MBT1 and MBT2 are materials with improved temperature dependence of core loss, which had been a weak point of conventional power supply materials, and show low energy loss values from room temperature to around 100°C[4–6]. Use of these materials has expanded to applications characterized by large changes in the temperature environment in which the products are used, beginning with automotive applications. MB1H features high saturation magnetic flux density of 460 mT (100°C), which makes it possible to increase the design magnetic flux density of transformers. This material is optimal for applications requiring downsizing of flyback mode switching power supplies of approximately 50 W and under. MC2 has a core loss value of 65 kW/m^3 (500 kHz, 50 mT, 100°C), which is

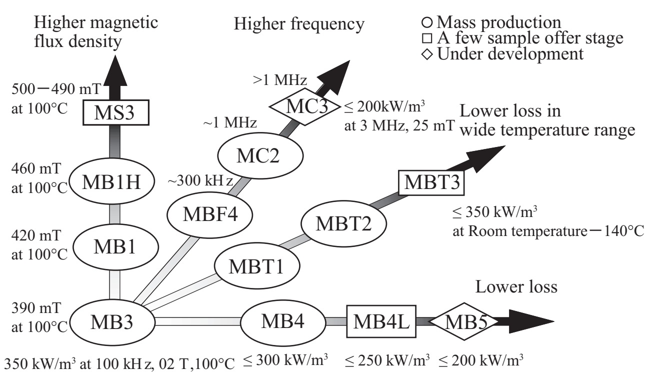

Fig. 1 Schematic diagram of development of low loss MnZn ferrites for switching power supplies

the No. 1 core loss property among industrial products. This product is used in special power supply applications at several hundred kilohertz and higher, where compact sizes and thin designs are required.

Next, the following will introduce three products which were developed as low loss materials for use in forward mode switching power supplies as substitutes for the general-purpose materials MB3 and MB4. These are a modified MB1H material with improved core loss, MBT3, and MBF4.

2.2 Reduction of Core Loss in MB1H with High Saturation Magnetic Flux Density in High Temperature Range

The saturation magnetic flux density of conventional ternary system MnZn ferrite can be enhanced by increasing the Fe_2O_3 concentration from approximately 52.5 mol%, this being the concentration at which the magnetostriction constant become zero. However, in the selection of a ternary system composition which includes ZnO, the saturation magnetic flux density at 100°C is at most around 440 mT. Furthermore, as shown in **Fig. 2**, the temperature at which energy loss is minimized decreases greatly to near room temperature, resulting in increased loss at around 100°C. Here, the temperature at which energy loss is minimized is shifted to the high temperature side by introducing NiO, as shown in Fig. 2. This modification makes it possible to increase the content of Fe_2O_3 in order to minimize energy loss in the vicinity of 100°C, and as a result, the saturation magnetic flux density at 100°C increases. The material developed by this approach is MB1H. However, its core loss is high in comparison with MB3 and MB4. This higher core loss is attributed to the fact that the composition deviates from the composition region for a magnetostriction constant of zero, the quantity of Fe^{2+} ions increases due to the large content of Fe_2O_3, and thereby the specific resistance of crystal grains decreases under the same sintering conditions and the effect of trace additives, which suppress eddy current loss by precipitating at grain boundaries, is weakened.

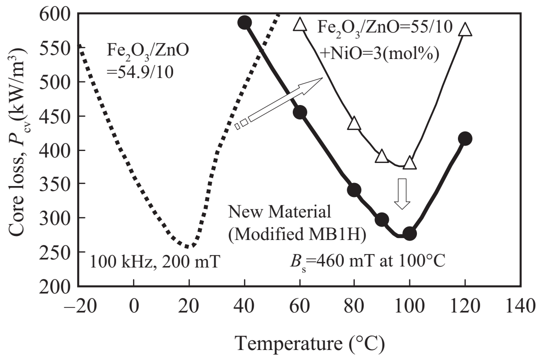

Fig. 2 Temperature dependence of core loss in the modified MB1H with high B_s

The kinds and amount of the trace additive were therefore reviewed and changed to an amount which makes it possible to obtain an adequate effect. Regarding the oxygen concentration in the cooling region of the furnace, the sintering conditions were adjusted to enable adequate formation of the grain boundary resistivity phase.

As a result, it was possible to obtain an MB4 class core loss value of 280 kW/m³ (100 kHz, 200 mT, 100°C), as shown in Fig. 2. Saturation magnetic flux density at 100°C was kept at 460 mT. Thus, it was possible to achieve a further reduction of energy loss while maintaining the distinctive features of MB1H. Although the range of applications of the existing MB1H material had centered on flyback mode switching power supplies, the fact that energy loss could be reduced to the MB4 class means that expansion to forward mode switching power supplies can be expected. However, because production of this material requires changes in the sintering conditions, adjustment to enable stable sintering with existing mass production furnaces is now underway.

2.3 Low Loss Material MBT3 with Small Core Loss Temperature Dependence

MBT1, which was shown in Fig. 1, is the world's first material in which the temperature-related changes in crystal magnetic anisotropy[7] were relaxed and the temperature dependence of core loss was reduced in a mass production product by substituting CoO for part of Fe_2O_3, which is the main constituent of MnZn ferrite. With this product, JFE Chemical achieved low energy loss with MBT2 while using this basic technology and succeeded in mass production with a continuous furnace, based on the following viewpoints.

(1) Selection of the composition of the main constituent and trace additive to reduce hysteresis loss.
(2) Accurate control of the sintering temperature and oxygen concentration in the sintering atmosphere in order to realize the crystal grain size and hole distribution which minimize core loss.
(3) Use of the high purity iron oxide raw material JC-CPW developed and produced by JFE Chemical[8].

In MBT3, lower loss is realized by implementing more accurate atmosphere control in sintering, centering on the key points mentioned above.

Figure 3 shows the temperature dependence of core loss in MBT3 in comparison with MB4 and MBT2. MBT3 realizes a core loss value of 350 kW/m³ (100 kHz, 200 mT) or less from room temperature to the high temperature range of 140°C, enabling use as a low loss material over a wide temperature range. Furthermore, core loss at 100°C is somewhat less than 250 kW/m³, thus realizing the lowest value among the various types

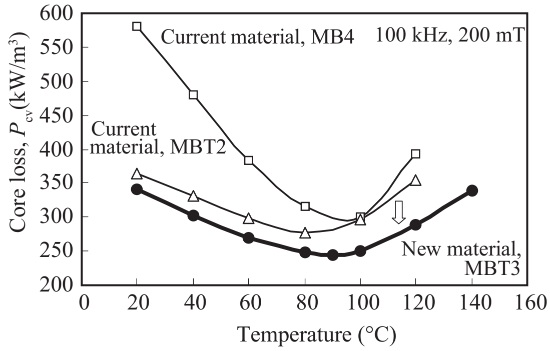

Fig. 3 Temperature dependence of core loss in a new material, MBT3

of low loss power supply materials. Although the composition of MBT3 is unchanged from that of the conventional MBT1 and MBT2, this product is manufactured under sintering conditions which enable the largest overall reduction of core loss across a wide temperature range.

2.4 Low Loss Material MBF4 for Frequency Range from 100–300 kHz

MBF4 is a material which has the same core loss as MB4 at 100 kHz, but realizes lower core loss than MB4 in the higher frequency ranges up to approximately 300 kHz[9]. This considers the fact that the general driving frequencies of existing forward mode switching power supplies are 100 kHz to 300 kHz. **Figure 4** shows

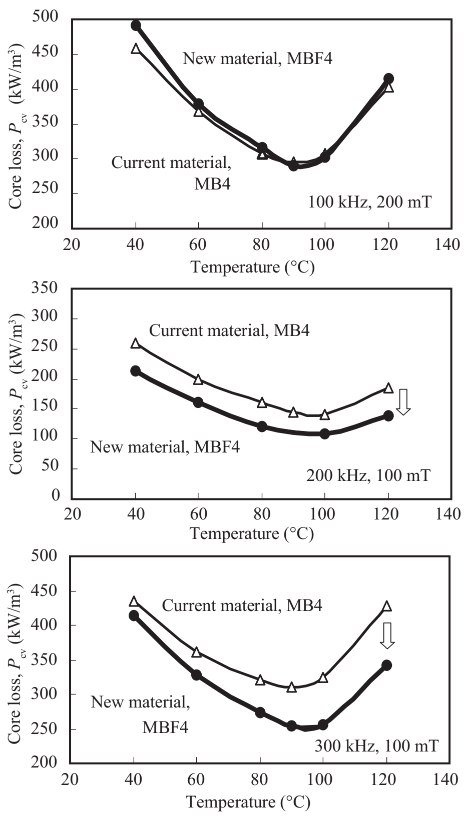

Fig. 4 Temperature dependence of core loss in a new material, MBF4

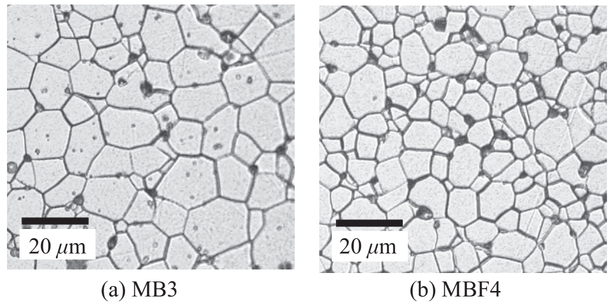

Photo 1 Microstructures of (a)MB3 and (b)MBF4 with the average particle sizes of 9 μm and 6 μm, respectively

the temperature dependence of core loss of MBF4 in comparison with that of MB4 at each frequency. As shown in Fig. 4, MBF4 shows substantially the same temperature dependence of core loss under conditions of 100 kHz and 200 mT, and lower core loss than MB4 at the higher frequencies of 200 kHz and 300 kHz. This feature is the result of reduction of core loss in the high frequency range by reducing the average crystalline grain diameter of approximately 6 μm in the conventional material to approximately 9 μm, as shown in **Photo 1**, which was achieved by adopting low temperature and short time for the maximum temperature keeping condition in comparison with the sintering conditions of the conventional MB3 and MB4. This average crystalline grain diameter was selected as the optimum value because core loss at 100 kHz increases if the grain diameter is decreased beyond 6 μm. In addition, the other sintering conditions were optimized.

MBF4 also has the unprecedented feature of having a core loss value of 300 kW/m^3 or less over a wide frequency range, namely, under conditions of both 100 kHz, 200 mT and 300 kHz, 100 mT. Because many recent forward mode switching power supplies are designed at 200–300 kHz, development to devices of this type is expected.

3. Packaging Evaluation of Transformer Core to Forward Mode Switching Power Supplies

3.1 Forward Mode Switching Power Supply and Measurement Method

Practical shape transformer cores were prepared using various types of low loss MnZn ferrites for power supplies. Power supply characteristics were evaluated in a core substitution mounting test in which the specimens were mounted in a commercial forward mode switching power supply, and the results were compared with the magnetic properties of the core materials and studied.

Using a general commercial forward mode switching power supply (output: 12 V/10 A), packaging characteristics were evaluated by substituting cores of various materials for the core of the main transformer. Because it was assumed that these were transformers in which the bobbin and winding condition were the same and only the core material was different, the substrate part in which the transformer terminal is inserted was improved, and the specimens were modified to receive the terminal from the transformer bobbin by way of an attachment. Power from a commercial 60 Hz, AC100 V power supply was converted to AC200 V by an autotransformer for voltage change and was supplied via an insulation transformer for noise rejection. A wattmeter was connected to the input side, and the electronic load (maximum: 144 W) was connected to the output side. Power supply efficiency was measured from the ratio of the input power and load power. Thermocouples were attached to the region of the outside leg of the transformer core at 4 points and the region of the back at 1 point, and the temperature change in the core were measured after operating the device at room temperature in the condition that the power supply section was exposed. The waveforms of the input current and input voltage of the primary winding of the transformer were observed using an oscilloscope in order to confirm normal operation.

3.2 Results of Packaging of Transformer Cores Using Various Power Supply Materials

Practical shape transformers were prepared using cores of various materials and substituted for the original core (EER-35A shape, unknown material) of a commercial power supply. The power supply characteristics when these specimens were driven at a frequency of 200 kHz are shown in **Table 1**. The transformer core was the same EER-35A shape, and four materials were used, namely, MB3, MB4, MBT3, and MBF4. As the power supply drive condition, the electronic load was set so as to secure an input voltage of AC200 V and output current of DC10–8 A. The output voltage and input current were 12 V and 1–0.6 A, respectively.

The lowest power supply efficiency η was measured with the original core (η: 83.2%). In contrast, with the transformer cores using the various materials mentioned above, efficiency increased in the order MB3<MB4<MBT3<MBF4. MBT3 and MBF4 showed substantially the same high efficiency. In particular, MBF4 shows a value of 86.8%, which is 3.6% higher than that of the original core and 2.0% higher than the MB3 core.

In all cases, the absolute value of temperature was on a low level and presented no problems. The temperature rise $\varDelta$T of the original core was 23°C (average). In contrast, the relative difference of the test cores was small, temperature rise being in the range of 18–23°C. The fact that $\varDelta$T was low is attributed to the favorable conditions for heat radiation in the test, which was conducted with the device in an open condition, i.e., with no

Table 1 Comparison of power supply efficiency and temperature rise in driving at 200 kHz

Driving frequency: 200 kHz		Original core	MB3 EER35A	MB4 EER35A	MBT3 EER35A	MBF4 EER35A
Input	V_{in} (V)	200	200	200	200	200
	I_{in} (A)	1.02	0.99	0.98	0.96	0.95
	W_{in} (W)	142	139.2	139.2	136.2	136
Output	V_o (V)	11.81	11.81	11.81	11.80	11.80
	I_o (A)	10	10	10	10	10
	W_o (W)	118.10	118.10	118.10	118.00	118.00
Efficiency	η(%)	83.17	84.84	84.84	86.64	86.76
Environment	RT (°C)	29.8	27.7	28.2	15.1	15.6
Core temperature	T_1	48	49	46	40	37
	T_2	55	51	45	39	34
	T_3	54	48	44	40	37
	T_4	52	50	47	38	32
	T_5	54	50	46	48	48
	$T_{average}$	52	49	46	41	37
Temperature rise	$\varDelta T_1$	18	21	18	25	21
	$\varDelta T_2$	25	23	17	24	18
	$\varDelta T_3$	24	20	16	25	21
	$\varDelta T_4$	22	22	19	23	16
	$\varDelta T_5$	24	23	18	19	18
	$\varDelta T_{average}$	23	22	18	23	19

V_{in}, V_o, I_{in}, I_o, W_{in}, W_o: Input and out put voltage, current and power, respectively
η: Power supply efficiency, W_o/W_{in} RT: Room temperature
T_1–T_5: Temperatures at five points of the core
$\varDelta T_1$–$\varDelta T_5$: Temperature rises at five points of the core

Table 2 Comparison of power supply efficiency and temperature rise in driving at 122 kHz

Driving frequency: 122 kHz		MB4 EER35A	MBT3 EER35A	MBF4 EER35A
Input	V_{in} (V)	200	200	200
	I_{in} (A)	0.66	0.6	0.56
	W_{in} (W)	111	109.3	108.7
Output	V_o (V)	11.80	11.80	11.80
	I_o (A)	8	8	8
	W_o (W)	94.40	94.40	94.40
Efficiency	η(%)	85.05	86.37	86.84
Environment	RT (°C)	16	14.5	13.5
Core temperature	T_1	31	26	28
	T_2	26	23	22
	T_3	27	23	21
	T_4	21	17	20
	T_5	18	22	23
	$T_{average}$	25	22	23
Temperature rise	ΔT_1	47	41	42
	ΔT_2	42	38	36
	ΔT_3	43	38	35
	ΔT_4	37	32	34
	ΔT_5	34	37	37
	$\Delta T_{average}$	41	37	36

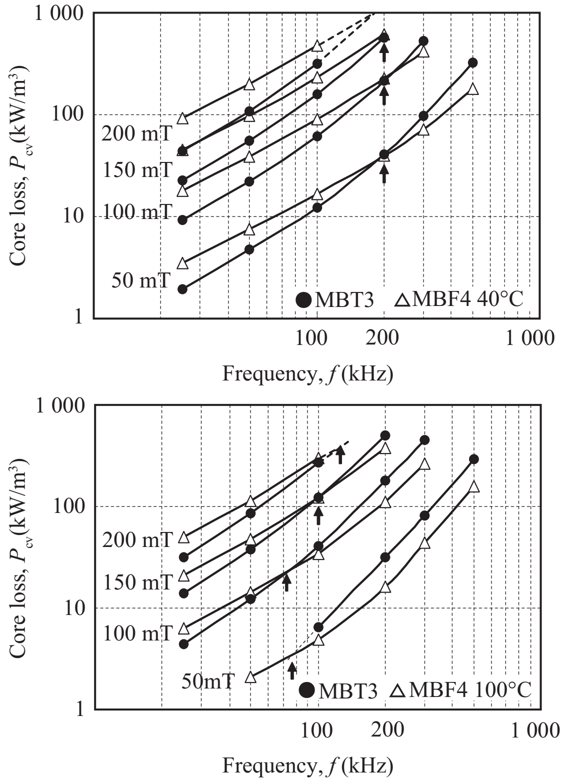

Fig. 5 Frequency dependence of core loss in the new MnZn ferrite materials, MBT3 and MBF4 at 40ºC and 100˚C

power supply cover. The results when the test was performed under the same conditions, but with the driving frequency reduced to 122 kHz, are shown in **Table 2**. Power supply efficiency was unchanged from that when the driving frequency was 200 kHz, and was high in the order of MB4<MBT3 ≒ MBF4.

3.3 Correlation of Core Loss Characteristics and Power Supply Packaging Characteristics with Various Materials

As shown up to the previous section, MBF4 was the most favorable core material under the forward mode switching power supply and transformer conditions used in this research, followed by MBT3, which displayed virtually the same level of performance. Considering the fact that the working temperature of transformers is 40–50°C, the highest efficiency is expected from MBT3, which has excellent temperature dependence of core loss characteristics, as shown in Fig. 3. However, MBF4, which displayed the same temperature characteristics as MB4, demonstrated slightly higher efficiency.

In order to examine the cause of this phenomenon, the detailed magnetic properties of MBF4 and MBT3 were investigated systematically and compared. Core loss characteristics were measured at a wide range of temperature, frequency, and magnetic flux density values using a standard ring core of R31 shape (outer diameter: 31 mm, inner diameter: 19 mm, height: 7 mm). **Figure 5** shows the core loss characteristics of MBT3 and MBF4 when the frequency and magnetic flux density were changed. Temperature shows the cases of 100°C and 40°C. At 100°C, the core loss values of the two cores were reversed at approximately 80 kHz when the magnetic flux density was 50 mT and 100 mT, at approximately 100 kHz with 150 mT, and at 120 kHz with 200 mT. In general, MBF4 shows lower loss as the frequency increases. Under the conditions of 100 kHz, 200 mT, the core loss of MBT3 is the lowest, but when the frequency increases above this level, MBF4 displays lower loss. Thus, for practical use, it is necessary to consider a wide range of power supply operating frequency conditions. In the case of 40°C, the frequency at which core loss performance is reversed shifts slightly to the high frequency side and is approximately 200 kHz in the range of 50–200 mT.

Because forward mode switching power supplies are generally driven by the rectangular wave current and rectangular wave voltage of superpositioned triangular waves, the excitation waveform includes many harmonics with respect to the fundamental frequency. If the fundamental frequency is 122 kHz, 366 kHz and 610 kHz harmonics will exist, and if the fundamental frequency is 200 kHz, harmonics of 600 kHz and 1 MHz are superpositioned. If the core loss in these higher frequency ranges is taken into account, it is therefore considered that the total core loss of MBF4 is lower than that of MBT3. Accordingly, it can be estimated that the efficiency of MBF4 is slightly higher than that of MBT3, including at 40°C. Because the above-mentioned core loss reversal frequency is in the decreasing direction, even as the overall temperature increases, MBF4 is considered to be all the more advantageous. From these results, it will be concluded that selection of the optimum material based on the balance of the temperature dependence of core loss and the frequency characteristics of the material is necessary, considering not only the results of core loss evaluations under a specific condition, but also the working temperature and frequency range of the power supply.

Although the above are the results of an evaluation of a specific power supply under a specific condition, MBF4, in which greater priority was attached to frequency characteristics than to temperature dependence, was judged to be the optimum material for the forward mode switching power supply studied here. In the future, it will be necessary to conduct characteristics analyses for cases of driving under various conditions, in which the working temperature and set magnetic flux density varied over a wider range. However, this work has presented one example in which improvement of the frequency dependence of core loss was more effective.

4. Conclusion

Directions for the development of the MnZn ferrite for use in the switching power supply transformer cores developed to date were presented, summarized for the 4 directions of (1) improvement of core loss at 100 kHz, 200 mT, 100°C, (2) improvement of the temperature dependence of core loss, (3) improvement of core loss in the higher frequency ranges, and (4) improvement of saturation magnetic flux density. Among these, in particular, this paper has presented a detailed summary of MBT3, a material in which the temperature dependence of core loss was improved in comparison with conventional materials and had been considered the optimum material for forward mode switching power supplies, and similarly, MBF4, a material in which frequency dependence was improved.

In order to determine the optimum core material for transformer cores of forward mode switching power supplies, transformer cores of various materials were substituted and packaged using a commercial power supply, and the relationship of power supply efficiency and temperature rise was investigated. Measurements were made at the two driving frequencies of 200 kHz and 122 kHz. In all cases, MBF4 was the most favorable material, followed by MBT3, which was on virtually the same level as MBF4, and then by MB4 and MB3, which displayed substantially similar performance. Under the standard conditions of 100 kHz, 200 mT used in material evaluations, the core loss of MBT3 is lowest. However, at higher frequencies of 200 kHz and above, the core loss of MBF4 decreases greatly in comparison with the other materials, even in the low temperature range from room temperature to around 60°C. It is considered that this effect contributed to the improvement of power supply efficiency observed in this research. In the future, the authors plan to conduct an investigation of the detailed magnetic properties of the various materials and apply the results to the development of optimum materials, including evaluation of packaging in power supply transformers.

References

1) Soga, N.; Nishizawa, K.; Fukuda, Y.; Fujita, A.; Gotoh, S.; Nakashima, S.; Togawa, J. Proc. of the 9th International Conference on Ferrites, San Francisco. 2004, p. 567–572.
2) Fujita, A.; Fukuda, Y.; Nishizawa, K.; Togawa, J. JFE Giho. 2005, no. 8, p. 32–37.
3) Togawa, J. Jitsuyo Dengen Kairo Sekkei Handbook. CQ Publishing, 1998, p. 148–174.
4) Fujita, A.; Gotoh, S. J. Magn. Soc. Jpn. 2002, vol. 26, p. 471–474.
5) Fujita, A.; Gotoh, S. Kawasaki Steel Giho. vol. 34, no. 3, 2002, p. 111–115.
6) Fujita, A.; Gotoh, S. J. Appl. Phys. 2003, vol. 93, no. 10, p. 7477–7479.
7) Stijntjes, T. G. W.; Klerk, J.; Broese van Groenou, A. Philips Res. 1970, rep. 25, p. 95–107.
8) Tsuzaki, M.; Takagi, K.; Yoshikawa, F.; Shimazaki, M. Kawasaki Steel Giho. 1992, vol. 24, no. 2, p. 148–149.
9) Gotoh, S.; Kikuchi, T.; Kijima, S.; Yoshimatsu, H.; Otake, T.; Fukuda, Y.; Togawa, J. Proc. of the 10th International Conference on Ferrites, Chengdu. 2008, p. 248–251.