Ferrite power material for high-frequency applications

Tadashi Mitsui, Chief Engineer
TDK Corporation, Narita, Japan
and
Gary Van Schaick,
Ferrite Product Manager,
MH&W International Corporation
Mahwah, New Jersey

Ferrite power material design continues to be a complex and difficult endeavor, but in power applications improvements are being made that allow higher operating flux under higher temperature conditions for any specific frequency with lower core loss.

The optimum ferrite material exhibits the lowest possible temperature rise and core loss under high flux density and high ambient temperature at specific frequencies. This characteristic is not easy to achieve, and no one material can produce this characteristic over a wide range of frequencies. Consequently, ferrite manufacturers can only design, develop and manufacture a ferrite material for a specific frequency range.

Power Material Specifications

The practicality of designing power supplies forces certain questions to be asked of the ferrite material. Questions such as:

Will the ferrite get too hot?

Is the operating flux higher than the saturation point?

Is there still inductance at 120°C?

Ferrite manufacturers provide specifications and typical data that will provide the answers to these and other questions. Specifications include:

- B_{ms} or B_{sat}: This is the saturation point measured at a specific magnetic field H and specific temperature.
- Core loss measured in some form of Watts/Volume (W/V) at a specific frequency and specific temperature.
- B_r: Remanence – measured at the same conditions as B_{ms}.
- T_c: Curie Temperature – A temperature below which a material is ferromagnetic or ferrimagnetic and above which it is paramagnetic.

Typical data is given by the ferrite manufacturers in the form of graphs, which must be taken only as typical data in that the tolerance around the graph points could be ±30%. Typical graphs include μ_a vs frequency, core loss vs frequency and flux B vs temperature. For this article we will be discussing these characteristics for several materials in the range of 100kHz to 10MHz. In looking at ferrite material in this wide range, there is one problem – a standardization of the testing procedures that is valid at all frequencies. To resolve this problem we are defining a test constant:

$$B \times f = 25 \times 10^3 (T \times Hz) \quad (1)$$

After the test frequency is chosen, the flux B is then calculated. This provides realistic operating conditions, i.e. 100kHz at 250mT (2500 Gauss) and 1MHz at 25mT (250 Gauss).

Typical material characteristics are provided in table form, as shown in **Table 1**.

Amplitude Permeability

Amplitude Permeability μ_a is the permeability of the ferrite material at stated operating conditions. **Figure 1** shows the amplitude permeability μ_a as frequency increases from 100kHz into the MHz region using the test conditions stated above at 25°C. From this graph, a recommended material for any frequency range can be determined.

Flux Density B

For any given power supply we can define a term B_{max} as the maximum operating flux density. In normal opera-

	PC40	PC44	PC50	H6F	K5	K6A
μ @ 100KHz	2300 ± 25%	2400 ± 25%	1400 ± 25%	800 ± 20%	200 + 30 − 20%	70 + 20 − 30%
Bms (mT) @ 25°C @ 100°C	(1000A/m) 510 390	(1000A/m) 510 390	(1600A/m) 470 380	(2400A/m) 400 300	(2400A/m) 330 270	(2400A/m) 300 270
T_c (°C)	>215	>215	>240	>200	>280	>350
Core Loss (mW/cm³) @25°C @80°C @100°C @120°C	(100KHz) (200mT) 650 450 410 500	(100KHz) (200mT) 500 340 250	(500KHz) (50mT) 130 80 80	Not Specified	Not Specified	Not Specified

Table 1.
Typical performance characteristics of various ferrite materials

tion B_{max} must be less than B_{ms}. In topologies such as a full bridge design the flux swings between $+B_{max}$ and $-B_{max}$. For topologies like a forward converter, the flux swings between $+B_{max}$ and $+B_r$. It is critical to know that as temperatures increase in a ferrite core, B_{ms} decreases (see **Figure 2**). It must also be noted that for the materials shown, the B_r also decreases. This is a desirable effect for the forward converter type topologies. There are ferrite materials being used for power applications where the B_r increases; here, the available flux decreases as the core temperature increases.

Core Losses

Core Losses are defined as:

$$P_c = P_h + P_e + P_r \qquad (1)$$

where: P_c = total core loss

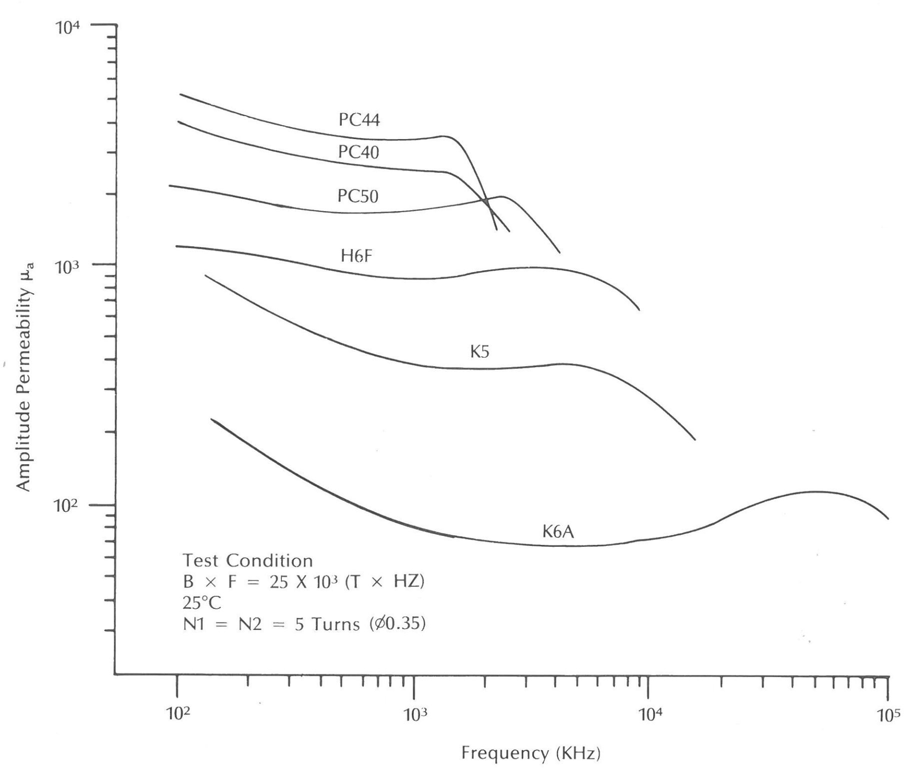

Figure 1.
Graph of amplitude permeability (μa) vs. frequency

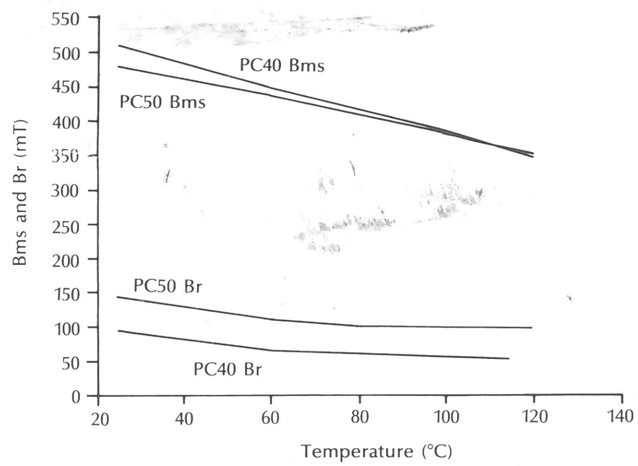

Figure 2.
B_{ms} and B_r vs. temperature

P_h = hysteresis loss
P_e = eddy current loss
P_r = residual loss
Further description of the hysteresis loss and eddy current loss yields the following:

$$P_h = f \times \circ H \times dB \quad (2)$$

$$P_e = k_e \times f^2 \times B^2/\rho \quad (3)$$

A casual inspection of the formulas suggests that the hysteresis loss increases linearly with increasing frequency and flux. The eddy current loss increases exponentially with increasing frequency and flux. In practice the hysteresis loss is the dominant component of core loss up to a specific frequency, the frequency determined by the other components in the core loss equation. Above this specific frequency the eddy current loss becomes the most prevalent component of total core loss. A comparison of total core losses at two different frequencies can be seen in **Figure 3** [4]. In Figure 3**A**, the presence of eddy current losses is small at 100kHz compared to the hysteresis loss. In Figure 3**B**, at 400kHz with B reduced by 50%, the eddy current losses increase and tend to be equal to or greater than the hysteresis losses. This fact has a significant impact on ferrite manufacturers. In the region of 100kHz to ~500kHz, the power material must be formulated to control and reduce the hysteresis losses. Over ~500kHz the power material must be formulated to control and reduce the eddy current losses. The goal is to minimize total core loss by balancing the hysteresis and eddy current losses [5].

TDK Corporation has found that to achieve this goal, the following model is required:

1. Powder preparation must be carefully controlled. Raw material must be free of impurities. The grain size of the sintered body is dependent upon the operating frequency; i.e., the higher the frequency, the smaller the grain size. Grain composition must also be uniform, the inner part of the grain being homogeneous and free of voids. TDK has improved upon the raw material processing and powder preparation through a new "Spray Roasted Powder Preparation Method" [5].

2. The sintering process is very critical. During the initial state of sintering there is an oxygen discharge reaction within the Mn-Zn ferrite forms. This occurs as the temperature is increased up through the 900°C to 1100°C range. TDK has developed new sintering technologies that are very effective in controlling oxygen discharge, suppressing discontinuous grain growth, eliminating pores within the grain boundaries and in precipitating additives and impurities at the grain boundary [5].

New Ferrite Development

The above model was determined during development of TDK's PC50 material, the next logical step in the material development cycle above the industry standard PC40. To achieve control of the eddy current losses in PC50, it is necessary to reduce grain size significantly and ensure that the grain structure is uniform. This process increases the resistivity of the material, which decreases eddy current losses. However, a side effect of increasing resistivity is that hysteresis losses also increase. The net result is an increase of total core loss, at lower frequencies, over that of the PC40, demonstrated in **Figure 4**. For the stated conditions there is a cutover frequency where PC40 demonstrates lower losses than PC50.

Upon finishing the development of PC50 based upon the above model, TDK engineers then went about applying the model to the standard PC40 material. By modifying the basic formation for PC40 with the new processes, TDK was able to more precisely control the grain size and structure. The newly developed sintering control was also applied to the PC40 material. The end result showed significant improvements in core losses in the same frequency range as PC40. The differences are important enough to fully develop and announce a new power material for the 100kHz to 500kHz range. This new power material is designated PC44, and its advantages over PC40 are demonstrated in Figure 4.

Many materials have been available for years which

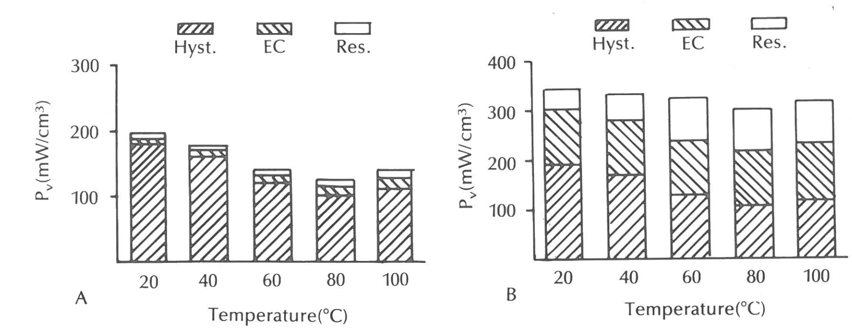

Figure 3.
Components of core loss vs. temperature; ETD 29-3C85, losses at 100kHz, 1000G (A); ETD 29-3C85, losses at 400kHz, 500G (B)

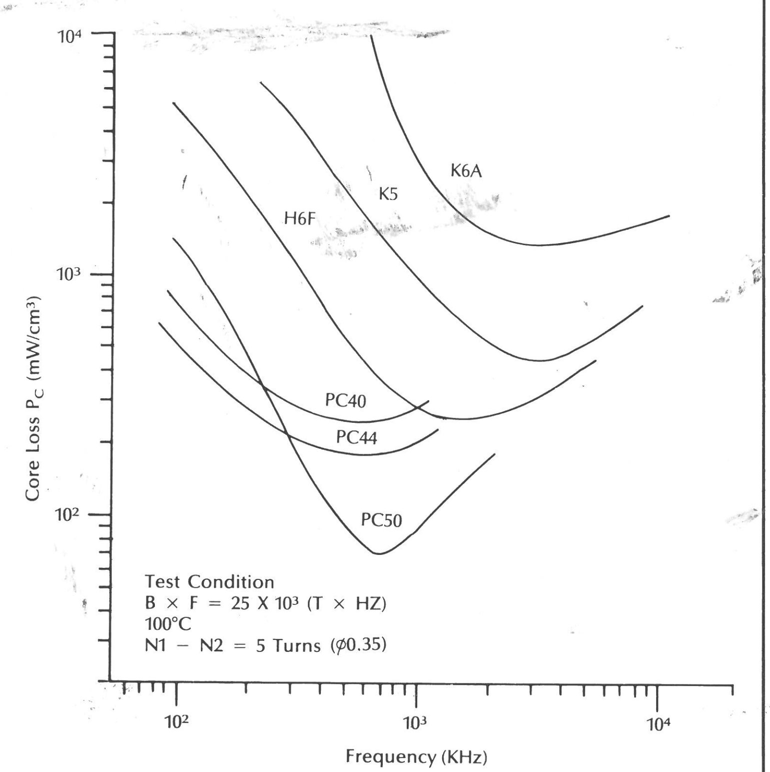

Figure 4.
Core loss vs. frequency

maintain inductance into the MHz region. These materials have been used in frequency selective inductors. Most of them have been Ni-Zn materials with one Mn-Zn material. The introduction of PC50 and now PC44 offers new alternatives and opportunities for power supply designers never before realized. There is a distinct advantage to Mn-Zn power materials designed for these high frequencies. The older frequency-selective ferrites were developed for use at room temperature and low flux. The temperature dependence of these ferrites is positive such that to operate these ferrites at high temperature causes the losses to increase disproportionately. Power ferrites, on the other hand, are designed such that core loss decreases as ambient temperature increases up to a specific point, which is usually in the 80° to 100°C range. Figure 4 shows core losses for the various materials over their recommended frequency range. The measurements were taken at the conditions for B × f stated above at 100°C.

Summary

Ferrite materials are created, developed and manufactured for the application by all of the ferrite vendors. This allows optimization of the material characteristics for power applications by allowing the highest operating flux under high temperature conditions for any specific frequency. The power supply and power magnetics designers now have many ferrite options available. Most of the ferrite materials presented here are available from ferrite vendors other than TDK Corporation, if only with minor variations. Core loss curves for other materials have been shown to be within the 30% tolerance range for typical values around each frequency characteristic curve. □

About the authors: Tadashi Mitsui has been in ferrite engineering in TDK Corporation for 20 years and is currently chief engineer. He has a diploma in electrical engineering from Tokyo Metropolitan Technical College, Tokyo, Japan. Gary Van Schaick has been in marketing and applications engineering in the ferrite industry for nine years. He received his BSEE from Clarkson University, Potsdam, NY, and a MS in Systems Management from University of Southern California. He is currently product manager for ferrite products at MH&W International.

References

[1] Th.G.W. Stijnjes, J. Klerk and A. Broese van Groenou, "Permeability and Conductivity of Ti-Substrated Mn-Zn Ferrites," Philips Res. Rep. 25, 95-107, 1970.

[2] A.D. Giles and F.F. Westendorp, "Simultaneous Substitution of Cobalt and Titanium in Linear Manganese Zinc Ferrites," J. Phjs., Suppl. No. 4, 38, 47-50, 1977.

[3] T. Ochiai and K. Okutani, "Ferrites for High-Frequency Power Supplies," Advances in Ceramics, Vol. 16, ICF4, 1985.

[4] Dr. C. Buethker, D.J. Harper, "Improved Ferrite Materials for High-Frequency Power Supplies," Proceedings for the First High-Frequency Power Conversion Conference, Intertec Communications Inc., Ventura, CA, 1986.

[5] T. Sano, A. Morita, A. Matsukawa, "A New Power Ferrite for High-Frequency Switching Power Supplies," Proceedings for the Third High-Frequency Power Conversion Conference, Intertec Communications Inc., Ventura, CA, 1988.