Development of Low-Iron-Loss Powder Magnetic Core Material for High-Frequency Applications

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Recently, there has been a growing trend toward reducing society's carbon footprint. In the field of energy, development of clean power generation systems, such as solar and wind generators, have been promoted. Electric vehicles are also replacing petrol vehicles in the automotive industry, and energy-saving electrical appliances are in demand more than ever. Due to this trend, small and powerful power-supply devices with better conversion efficiency are increasingly demanded, and accordingly, high performance inductors are required.
Thus far, the authors have engaged in the development of powder magnetic cores, which are made by press compacting soft magnetic powder coated with insulating film, for use in motors and solenoid valves. In this study, the technology accumulated in the development of these cores has been successfully applied to that of an inductor core. The developed inductor core shows superior properties to ferrite and dust cores which are commonly used for inductors. In this paper, the advantageous properties of the developed core and the result of application to the inductor are reported.

Keywords: soft magnetic material, inductor, reactor, choke coil, converter, inverter, eco-friendly vehicle

1. Introduction

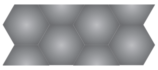
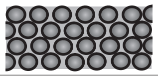
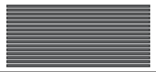
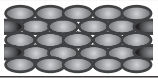
There has been a shift in recent years toward green power characterized mainly by solar- and wind-generated power in the energy field, with an aim toward reducing society's carbon footprint. The automotive industry is transitioning from internal combustion engines using fossil fuel to electric-power-driven systems, and there is also a movement to reduce the consumption of electricity in the field of household appliances. Power storage, energy recovery and voltage control technologies are critical to moving these trends forward, and electric power devices that efficiently convert energy to the required power are in demand. Switching power supplies have recently become the mainstream from the viewpoint of conversion efficiency and component downsizing. The choke coils, inverter coils used in transformer circuits and rectifier circuits, coil components such as power inductors, electric reactors comprising an iron core and a winding greatly affect the performance of power devices. There is also a shift from conventional energy systems, wherein power is conducted in one-way systems from the power generation source or storage battery to the electronic device, to two-way systems that recover the excess energy generated by power-consuming devices. To this end, power devices and power coils are needed to show complex transforming and rectifying functions, to be capable of handling greter power levels, and also to be smaller in size.

Recently, we have developed a “powder magnetic core material" obtained by press compacting magnetic metal powder, which is used used as a soft magnetic material in the iron core of coil components.(1),(2) Using the developed technoogy to the problems of power devices described above, we have improved the high-frequency response in the several-hundred-kHz band, which is the target frequency band wherein the material characteristics are to be applied, and as a result, we have successfully achieved a low-iron-loss powder magnetic core material for high-frequency applications with characteristics superior to ferrite or general-use dust cores previously used in these applications.(3),(4) In this study, the various characteristics of the developed material and result of application to power coils are reported.

2. Current Technologies Aimed at Development Objectives and Issues

From the viewpoint of downsizing and high electric power capacity, the iron core material used in power coils should show a high saturation flux density and a high electromagnetic conversion efficiency. **Table 1** shows the typical soft magnetic materials used in high-frequency applications, and compares their power characteristics. Soft magnetic materials generally used in iron cores for processing power included ferrite and general-use dust cores. Ferrite shows low loss (iron loss), and superior power efficiency, but as shown in **Fig. 1**, because of its low saturation flux density, it lacks the operation flux density required for high-capacity power supplies, and so the device becomes large in size and requires much copper for use in the winding. General-use dust cores, on the other hand, are obtained by compression-molding magnetic metal powder in the same way as powder magnetic cores, and they show superior saturation flux density compared to ferrite and have a good high current handling capacity (DC bias characteristic), thus facilitating a compact device. However, compared to ferrite, they have a number of problems, including heat generation and low power efficiency due to large iron loss. In addition to the above, there is also amorphous ribbon that realizes high flux density and conversion efficiency, but because it uses a laminated structure that requires a rolling process to manufacture, it is difficult to form the core into complex

Table 1. Soft magnetic materials used in power coils for high-frequency applications, and their power

Material	Schematic View	Magnetic material content	Downsizing	Power capacity	Power efficiency	Shape complexity
Controlling factors in soft magnetic material		–	Magnetic flux density Packing density	Magnetic flux density Packing density	Iron loss Electrical resistance	Complex shape formability
Ferrite (Spinel type)		100vol%	△	△	◎	○
General-use dust (Fe-Si-Al, Fe-Si-B)		50 ~ 70	○	○	△	○
Amorphous foil (Fe-Si-B)		80 ~ 90	◎	◎	○	×
Conventional sintered soft magnetic material (pure iron, Fe-3Si)		90 ~ 95	◎	◎	×	◎

Note: ◎: Excellent ○: Good △: Fair ×: Poor

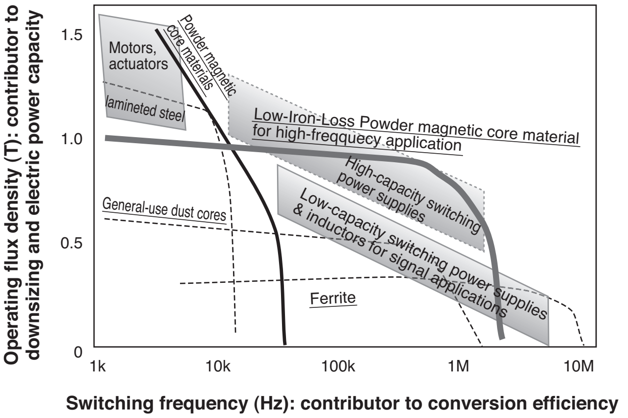


Fig. 1. Applications and performance ranges of typical soft magnetic materials and their development objectives

shapes. Further, the production cost is much higher than that of powder metallurgical processes, and the electrical resistance is low, which greatly reduces the conversion efficiency in the high-frequency range. For these and other reasons, amorphous ribbon has limited application. As explained above, existing soft magnetic materials all present obstacles to realizing the kind of compact devices with high electorical power capacity that will be in demand in the near future, so a new kind of soft magnetic material with superior characteristics is desired.

3. Various Characteristics of Developed Material

3-1 Approach and Experimental Method of Development

We previously developed a powder magnetic core material with superior soft magnetic properties for use in devices such as motors and actuators that operate in a relatively low frequency range (up to several kHz), whereby technology that greatly improved the saturation flux density and loss characteristic of the powder magnetic core material is achieved. However, due to the high drive frequency (i.e., tens to hundreds of kHz) of switching power supplies, the material shows extremely large iron loss, thus resulting in heat generation greater than that in general-use dust cores and lower conversion efficiency. Therefore, we set out to develop a new soft magnetic material superior to general-use dust cores and ferrite through optimization of the characteristics of our previous powder magnetic core materials to the several-hundred-kHz frequency range.

Figure 2 summarizes the controlling factors that affect iron loss in powder magnetic core materials.(2) Iron loss is the sum of hysteresis loss (Wh) and eddy-current loss (We). A low coercive force is required to reduce the Wh, which is the external energy required to change the magnetic field direction. Reducing the amount of impurities in the material and using a magnetic alloy with a small magnetic anisotropy or magnetostriction constant are effective, additionally, eliminating the strain generated during powder compacting through heat treatment is an important technology, particularly in powder magnetic core materials. On the other hand, the Joule heat from the eddy-current gen-

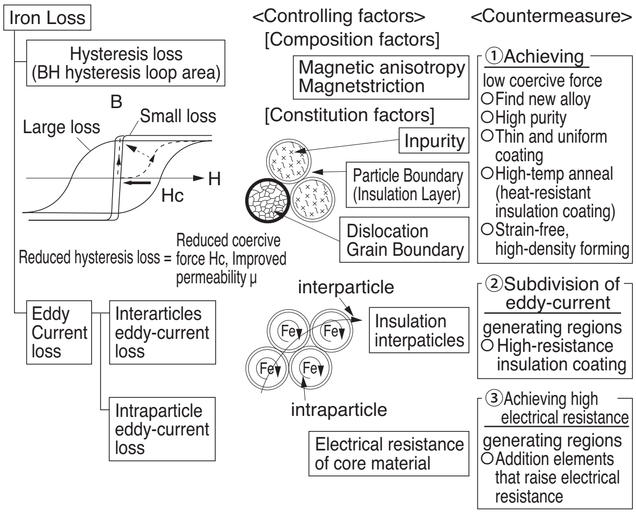


Fig. 2. Controlling factors that affect iron loss in powder magnetic core materials

erated by the induced electromotive force is known as We, and in order to suppress We, it is necessary to increase the electrical resistance of the material. Using a magnetic alloy with a large electrical resistance can be effective, and both processing to form electrical insulation between powder particles and subdividing the over-current-generating regions through further miniaturization of the powder particles are important techniques for achieving this in powder magnetic core materials. While Wh is proportional to the frequency, We is proportional to the square of the frequency, so reducing We was critical in our development, which can become prominent within the high-frequency ranges.

To obtaion powder magnetic core material that shows low loss and high saturation flux density, we developed following four technologies. That is,<1> a high-temperature technology technique that uses a high heat-resistant insulation formation process, and <2> a thin, uniform coating formation technology that realizes both high electrical resistance and high saturation flux density. Here, we report on our further development of <3> powder particle design technology and <4> technology to adopt and optimize the structure of magnetic alloy powder with superior soft magnetic characteristics, and a study of their application. That is, in order to replace the easily deformable pure iron powder used previously with high-alloy powder which shows superior soft magnetic characteristics, the key point is technology that enables pressure-compacting hard powder in high density, maintaining insulation resistance.

After applying the developed insulation film forming process to a Fe-Si-Al (Sendust) alloy powder that shows a superior low-loss characteristic as a soft magnetic alloy powder, we mixed it with a lubricant and compacted it into a ring shape 5 mm high with a 34 mm outside diameter and 20 mm inside diameter at 980 MPa using a uniaxial press compacting method. Then, the compacting strain is removed by heat-treatment in a nitrogen atmosphere, and magnetic characteristics are measured.

3-2 Various characteristics of the developed material

Table 2 lists the various characteristics of the developed material, and **Fig. 3** shows the frequency dependency of core loss of the developed material in a comparison with conventional materials, i.e., general-use dust cores and ferrite. For the general-use dust core, a commercially available dust core that used an Fe-Si-Al alloy powder is selected, same as in the developed material, and for the ferrite, an Mn-Zn ferrite is selected for comparison. Hysterisis loss coefficient Kh and eddy-current loss coefficient Ke are calculated from the frequency dependency of iron loss using equation (1) below. It is shown that both the hysteresis loss coefficient and eddy-current loss coefficient are lower in the developed material than in the general-use dust core. As a result, it was possible to reduce iron loss to less than half that of the general-use dust core in the 100 kHz range, which is the target frequency for application to power devices. Further, the developed material shows a saturation flux density more than 10% greater than that in the general-use dust core.

Table 2. Various characteristics of developed material

	Unit	Developed material	Dust core	Ferrite
Material		Fe-Si-Al alloy powder	Fe-Si-Al alloy powder	Mn-Zn ferrite
Saturation flux density*	Tesla(T)	0.89	0.80	0.51
Iron loss** (W)	kWm^{-3}	380	843	57
Hysteresis loss coefficient*** (Kh)	$kWsm^{-3}$	3.1×10^{-3}	6.6×10^{-3}	0.5×10^{-3}
Eddy-current loss coefficient*** (Ke)	kWs^2m^{-3}	7.5×10^{-9}	1.8×10^{-8}	5.5×10^{-9}
Permeability****	–	56	52	2400

* Measured at room temperature
** Measured at flux density 0.1T, frequency 100kHz, temperature 100°C
*** Calculated from frequency dependency of iron loss in 10k to 100kHz frequency range
**** Permeability during iron loss measurement

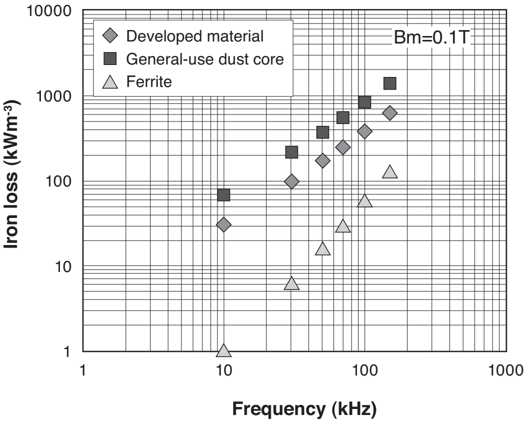


Fig. 3. Frequency dependency of iron loss

$$W_{B/f} = Kh\times f + Ke\times f^2 \quad \cdots\cdots\cdots\cdots (1)$$

* $W_{B/f}$ represents the iron loss when operated at magnetic flux density B and frequency f.

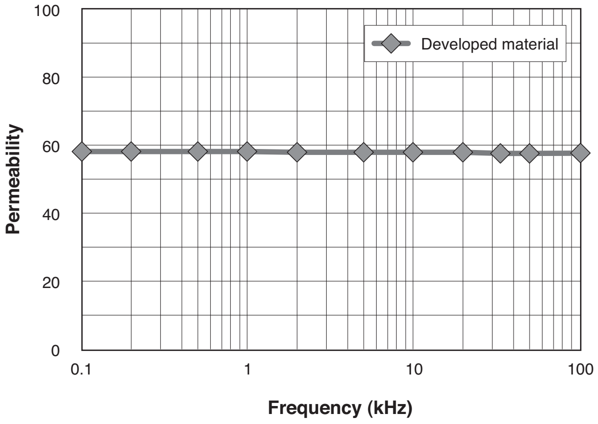


Fig. 4. Frequency dependency of permeability

With respect to ferrite, on the other hand, the saturation flux density of the developed material was 1.7 times greater, thus the developed material shows an advantage for more compact power devices and greater power handling capacity. Iron loss was still inferior to ferrite, and the extent of the difference with respect to power coils is described below. **Figure 4** shows the frequency dependency of the permeability of the developed material. The developed material demonstrates a flat permeability up to 100 kHz, which is an excellent characteristic for coils in power applications.

4. Application of Developed Material to Power Inductors

4-1 Design and fabrication of power coils using the developed material

In order to investigate the performance of the developed material in a Power Inductors, we selected a commercially available automotive step-down DC-DC converter, assuming the developed material would be used in this type of DC-DC converter in hybrid automobiles and other next-generation eco-friendly vehicles, and built an evaluation system capable of recreating similar operation. The power coil based on the required specifications shown in **Table 3** is designed. According to the DC magnetization properties of the ring sample, configuration of the power coil is determined so that it shows the target inductance Ls, based on Equations (2) to (4) below. The developed power coil is compared with the ferrite core already in the selected converter. The same rectangular wire shape as the ferrite core for the winding is used.

Table 3. Design requirements for choke coil core

Input voltage: V_{in}	200V	Frequency: f	100kHz
Output voltage: V_{out}	14V	Inductance: Ls	2.6μH
Output current: Idc	100A	Coil specification	8 x 2mm rectangular wire

$$Ls = \frac{N^2}{Rm} \quad \cdots\cdots \text{(Equation 2)}$$

$$B_{max} = \frac{LI_{max}}{NS} = \frac{NI_{max}}{RmS} \quad \cdots\cdots \text{(Equation 3)}$$

$$Rm = \frac{lc}{\mu_r \mu_0 S} + \frac{lg}{\mu_0 S} \quad \cdots\cdots \text{(Equation 4)}$$

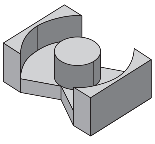
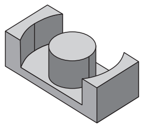
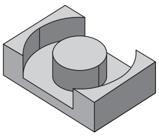
N: number of coil windings
I: DC current
S: core cross sectional area
lc: core magnetic path length
lg: gap length
μ_r: core relative permability
μ_0: space permeability

Two cases are designed, as described below. For the first case (Case 1), reducing the space was mainly aimed, particularly the mounting area, using the same winding conditions. For the second case (Case 2), reducing number of windings was mainly aimed. The winding is a significant contributor to the product cost and weight, so reducing the number and amount of windings is important. However, when the number of windings is reduced in a ferrite core that has a low saturation flux density, the DC bias characteristic is degraded and the inductor cannot run at the desired current, which makes it is difficult to reduce the number of windings.

Table 4 shows the power coil design results using the developed material. The developed material, as described above, has a saturation flux density superior to that of ferrite material, so it is possible to achieve a more advantageous shape in both Cases 1 and 2. In Case 1, it was possible to greatly reduce the mounting area, core volume and overall weight with the same number of windings (n=5). In Case 2, it was possible to reduce the number of windings to 4 by using the developed material, which reduced the product size and weight.

Based on the above design results, power coils are actually fabricated. The fabricated core material and choke coil parts are shown in **Photo 1**. The core using the developed material was fabricated by machining a rough part measur-

Table 4. Choke coil core design results

Core material		Ferrite	Developed material	Developed material
–		–	Case1	Case2
Part view				
Mounting area		1120mm^2	760mm^2 (-35%)	1120mm^2
Part height		28mm	25mm (-11%)	22mm (-25%)
Core	Weight	70g	59g (-16%)	75g (+7%)
	Volume	14cm^3	10cm^3 (-30%)	13cm^3 (-7%)
Coil	Windings	5 turns	5 turns	4 turns
	Weight	71g	66g (-7%)	59g (-17%)
Overall weight		141g	125g (-12%)	134g (-5%)

Note: Values shown in parentheses indicate percent difference from ferrite

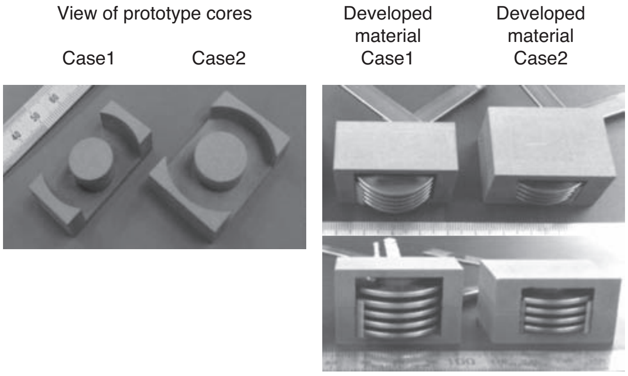


Photo 1. Prototype core material (left) and choke coil parts (right)

ing 30 x 50 x 20 t (mm) to the prescribed dimensions.

4-2 Evaluation of prototype power coil

Figure 5 shows the DC bias characteristics of the inductance of the prototype coil. The characteristics of the coils using the developed material are nearly the same in both Cases 1 and 2. We obtained an inductance value of 2.4 μH, which was close to the design requirement (Ls 2.6 μH @ Idc 100 A). The slight shift from the design value was likely due to a slight change in the DC magnetization characteristic resulting from the large density distribution in the rough part (30 x 50 x 20 t (mm)) used to fabricate the actual shape of the component as opposed to the well-uniformed ring sample (34 mm outer diameter, 20 mm inner diameter, 5 mm height) used in the design. With respect to this point, the precision will be improved by reflecting this result in the DC magnetization characteristic used in the design.

Comparing to existing ferrite cores, the developed material demonstrates a relatively high inductance in the high current range, while ferrite cores demonstrate a sharp drop of inductance in the high current range exceeding 100 A, which is the specification requirement. This drop in inductance observed in ferrite cores in the high current range occurs due to the magnetic flux saturation, which causes decrease of permability. Therefore, by using the developed material, which has a superior saturation flux density, it is possible to make components smaller and reduce the number of windings as compared to ferrite cores, and still be able to use them in a higher current range (i.e., they will facilitate processing higher power levels).

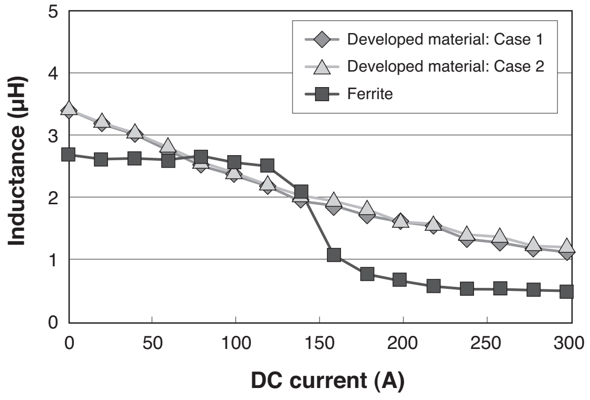


Fig. 5. DC bias characteristics of prototype choke coils

Figure 6 shows the measurement results for the temperature dependency of inductance at a DC current of 100 A. While the developed material demonstrates a stable inductance from room temperature up to 150˚C, inductance in the ferrite core drops off sharply in the high temperature range above 90˚C.

Figure 7 shows the respective temperature dependencies of the DC bias characteristics of the developed material and ferrite. The developed material demonstrates a consistent dependency up to 150˚C. On the other hand, the

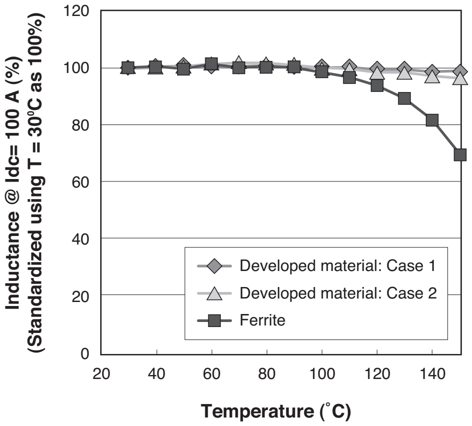


Fig. 6. Temperature dependency of inductance at Idc = 100A

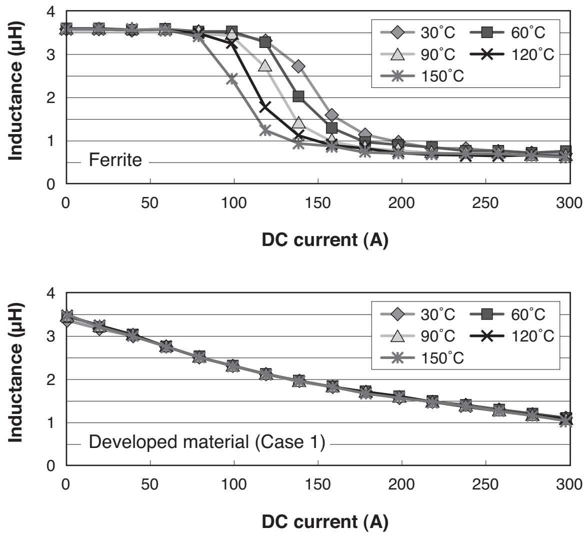


Fig. 7. Temperature dependency of DC bias characteristic (upper graph: ferrite; lower graph: developed material)

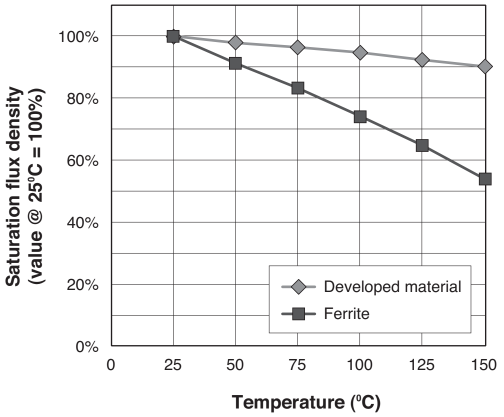


Fig. 8. Temperature dependency of saturation flux density

point of current in which the inductance of ferrite drops shifts downward as the temperature rises. This causes the sharp drop in the temperature dependecy of the inductance of ferrite as explained above. The difference in the temperature dependency of the DC bias characteristic observed between the developed material and ferrite is clearly related to the temperature dependency of the saturation flux density. As shown in **Figure 8**, the saturation flux density of ferrite at 150˚C is only half of what it is at room temperature, while that of the developed material drops by only about 10%. The main reason for this is that the Curie temperature point for ferrite is around 200˚C, while that of the developed material is much higher at 500˚C.

4-3 Evaluation of the fabridcated inductors mounted in converter

The fabricated inductors are mounted in the above commercially available automotive step-down DC-DC converter and operated it at the power specifications shown in **Table 3**. The temperature increase in the core and coil is evaluated. The power device was equipped with a cooling mechanism that used a water-cooled jacket, and this was used to cool the unit (the temperature of cooling water: 60˚C). In addition to the inductor, the parts around the power coil may be affected by the heat it generates in a power device, so reducing temperature increases in the power coil is critical to improving the reliability of the device itself.

Figure 9 shows the ambient temperature dependency of the core surface temperature in the prototype power coil. The developed material showed a slight difference between Case 1 and Case 2, which was likely due to the difference in part shapes. However, the operating temperatures were nearly the same as the ferrite core. This indicated that a difference in the iron loss characteristic, which is inferior to ferrite as a material characteristic, did not translate into a significant difference in temperature increase during operation of the power device. As shown in **Fig. 10**, the thermal conductivity of the developed material is superior to that of ferrite, which can be assumed to be the main reason for the above result.

Figure 11 shows the ambient temperature dependency of the temperature on the winding coil surface in the prototype power coil. Comparing with the result of the core temperature, all materials showed a higher coil temperature. Though it is also dependent on operating conditions, the power circuit system, and other factors, there are many instances where the coil temperature presents a problem in power devices as demonstrated here. Further, the results showed that although the temperature increase was nearly the same for the Case 1 developed material and the ferrite core, the Case 2 developed material showed a temperature increase that was more than 10˚C lower. Joule heat caused by DC current flowing through the coil accounted for the majority of the heat generated in the coil, and since the number of windings was reduced in the Case 2 developed material, the reduced DC resistance in the coil was likely the main reason for the above result. This indicates that using the developed material, which has a saturation flux density superior to ferrite, and designing the coil with fewer windings will effectively suppress temperature increase in the coil.

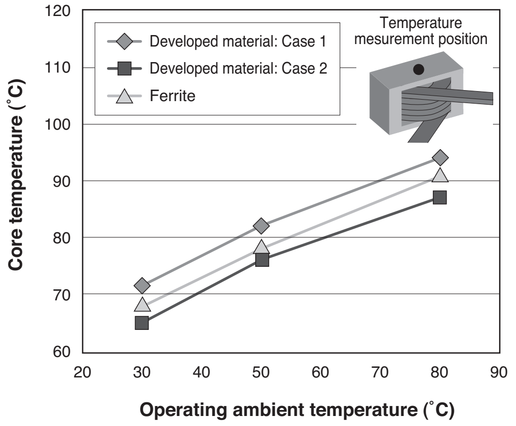


Fig. 9. Operating ambient temperature dependency of core temperature

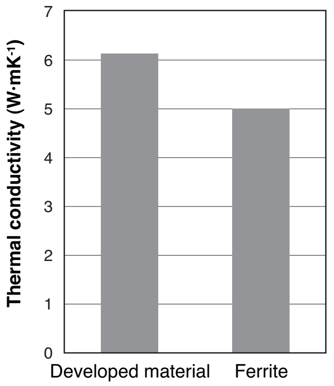


Fig. 10. Thermal conductivity of developed material

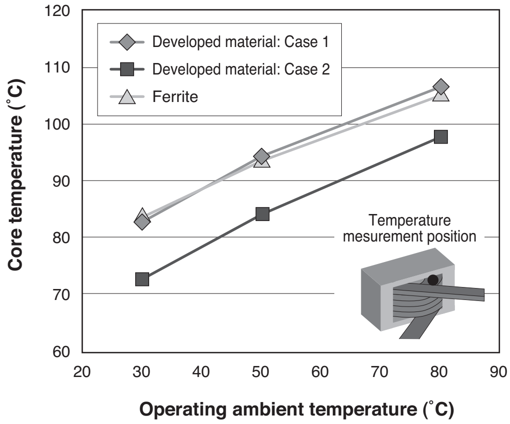


Fig. 11. Operating ambient temperature dependency of coil temperature

5. Conclusions

In this study, using our high-performance powder magnetic core material technology as a starting point, we set out to develop a new soft magnetic material that can be applied to power inductors, for which there will be increasing demand in the coming years as society attempts to reduce its carbon footprint. The results are summarized below.

(1) By optimizing material characteristics for the 100 kHz band, in which power devices frequently operate, a material with superior characteristics is successfully developed, such as less than one-half the iron loss of conventional general-use dust cores and a saturation flux density more than 1.7 times greater than that of ferrite.

(2) By optimizing the design of a inductors for application to automotive DC-DC converters, it is confirmed that it is possible to reduce the size and weight of components and reduce the amount of winding used with respect to existing ferrite cores by using the developed material.

(3) Power inductors are fabricated with developed material, and it demonstrated that it is possible to reduce size and increase electrical power capacity compared to ferrite, and that the developed material could operate with stable inductance up to 150°C, which was not possible with ferrite.

(4) The fabricated Power inductors is mounted on a DC-DC converter and the increase in temperature during operation is evaluated, then it is confirmed that the temperature increase in the core is almost equal to that of ferrite and that the coil temperature increase could be suppressed by using a reduced-winding design.

The above results demonstrate that the developed material has excellent potential for meeting demand for power devices that are compact and require little space while offering greater electrical power capacity. We will continue development aimed at the material's practical application.

6. Acknowledgment

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