Downsized High-Heat-Dissipation Choke Coil Designed with Powder Cores

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Sumitomo Electric Industries, Ltd. has developed magnetic powder core materials for power inductors used in eco-friendly vehicles. Pure iron based powder cores with an operating frequency range from 10 kHz to 30 kHz have been used for boost converter reactors in hybrid-electric vehicles (HEVs), while low-loss Fe-Si-Al alloy powder cores with an operation range of several hundred kHz have shown the potential to replace ferrite cores for buck converter choke coils. Our low-loss alloy powder cores are also a competitive alternative for choke coils in plug-in HEV and EV on-board chargers, which generally operate in a range from 50 kHz to 200 kHz. This paper compares differences in size, weight, power loss, and DC-bias characteristics between E-type choke coils that are respectively designed with the Fe-Si-Al alloy powder cores and ferrite cores for the power factor correction (PFC) of the charger. The simulation results show that alloy powder cores significantly reduce the size and weight of choke coils compared with ferrite cores. This paper also describes a new choke coil structure that we have developed to improve the heat dissipation of E-type choke coils. The experimental results indicate that the newly designed coil has a lower operating temperature than that of E-type choke coils.

Keywords: inductor, choke coil, PFC, charger, powder core, heat dissipation

1. Introduction

Solving the problems of global warming and fossil fuel exhaustion requires continuous efforts from industry. In the automotive industry, in order to reduce CO_2 emissions and fuel consumption of vehicles, electric-drive systems have been developed and used in hybrid-electric vehicles (HEVs), plug-in hybrid-electric vehicles (PHEVs), and electric vehicles (EVs). For these vehicles, power conversion equipment is as important as motors and batteries. The power conversion equipment includes boost converters to enhance motor output in HEVs, buck converters to step down the main battery voltage to 12 V in HEVs and EVs, and AC-DC converters to charge the main battery in PHEVs and EVs. The power conversion equipment is a switching power supply*1 that uses a lot of power inductors, called reactors or choke coils, for voltage conversion and energy transmission. These power inductors are composed of magnetic cores and copper winding wire. The magnetic core largely determines the size and performance of a power inductor and power conversion equipment.

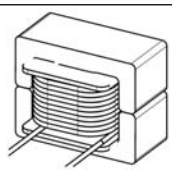
Sumitomo Electric Industries, Ltd. has developed pure iron based powder core*2 materials suitable for operation at a frequency from 10 kHz to 30 kHz, and applied them to reactors of boost converters used in HEVs by developing coil processing and assembly techniques(1), (2). We have also developed Fe-Si-Al alloy powder cores with a low loss at several hundred kHz. As reported in our previous paper, this low-loss powder cores can replace the conventional ferrite cores of choke coils for duck converters used in HEV/EVs(3).

Meanwhile, development of PHEVs/EVs has been promoted as these vehicles can be charged via a power charger at home and contribute to the reduction of CO_2 emissions. Choke coils used in such a charger generally operate in a frequency range from 50 kHz to 200 kHz, in which the developed alloy powder cores can be a competitive alternative. In this study, we analyzed electrical requirements for choke coils used in charger circuits, compared choke coil designs in using alloy powder cores and ferrite cores, and investigated the heat dissipation of choke coils in a water-cooling condition. As the result, we successfully developed a small high-heat-dissipation choke coil using our alloy powder cores for chargers in PHEV/EVs. The simulation and experimental results are reported below.

2. Overview of Choke Coils and Our Development Policy

Choke coils can be classified into two basic types according to the core shape: toroidal and E-type. **Table 1**

Table 1. Comparison between toroidal and E-type choke coils

	toroidal	E-type
		
Core materials	Ferrite core, powder core, etc.	
Introduction of air gap	Not easy	Easy (good design flexibility)
Heat dissipation	Copper loss is priority	Core loss is priority
Coil winding	Manual	Automation

compares the two types of choke coils in core materials, air gaps, heat dissipation, and the ease of coil winding. In general, ferrite and powder materials are used for their cores. The air gap inserted into the magnetic flux path changes the properties of the magnetic core. It is easier to insert a gap into an E-type core than a toroidal core as the length of its center leg can be changed, giving great flexibility of magnetic design. In addition, considering the mounting method and the positional relationship between the core and windings, the heat of windings is easily extracted for the toroidal type, whereas the heat of the core is easily extracted for the E-type. In the winding process, as winding copper wires onto a ring core is difficult, manual winding is generally adopted for the toroidal type. For the E-type, it is easy to achieve the automation through winding copper wire to a bobbin.

In the development of the choke coils for the charger of PHEVs/EVs, size reduction, high heat dissipation, and ease of production need to be considered. Downsized choke coils reduce the amount of materials used, resulting in cost saving and contribute to the downsizing of a charger. To design a small choke coil, it is necessary to choose appropriate core materials which meet the electrical specifications required by charger circuits. Next, the magnetic parameters, including the number of turns, cross sectional area, and the length of a gap, need to be optimized. The downsized design leads to an increase in heat density, and therefore, the choke coil needs an effective heat dissipation structure. On the other hand, the ease of production is also important for choke coils. In view of these, we have worked on the development of a choke coil used in chargers for PHEVs/EVs.

3. Choke Coil Designs for Charger in PHEVs/EVs

3-1 Electrical specifications of choke coils

In this section, electrical specifications of choke coils are estimated based on the charger circuit example shown in **Fig. 1**. The charger consists of a power factor correction (PFC), an isolation transformer, and a rectifying and smoothing circuit. In this circuit, two choke coils are used in the PFC, and another one choke coil is used in the smoothing circuit. Here, the inductance requirement of choke coils used in the PFC is estimated.

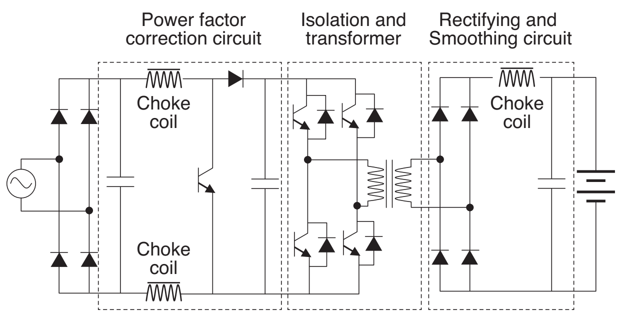


Fig. 1. A charger circuit

In the case where the input voltage of the charger is 200 V and power output is 3 kW, typical rated input-output specifications of the two choke coils can be determined as in **Table 2**. The relationship between inductance and maximum DC current is determined by the ratio of ripple current to average current. This relationship is shown in **Fig. 2**. In general, to reduce the peak current in a 3 kW PFC circuit, the continuous current mode is desirable, in which the current of choke coils is higher than 0 A. **Figure 2 (a)** and **Fig. 2 (b)** show the current waveform in ripple ratios of 200% and 50%, respectively. As can be seen, by reducing the ripple ratio from 200% to 50%, the peak current is lowered from 42.4 A to 26.5 A. Lower peak current can lower the required DC-bias characteristics[*3] of a choke coil and the specifications of other components used in the charger circuit such as capacities and power semiconductors.

With a design goal of a ripple ratio of 50% at maximum input current, inductance required at a peak current of 26.5 A was calculated to be 78.1 uH based on the circuit in **Fig. 1** and the rated input-output in **Table 2**. In the section 3-3, the choke coil is designed to meet this specification (78.1uH@26.5A).

Table 2. Rated input-output specifications of choke coil for PFC

Input voltage	Output voltage	Average current
100V (50Hz)	200VDC	15A (50Hz)

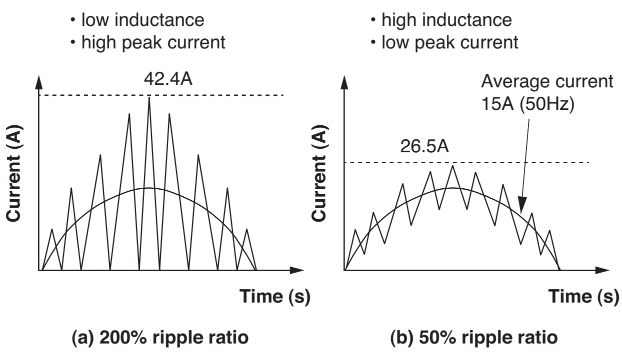


Fig. 2. The ripple current in choke coil

3-2 Comparison of magnetic properties between ferrite core and powder core

Table 3 compares the magnetic properties of the conventional ferrite and Fe-Si-Al alloy powder core materials developed by Sumitomo Electric. By applying the coating formation technology that realizes both high electrical resistance and high saturation flux density and the technology that optimizes the structure of alloy powder with a superior soft magnetic property, the newly developed alloy powder core material achieved higher saturation flux density and lower loss than the general dust core. The devel-

Table 3. Comparison of magnetic properties between ferrite and developed alloy powder core materials

	Unit	Powder core	Ferrite core
Materials		Fe-Si-AL alloy powder	Mn-Zn ferrite
Saturation flux density *1	Tesla	~0.89	~0.50
Core loss *2	kWm^{-3}	400~1000	60~350
Initial permeability	–	50~80	2000~5000
Operating temperature	˚C	Over 150	Under 120

*1: Values at room temperature
*2: Measured at flux density 0.1T, frequency 100kHz, temperature 100˚C

oped alloy powder core material has nearly 2 times higher saturation magnetic flux density than ferrite. In addition, due to a high Curie temperature[*4] of 500˚C, the alloy powder core material has stable magnetic properties at a high temperature of 150˚C or higher.

Since inserting an air gap in the magnetic flux path can change the properties of the magnetic cores, magnetic properties of gapped cores were compared. A variation of inductance-per-turn^2 (AL, nH/N^2) with magnetomotive force (NI, Ampere•Turns) was calculated for the two materials by FEM[*5] simulation. An arbitrary E-type core model, as shown in **Fig. 3**, was used. Ferrite with permeability of 3300, which is a typical material for power inductors, was chosen. The gaps varied from 0.5 to 5 mm and from 0 to 2.5 mm for ferrite cores and alloy powder cores, respectively.

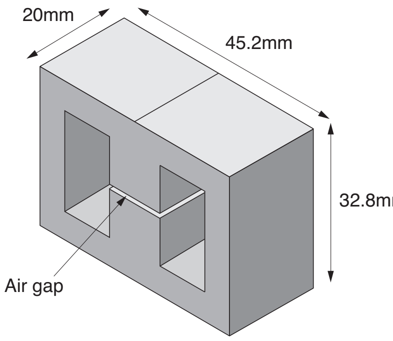


Fig. 3. E-type core used in magnetic property comparison

Figure 4 (a) shows a family of AL-NI curves with different gaps for ferrite cores. These curves are horizontal until saturation, and the gap increases the DC bias capability at the expense of a lower AL value. The line connecting the points where the saturation starts in each curve represents the limit of magnetic properties of ferrite cores. **Figure 4 (b)** shows the AL-NI curves of Fe-Si-AL alloy powder cores. The AL value declines with increasing NI due to the nonlinearity of permeability. Similarly, the line connecting the maximal AL values of these curves represents the limit of magnetic properties of alloy powder cores.

In **Fig. 4 (c)**, the two lines that represent magnetic property limits are crossed at a point. In region I, where NI is low, the AL value of ferrite cores are higher than that of the powder cores, which means that the ferrite cores are more suitable for applications requiring relatively high inductance and low DC bias current. Conversely, in region II, the powder cores have a higher AL value and can provide higher inductance than ferrite cores. In region III, where NI is high, gaps over 5 mm need to be inserted to ferrite cores to prevent the saturation. This causes a larger

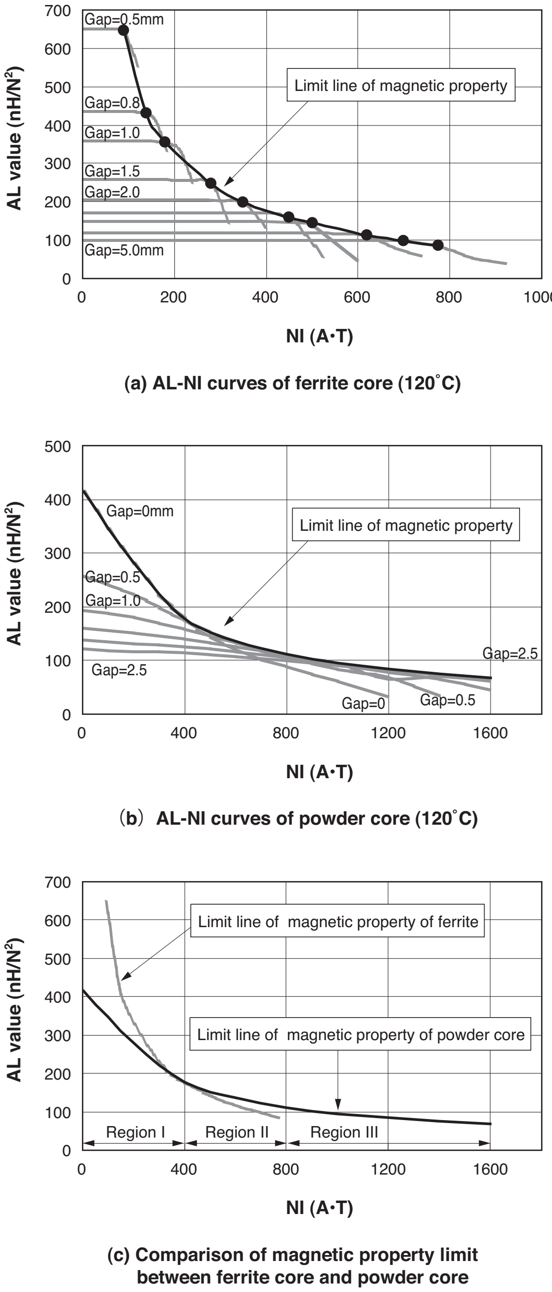


Fig. 4. Comparison of magnetic property of gapped core

leakage of magnetic flux, resulting in a considerable increase in AC copper loss in windings. This is a limiting factor of designing a choke coil with ferrite cores in region III. In contrast, powder cores have a relatively small gap of below 2.5 mm, which ensures that they are usable for choke coil design.

The inductance provided by magnetic cores is calculated by multiplying the square of the number of turns, which means that increasing the number of turns can lead to the downsizing of the choke coil. An increased number of turns lead to a higher NI value. According to the results in **Fig. 4 (c)**, the alloy powder cores can be used to design small choke coils in region III with an increased number of turns. On the other hand, for the 3 kW charge application, because of the relatively low current range of 10 to 20 A in choke coils, wires with a diameter of below 2.0 mm can be used, so that increasing the number of turns does not lead to a great increase in the size of choke coils.

For the inductance requirement of 78.1uH@26.5A estimated in section 3-1, if the choke coil is designed with a ferrite core in region I, where ferrite is more advantageous than powder cores, the maximum NI is approximately 400 A•T and the number of turns is approximately 15 at most. This means that a larger core is needed for the desired inductance, while the powder core design can provide a smaller choke coil by increasing the number of turns in region II or III. The design with a high NI value is attributed to the high saturation flux density of powder cores.

3-3 Comparing designed choke coils using ferrite cores and power cores

In this section, the detailed designs of choke coils using the two materials are compared. The target inductance is 78.1 uH at a maximum current of 26.5 A. The magnetic parameters, including the number of turns, magnetic cross sectional area, and gap, were optimized with a design algorithm we developed. Simulation results of size, weight, and losses are shown in **Table 4**.

As shown in **Table 4**, the powder core design reduces the size by 34% and weight by 45% compared with the ferrite core design.

Although the total power loss in the powder core is 2 W higher than that of the ferrite core, this is 0.13% to the entire output of 3 kW and its effect on the efficiency of the charger is insignificant. As for other losses, the powder core is higher in the core loss than the ferrite, whereas in the AC copper loss, the ferrite core is higher due to a larger amount of magnetic flux leakage around the gap. **Figure 5 and 6** show the shapes of choke coils and DC-bias characteristics, respectively. As the inductance of the powder core design within the range of 0 to 26.5 A is higher than that of the ferrite core design, the ripple current of the powder core is lower.

To consider the temperature rise in the two designs, the heat density is compared in **Table 5**. Due to the downsizing and high power loss, the average heat density of the powder core design is 2 times larger than that of the ferrite core design. This means that the powder core design has a higher temperature rise. As the heat density of windings is more than 10 times higher than that of cores in the two designs, the heat dissipation of windings need to be preferentially considered.

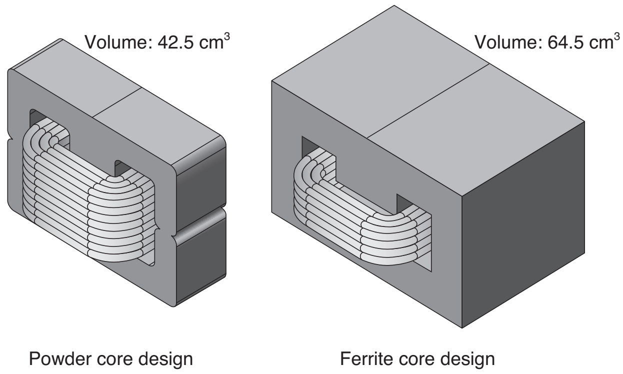


Fig. 5. Shapes of choke coils

Table 4. Results of ferrite core design and powder core design

		ferrite core design	Powder core design
Volume (calculated as cube)		64.5 cm^3	42.5 cm^3 (-34%)
Weight		214 g	118 g (-45%)
Inductance (target value: 78.1uH~@26.5A)		87.8uH@26.5A	88.7uH@26.5A
Windings	Turns	ø1.5 mm × 15 turns	ø1.5 mm × 36 turns
	Number of layers	3 layers	4 layers
Air gap		2.0 mm	1.0 mm
Max operating flux density		0.54 T	0.20 T
Losses	Core loss	0.13 W	1.6 W
	Copper loss (50 Hz)	4.3 W	6.0 W
	AC copper loss (50 kHz*)	1.7 W	0.64 W
	Total loss	6.2 W	8.2 W (+34%)

* Switching frequency: 50 kHz

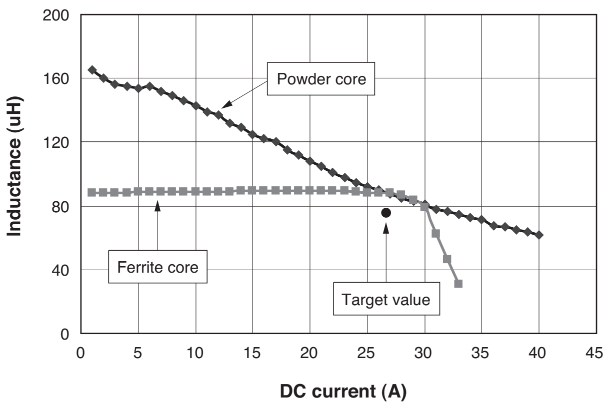


Fig. 6. DC-bias characteristics in simulation

Table 5. Heat density of choke coil

	Ferrite core design	Powder core design
Average heat density (W/cm^3)	0.10	0.19
Heat density of windings (W/cm^3)	1.98	1.37
Heat density of core (W/cm^3)	0.003	0.12

4. New Structure Choke Coil

In this section, the heat dissipation of the E-type choke coil designed with powder cores is investigated. To improve its poor heat dissipation, a new structure choke coil has been developed. An E-type choke coil was fabricated to examine the temperature rise at the time when it operated in the switching circuit. The cooling condition for choke coils in the charger was assumed to utilize the water-cooling system inside the vehicles and was imitated as in **Fig. 7**. The experimental results are shown in **Fig. 8**. At a current of 15 A or more, this E-type choke coil shows a higher temperature rise of more than 60°C. This will limit its use in most cases. The thermal resistance from the resin bobbin and the powder core between the windings and the heat sinking plane are responsible for this high temperature rise.

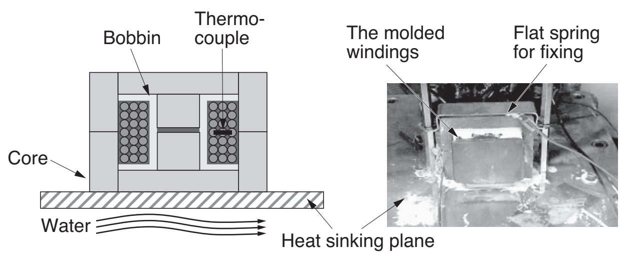


Fig. 7. Temperature measurement of E-type choke coil

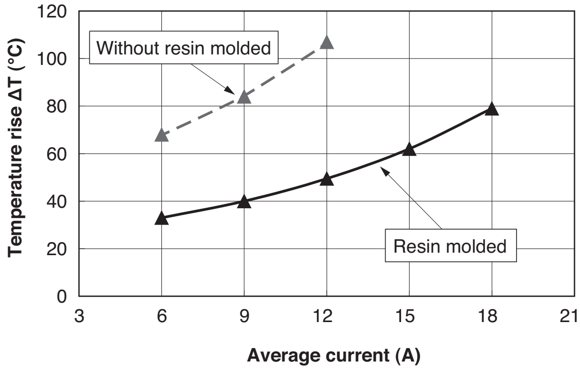


Fig. 8. Temperature rise in the E-type choke coil

To improve the poor heat dissipation of the E-type, we have suggested a new structure choke coil composed of two simple-shaped cores as shown in **Fig. 9**. **Figure 10** shows the cross-sectional view of the new structure when it is mounted. There is a direct path for heat transfer to the heat sinking plane for windings which have a higher heat density, as is seen in **Fig. 10**. In this structure, it is also easy to insert an air gap by changing the height of the inner core.

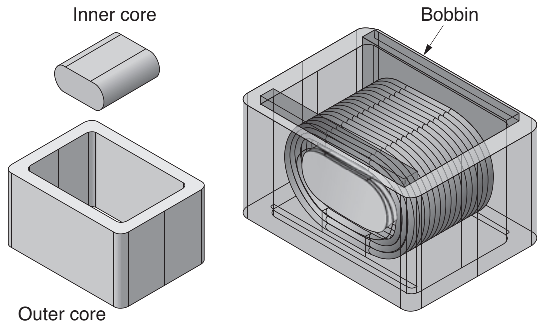


Fig. 9. The new structure choke coil

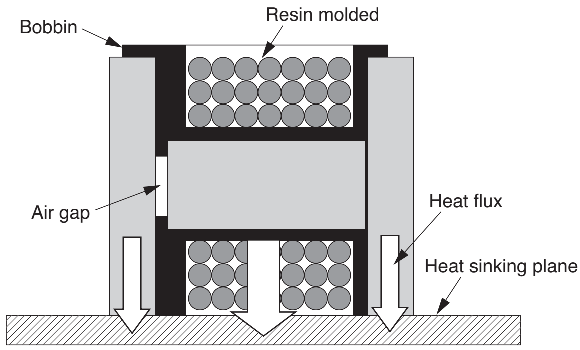


Fig. 10. Cross-sectional view of new structure choke coil

Table 6 compares the design details between the E-type choke coil and the new structure choke coil. The new structure choke coil has a rectangular shape, allowing it to be smaller in size than the E-type with an irregular shape. Due to the increase in gap length and the variation in magnetic flux leakage, total loss of the new structure is 1.4 W higher than that of the E-type. In **Fig. 11**, the similar DC-bias characteristics are shown for the two choke coils. **Photo 1** shows the prototypes.

The temperature rise of the new structure choke coil was tested under the same conditions as the E-type. The experimental results are shown in **Fig. 12**. At the current of 15 A, the temperature rise in the new structure choke coil is only 40°C while it is 60°C in the E-type choke coil. As expected, the new structure has better heat dissipation than the E-type. Regarding the ease of production, the new

Table 6. Comparison of designs between E-type and new structure

		E-type design	New structure design
Core materials		Alloy powder core	
Volume (calculated as cube)		42.5 cm^3	37.1 cm^3
Weight		118 g	130 g
Inductance (target value: 78.1uH~@26.5A)		88.7uH@26.5A	88.9uH@26.5A
Windings	Turns	ø1.5 mm × 36 turns	
	Number of layers	4 layers	3 layers
Air gap		1.0 mm	1.5 mm
Losses	Core loss	1.6 W	1.8 W
	Copper loss (50 Hz)	6.0 W	5.8 W
	AC copper loss (50 kHz*)	0.64 W	1.9 W
	Total loss	8.2 W	9.6 W

* Switching frequency: 50 kHz

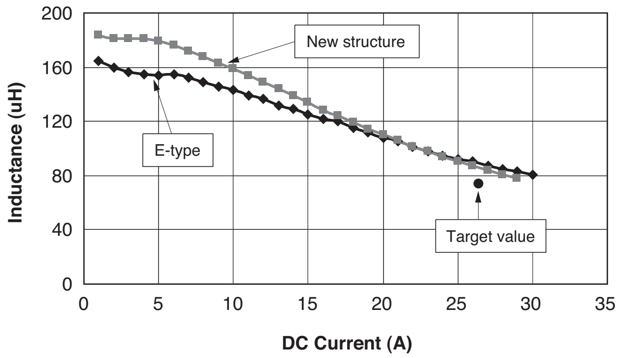
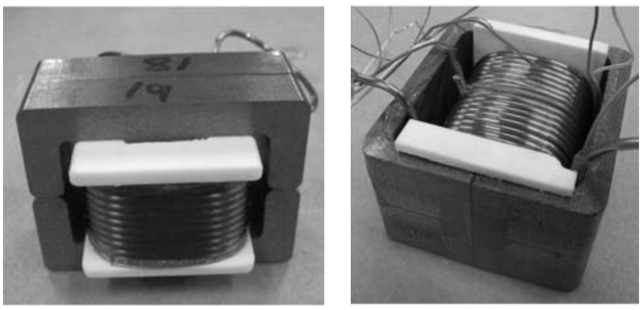


Fig. 11. DC-bias characteristics of E-type and new structure choke coil



(a) E-type **(b) New structure**

Photo 1. Prototypes of E-type and new structure choke coil

structure choke coil is easily manufactured through the automatic winding of copper wires to a bobbin just as the E-type. Also, the simple shapes of the inner and outer cores are suitable for powder cores that are manufactured by compacting.

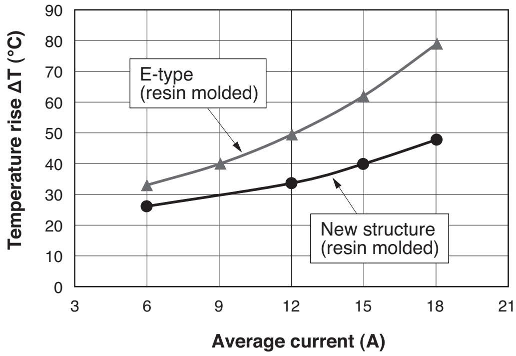


Fig. 12. Temperature rise of new structure choke coil

5. Conclusion

In this study, we have developed a new structure choke coil using our low-loss alloy powder cores for the PHEV/EV charger application. This new choke coil is compact in size, superior in heat dissipation, and easy to manufacture. The results are summarized as below:

(1) We have compared magnetic properties of ferrite cores and alloy powder cores through FEM simulation. The results indicated that an approach, which utilizes the high saturation flux density of alloy powder cores by increasing the number of turns, can downsize the choke coils.

(2) The E-type choke coils for PFC of chargers were designed using ferrite cores and alloy powder cores. The detailed design shows that the alloy powder core significantly reduces the size and weight compared to the ferrite core.

(3) To improve the heat dissipation of conventional E-type choke coils, we have developed a new structure choke coil composed of an inner core and an outer core. The effective heat dissipation of this new choke coil was confirmed through experiments. Also, the new choke coils are easy to manufacture as the coil can be wound automatically and the core shape is simple.

In the future work, we will promote the development of this new structure choke coil using powder cores to put it into practical use.

Technical Terms

*1 Switching power supply: A power supply that regulates either output voltage or current by switching on/off the inductors and capacitors with the power transistors.

*2 Powder core: A kind of inductor magnetic core manufactured by compacting soft magnetic metal powder coated with an insulating film.

*3 DC-bias characteristics: The relationship between the inductance of an inductor and DC bias current.

*4 Curie temperature: A temperature point at which the magnetic materials lose their magnetic properties.
*5 FEM: Finite Element Method.

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