Practical and Potential Applications of Soft Magnetic Powder Cores with Superior Magnetic Properties

Tomoyuki UENO*, Hijiri TSURUTA, Tatsuya SAITO, Asako WATANABE, Tomoyuki ISHIMINE and Koji YAMADA

Recently, environmental awareness has been growing worldwide, and energy saving vehicles, such as hybrid vehicles (HVs), and clean energy generated by solar and wind power are being promoted. Electrical operating systems and electric power devices are necessary for these applications, and electromagnetic conversion parts that are comprised of cores and windings are the key parts for them. While laminated steel and ferrite core are conventional materials for the cores, for downsizing these systems and devices and improving their power efficiency, we have developed a soft magnetic powder core (SMPC), which exhibits superior magnetic properties in a high frequency region and a high degree of forming freedom. Moreover, we have put it into practical use as an HV reactor, etc. The SMPC is produced by press-forming powder with an insulator film. In order to improve its magnetic performance, the modification of magnetic particles composition and the elimination of impurities are effective. In addition, the development and modification of insulation films, coating technologies, and additive materials such as lubricants and binders are also important. Our Fe-Si-Al alloy core exhibits superior characteristics of iron loss.

Keywords: soft magnetic powder core, low iron loss, high induction, shape flexibility, practical applications

1. Introduction

Aiming for a low-carbon society, electric vehicles, power saving in electric appliances and electronics, clean energy generation, and various other projects have been ongoing. In many of these projects, electrical mechanisms, power supply units, or other important devices that require electromagnetic conversion are used. Motors and transformers constitute two examples of these devices. An electromagnetic conversion coil consisting of an iron core and a copper winding constitutes, in turn, a key component of the aforementioned devices. As such, we are currently developing a soft magnetic powder core that exhibits excellent AC magnetic characteristics as an iron core material. This material is produced by press-forming magnetic particles covered with an insulation film. The soft magnetic powder core can be formed into various shapes and is, therefore, superior to magnetic steel sheets and ferrite, which have long been used for a wide range of applications. In addition, the insulated individual particles of the soft magnetic powder core give rise to a high electrical resistance, and the magnetic core material contains a significant amount of iron. The resistance and iron content yield a distinct electromagnetic conversion efficiency and magnetic flux density.*1 Owing to the aforementioned advantages, soft magnetic powder cores are used in an increasing number of applications with each passing year. In fact, there is increasing demand for downsized high-output devices and hence, high-performance magnetic core materials corresponding to the applications and usage environments are required. Research and development on the material composition, insulating films, etc. is essential for the realization of these materials. As such, this paper presents a summary of soft magnetic powder cores and describes our efforts to develop technology for reducing the loss associated with these cores, examples of their practical use in devices, and an outlook on the future of these cores.

2. Summary of Soft Magnetic Powder Cores

2-1 Types of soft magnetic materials and the position of soft magnetic powder cores

In general, magnetic materials are classified as either hard or soft. This paper describes a soft magnetic material that is magnetized by an external magnetic field and whose degree and direction of magnetization can be easily changed. Soft magnetic materials include soft magnetic powder cores, which are the subject of this paper, magnetic steel sheets, ferrite, and amorphous strips. These materials are used in various applications.

A conceptual diagram of applications based on the relationship between the operating frequency and the flux density of the major soft magnetic materials is shown in Fig. 1. Motors typically operate at low frequency and high flux density. Although radial flux motors constitute the conventional motor structure, axial flux motors*2 that consist of three-dimensional magnetic circuits have been used in some applications in recent years. Solenoid valves and reactors for high-capacity power supplies operate at high frequencies, and choke-coils and noise filters for small power supplies operate at frequencies close to 100 kHz. These applications are operated at high frequencies in order to meet recent demands for high operating speeds and response. To be used for these applications, magnetic cores need to have a high flux density at high operating frequencies and can be formed into various shapes, thereby allowing three-dimensional magnetic circuit design. Soft magnetic powder cores are produced from insulated magnetic powder by means of powder metallurgy. These cores have distinct magnetic characteristics in the high-frequency region, can be easily produced via net shaping,*3 and can be formed into various shapes.

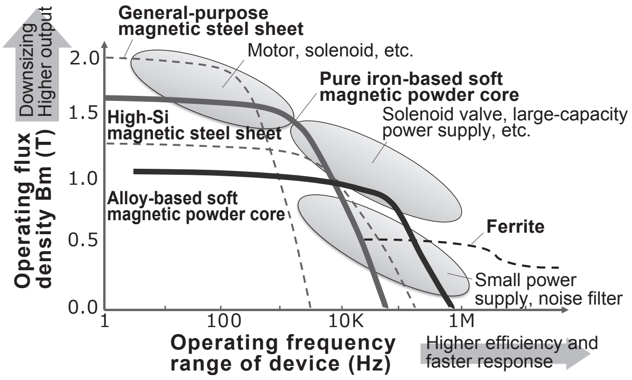


Fig. 1. Application area of each soft magnetic material

2-2 Structure and production process of soft magnetic powder cores

The schematic illustrations of a soft magnetic powder core and a magnetic steel sheet are compared in Fig. 2. Only the interlayers of the magnetic steel sheet are insulated. On the other hand, the particles of the soft magnetic powder core are all covered with an insulating film, thereby resulting in a high electrical resistance. The eddy current can therefore be contained in the particle during AC operation. Compared with the magnetic steel sheet, the soft magnetic powder core leads to a significant decrease in the energy loss (hereafter referred to as core loss) during electromagnetic conversion.

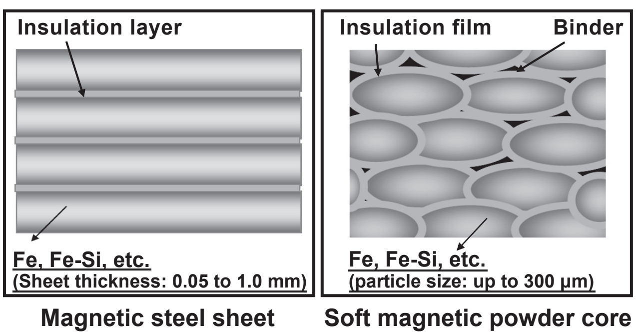


Fig. 2. Schematic illustrations of the soft magnetic materials

The production process that gives rise to soft magnetic powder cores is shown in Fig. 3. Each core is produced by injecting a magnetic powder (average particle size: approx. 50–300 μm) of pure iron or iron-based alloy (Fe-Si, Fe-Si-Al, etc.) into the dies. The powder, which is covered with an approx. 20–200-nm-thick insulation film, is then press-formed (under a pressure of 600–1,400 MPa) to high density (relative density: approx. 80–98%). Afterwards, the powder is heat-treated (at a temperature of 400–800°C) in order to relieve the residual distortion caused by press forming.

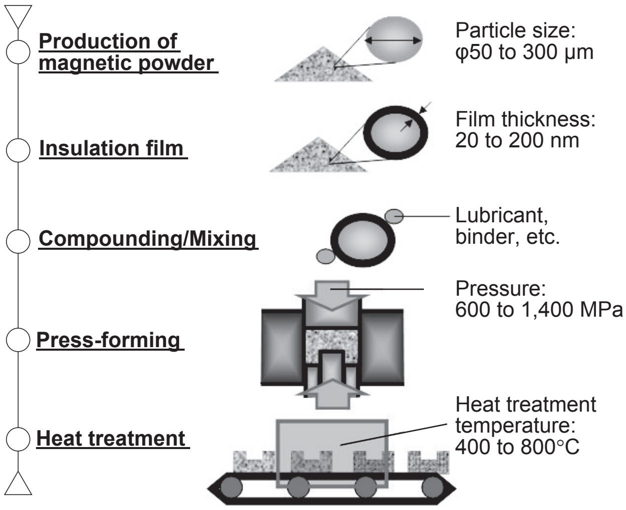


Fig. 3. Production process of soft magnetic powder cores

3. Example of Practical Use of Soft Magnetic Powder Cores

This chapter introduces examples of applications of our in-house-developed soft magnetic powder core that contributes to a decrease in the fuel consumption of automobiles. A common-rail type fuel injection valve for clean diesel engine and an ignition coil for gasoline engine, which can be used in internal combustion engines, are described. A boosting reactor, which can be used as an inverter for hybrid automobiles, is also described in detail.(1),(2)

3-1 Application to a common-rail system for diesel fuel injection valves

A common-rail type diesel fuel injection valve (Photo 1) was required for the rapid (within several hundred microseconds or less) repeated injection of up to approx. 1,800 bars of diesel fuel. Therefore, a soft magnetic powder core was required to achieve high magnetic attraction and a rapid response. The high processing accuracy, i.e., high strength at high temperatures, high dimensional accuracy and low surface roughness were also required. In order to use the aforementioned material in practical applications, [1] the development of a binding resin that can ensure high insulation performance and improve strength at high temperature with a trace amount, and [2] the development of a process capable of achieving high density were necessary. The valve was used in a position close to the engine, and therefore, the binding resin described in [1] needed to withstand a temperature of 200°C.

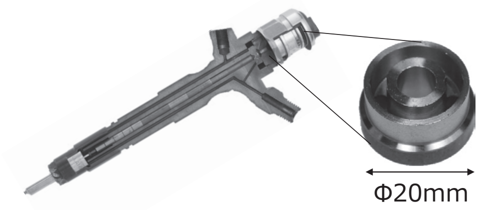


Photo 1. Diesel fuel injection valve (cross-section) and soft magnetic powder used for the valve

In the present work, the soft magnetic powder core was developed by using a pure iron powder covered with an insulating film. A binder (up to 0.5 wt.%) and a lubricant (0.6–1.0 wt.%) were added to the powder for shape retention and to reduce sliding friction with the dies during press-forming, respectively. However, in order to achieve higher density core than the conventional core, we developed a process in which a lubricant is applied to the surface of the dies (rather than adding to the powder). By combining the process with a press-forming process that heats the dies, we achieved an approx. 20% higher density, under the same compacting pressure, than that achieved when a lubricant was added (0.6 wt.%).

The dependence of the flux density $B_{8000A/m}$ on the density of the developed and conventional materials is shown in Fig. 4. As the figure shows, the flux density of both materials increases with increasing density. However, the developed material exhibited a higher flux density than the conventional material, under the same compacting pressure of 882 MPa.

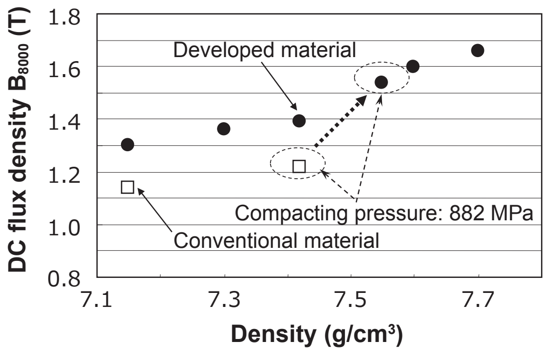


Fig. 4. Dependence of the flux density of the developed and conventional materials on the density

To improve the bending strength, we developed a resin that has high strength at high temperatures. This resin also prevents damage on the insulating films owing to friction among the powder particles during press. Figure 5 shows the temperature dependence of the bending strength (at the same compacting pressure) for temperatures ranging from room temperature to 200°C. The strength of the developed material was approx. 15% higher than that of the conventional material, at room temperature.

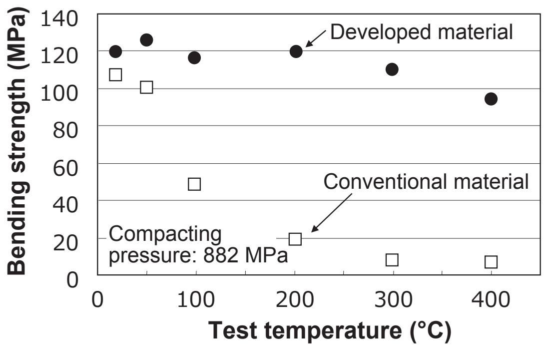


Fig. 5. Bending strength of the developed and conventional materials as a function of the test temperature

3-2 Application to ignition coil for gasoline engines

An ignition coil serves to increase the battery voltage to several tens of thousand volts and ignite gasoline with the aid of a spark plug. Ignition coils capable of generating extremely high energy and voltage are needed, owing to the recent widespread proliferation of exhaust gas recirculation and supercharging technologies.

Photo 2 shows a soft magnetic powder core that is used for ignition coil applications and an ignition coil, which uses this core. Soft magnetic powder cores were used in the ignition coils because they facilitate the formation of three-dimensional magnetic circuits and are less likely (than other cores) to result in magnetic saturation. Furthermore, technology that removes the high-density compacted material from the dies without damaging the insulating films is particularly important

Photo 2. Ignition coil (left) and appearance of soft magnetic powder cores for ignition coil applications

for the development of a flanged, cylindrical soft magnetic powder core.(3)

We started the mass production of a soft magnetic powder core for this application in 2014. This product also won the New Product Award of the Japan Powder Metallurgy Association.

3-3 Application to reactors in boost convertors for hybrid automobiles

A reactor is contained in a boosting converter for a motor-driven system for hybrid automobiles. The reactor is used to convert the voltage through repeated charging and discharging of magnetic energy (boosting mechanism) and smooth the ripple current (pulsation component of the current) in the process. Compared with magnetic steel sheets that have typically been used for the magnetic cores of reactors, soft magnetic powder cores perform excellently in the high-frequency region and are magnetically isotropic. Therefore, we developed the aforementioned soft magnetic powder core with the aim of reducing the size and weight of reactors.

The core of a reactor consists of a simple semicircular side core and a rectangular parallelepiped middle core chamfered along the coil. The reduction of the core loss (eddy current loss) in the core is essential for the use of the soft magnetic powder in reactors.

First, reduction of eddy current loss by modifying the side core is described. In the case of conventional cores, the simple semicircular shape of the side core was obtained by using a punch (as shown in Fig. 6) to simplify the structure of the dies. This results, however, in damage to the insulating film of powders in the portion orthogonal to the face that slides against the dies. Consequently, the face opposite the middle core is electrically conducting, and an excessive surface eddy current is generated, thereby resulting in a significant increase in the core loss. This increase was prevented by press-forming along a direction perpendicular to this face, and the compacting method was changed such that the face opposite the middle core was formed with the punch. Moreover, damage to the dies, owing to stress concentration on the lower punch, was prevented by using a stepped die.

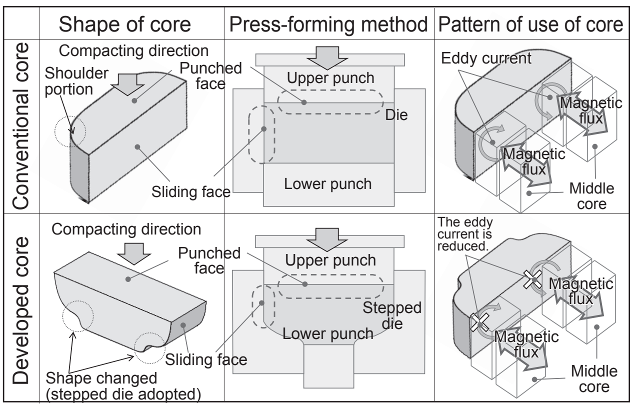


Fig. 6. Reduction of eddy current loss by employing the side core compacting method

The eddy current flowing through the middle core must also be taken into consideration. The shape of the core and the press-forming method are shown in Fig. 7. The problem in this case is that a conducting layer is formed on the surface of the four faces of the core, except for the face press-formed by the upper and lower punches. This layer results from sliding during the removal of the core from the dies, and leads to a significant increase in the core loss. To overcome this drawback, we developed a new laser processing method that removes the conducting layer and forms a highly electrically resistant layer on the surface of the core (Fig. 8). The sectional structure of the sliding face of the core is shown in Photo 3. Adjoining, conducting particles with vague boundaries are present prior to irradiation. However, after irradiation, oxides with high electrical resistance are formed, the particle-particle boundaries are sharpened, and the conducting particles are eliminated.

The development of the aforementioned technology enabled the mass production of the reactor core for hybrid automobiles. Reactors that use this core are approx. 10% smaller and lighter than conventional reac-

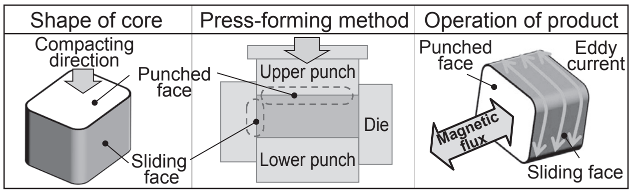


Fig. 7. Middle core press-forming method and problem of continuity of the sliding face

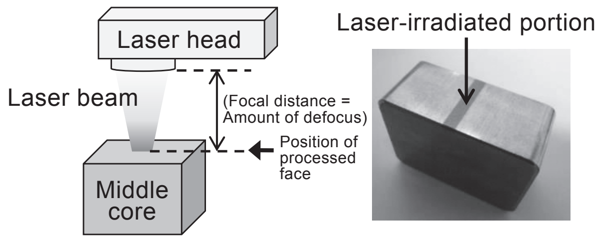


Fig. 8. Laser irradiation method

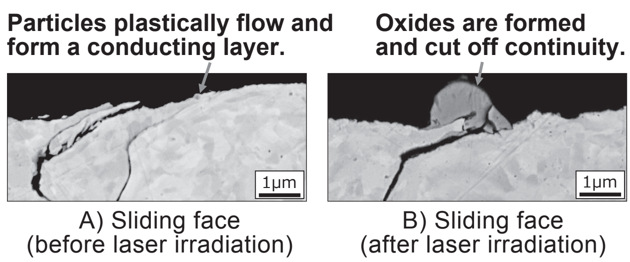


Photo 3. Sectional structure of the die sliding face before and after laser irradiation

tors keeping the same performance. This product won the New Product Award of the Japan Powder Metallurgy Association.

4. Future Outlook on Soft Magnetic Powder Cores

The core loss of pure iron-based soft magnetic powder cores may be reduced even further. This reduction will increase the spectrum of applications, for which these cores can be used, and their applicability to electric motors. This section also describes the development of an alloy-based soft magnetic powder core with extremely low core loss, in preparation for the proliferation of next-generation semiconductor devices.

4-1 Reduction of the core loss of pure iron-based soft magnetic powder cores and their application to motors

Using high-purity iron powder and a heat treatment at 650°C, which leads to minimal coercive force, is essential for reducing the core loss of pure iron-based soft magnetic powder cores. The core loss of a soft magnetic powder core (using pure iron powder produced by a water or gas atomization process*4) and a magnetic steel sheet (35A360) are compared in Fig. 9.(4) The developed material exhibits a lower core loss, and soft magnetic powder core can be formed to a various shapes than the magnetic steel sheet. The developed material is therefore well-suited for use in axial flux motors that contribute to the high torque density of motors.

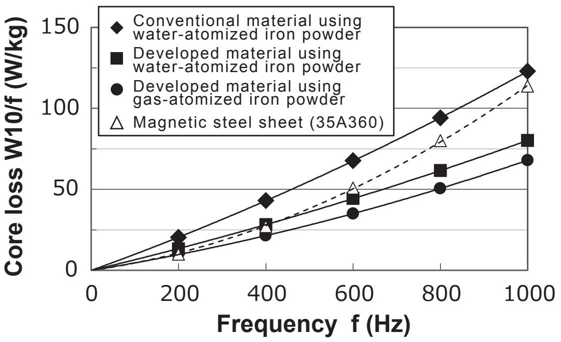


Fig. 9. Core loss of the soft magnetic powder core and a magnetic steel sheet as a function of the frequency

4-2 High frequency-compatible alloy-based soft magnetic powder core with extremely low core loss

The design of power supplies for operation at high frequencies by using next-generation semiconductors has been increasingly determined in recent years. These designs are aimed mainly at downsizing inverters and other devices and improving their performance. Accordingly, choke-coils and transformers require magnetic core materials that exhibit high-performance in the high-frequency region.(5) As such, we developed a new material [1] by fabricating a high-heat-resistant insulating film, [2] using technology that produces thin, uniform insulating films, which result in high density and low core loss. We achieved a considerable reduction in the core loss, compared with that of conventional Fe-Si-Al-based soft magnetic powder cores, by using an Fe-Si-Al-based alloy powder and applying our in-house-developed technology; this powder exhibits distinct soft-magnetic characteristics in the high-frequency range.(6) Furthermore, we developed another material, whose alloy composition is optimized and which exhibits low core loss in the high-temperature range (Fig. 10), for on-vehicle applications that require high-temperature operation of the devices. The Fe-Si-Al particle is hard and poor in plastic deformation, and is therefore, difficult to be compacted to high density. Hence, we developed powder processing technology that produces fine/coarse, homogeneous particle arrays (as shown in Photo 4) in order to increase the packing density of Fe-Si-Al particles and the resulting magnetic flux density.

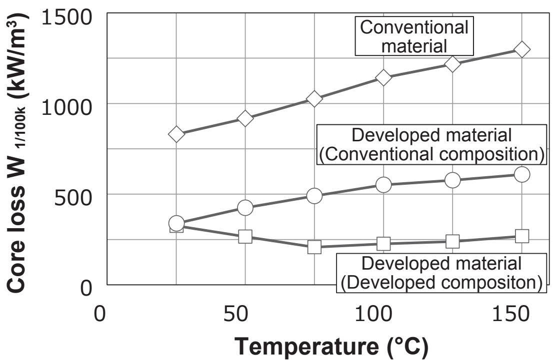


Fig. 10. Temperature dependence of the core loss of the conventional and developed materials

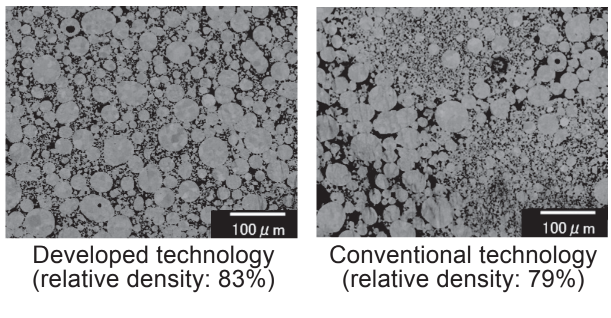


Photo 4. Improvement of the density by particle array control

The characteristics of Fe-Si-Al-based soft magnetic powder cores are shown in Table 1. The core loss of the developed material is significantly lower than that of the conventional Fe-Si-Al-based material, and is close to that of ferrite. In addition, the magnetic flux density of the developed material is 1.7 times higher than that of ferrite. This material is more suitable, compared to the conventional material and ferrite, for the downsizing of choke-coils and transformers and reduction of heat generated in them.

As Table 1 shows, the Fe-Si-Al alloys have a higher Curie point than ferrite and hence can maintain stable magnetic characteristics to higher temperatures. The temperature dependence of the inductance of choke-coils produced with ferrite and the developed material is compared in Fig. 11.

Table 1. Characteristics of the developed material unit

Material		Developed composition Fe-Si-Al alloy	Conventional Fe-Si-Al alloy	Mn-Zn-base ferrite
Magnetic flux density	Tesla	0.89	0.80	0.51
Core loss (25°C)	kW/m^3	325	830	57
Core loss (100°C)	kW/m^3	226	1142	50
Relative permeability	-	56	52	2400
Curie temperature	°C	500	500	250

* Core loss measurement condition: 0.1 T/100 kHz

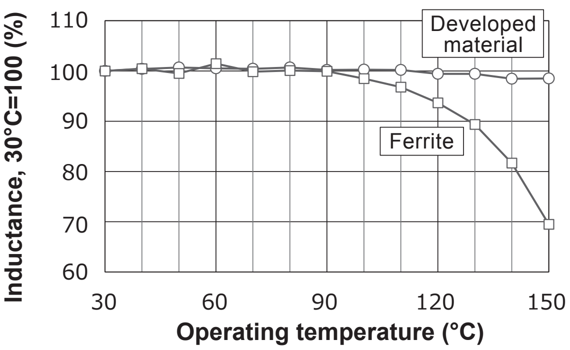


Fig. 11. Comparison of the temperature dependence of the inductance

As the figure shows, the inductance of ferrite decreases by up to 30% at 150°C, whereas the inductance of the developed material remains approximately constant. A cooling mechanism is therefore crucial for ferrite-based coils but is unnecessary for coils that are made of the developed material. This indicates that the developed material can contribute to cost reduction of the power supplies through downsizing and reducing the number of parts.

We received the Award for Innovatory Development of the Japan Society of Powder and Powder Metallurgy. Part of this research was implemented with the assistance of the "2009 Innovation Implementation Assistance Project" of the New Energy and Industrial Technology Development Organization (NEDO), an independent administrative institution.

5. Conclusion

In a society that promotes energy saving, magnetic core materials, which are the nucleus of electromagnetic conversion parts, need to deliver sustainable performance. The soft magnetic powder cores we developed by using powder metallurgy technology, exhibited both low core loss and high flux density. These cores have been mass-produced for more than ten years and have been used in key systems for automobiles with low fuel consumption. Our aim is to further improve the performance of the soft magnetic powder cores. These cores constitute optimal materials for motors (which are the basis of electric drive), choke-coils, and high-frequency transformers that will be used in next-generation semiconductor devices.

Technical Terms

∗1 Flux density, magnetic flux density: The maximum flux density (amount of flux per unit area) that a magnetic material can attain. The higher this value, the smaller is the core.

∗2 Axial flux motor: An axial flux motor has a structure in which the disk-like rotor and the stator are positioned opposite to each other. Compared with general radial flux motors, an axial flux motor has a thinner (flat) body and a higher torque density.

∗3 Net shaping: In this paper, the term is used to describe the method of forming the final target shape by means of powder pressure molding only, using dies and without machining, etc.

∗4 Atomization: Atomization is a metallic powder manufacturing process that produces a fine powder by atomizing water or gas into a molten metal at high speed.

References

(1) Y. Shimada et al., Development of High-Performance P/M Soft Magnetic Material, J-Jpn. Soc. Powder Powder Metallurgy, Vol.53, No.8, pp.686-695, August (2006)

(2) N. Igarashi et al., Pure Iron Based Magnetic Composite Core That Enables Downsizing Automotive Reactors, SEI Technical Review, No.186, pp.92-97, January (2015)

(3) A. Watanabe et al., Development of High Density and Low-Loss Soft Magnetic Powder Core, Proceedings of Euro PM 2015 (2015)

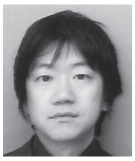
(4) T. Maeda et al., Development of Super Low Iron-loss P/M Soft Magnetic Material, SEI Technical Review, No.60, pp.3-9, June (2005)

(5) A. Ishimine et al., Development of Low-Iron-Loss Powder Magnetic Core Material for High-Frequency Applicatins, SEI Technical Review, No.72, pp.117-123, April (2011)

(6) T. Ishimine et al., Development of FeSiAl-Based Low Iron Loss Soft Magnetic Powder Cores, Proceedings of the 2014 International Conference on Powder Metallurgy & Particulate Materials, 09-189 (2014)

Contributors The lead author is indicated by an asterisk (*).

T. UENO*



• Dr. Eng.
Assistant Manager, Advanced Materials Laboratory

H. TSURUTA

• Advanced Materials Laboratory

T. SAITO

• Dr. Eng.
Advanced Materials Laboratory

A. WATANABE

• Assistant Manager, Advanced Materials Laboratory

T. ISHIMINE

• Assistant Manager, Advanced Materials Laboratory

K. YAMADA

• Group Manager, Advanced Materials Laboratory