Dust Core with Low Core-loss for High-frequency Applications

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Dust cores produced by compacting insulation-coated powder allow a high degree of freedom in shaping and are expected to be useful for the downsizing of parts; however, they have issues of energy loss, or core loss. A study has been conducted on reactors and choke coils, which are used at relatively high frequencies, to improve their core-loss characteristics by focusing on the particle size of the powder. As a result, "MAGMEL MH20D" powder was developed by designing powder, taking into account, not only the magnetic characteristics, but also power characteristics, and by combining Kobe Steel's conventional techniques of heat-resistant coating and grain coarsening. The newly developed powder has improved the core loss, reducing it to 30% of that achieved by conventional products, and has been adopted for the reactors of solar-power systems.

Introduction

Electromagnetic components are required to have higher efficiency, to save energy and reduce the environmental burden, and smaller sizes to save space. Laminated cores consisting of electrical steel have conventionally been used for the iron cores of electromagnetic components; however, downsizing has been limited due to the anisotropy intrinsic to laminated structure and to shape limitations.

Dust cores, on the other hand, being manufactured by compacting powder, have no anisotropy and less restriction as to shape; thus their downsizing is expected. In fact, dust cores made of Fe-Si based alloy powder have been adopted for the booster reactors of hybrid vehicles.[1)] With the beginning of a subsidy program for solar power generation as a part of the Renewable Energy Promotion Policy, the demand for solar-power generation systems has been increasing, and this has promoted the application of dust cores for downsizing and improving the efficiency of components used in power generation systems.

Commercially pure (CP) iron powder, a raw material of dust cores, has higher compressibility and greater saturated magnetic flux density compared with alloy powders, which makes further downsizing of components possible. Its soft particles ensure excellent compactibility and have the advantage of being easy to handle in the process of core manufacturing. On the other hand, there has been an issue as to how to reduce core loss, or energy loss.

In order to reduce the core loss of CP-iron-based dust cores, a study was conducted on the effect of powder particle size on core loss. Knowledge gained through the research, as well as coating technology and crystal grain control technology established so far, has been used to develop "MAGMEL MH20D" powder, which has a core loss improved by 30% over that of conventional CP iron powder. Its core loss characteristics are comparable to those of some of the Fe-Si-based alloy powders. MAGMEL MH20D has been adopted as a raw material for the reactors of power conditioners used in solar power generation.

1. Challenges and developmental approaches for CP-iron-based dust core

The characteristics required for magnetic core material are high magnetic flux density and low core loss. As described above, dust cores based on CP iron powder have the disadvantage of significant core loss, despite their possessing magnetic flux densities higher than those of alloy powders. Core loss mainly consists of eddy-current loss and hysteresis loss. Eddy-current loss is a joule loss caused by eddy current generated when magnetization fluctuates, while hysteresis loss is an energy loss caused when a magnetic material is magnetized. **Fig. 1** illustrates these control factors. Dust cores have the capability of suppressing the inter-particle eddy current, which flows throughout the component as a result of insulation coating on the particle surfaces. In high-frequency regions, however, the proportion of eddy-current loss is

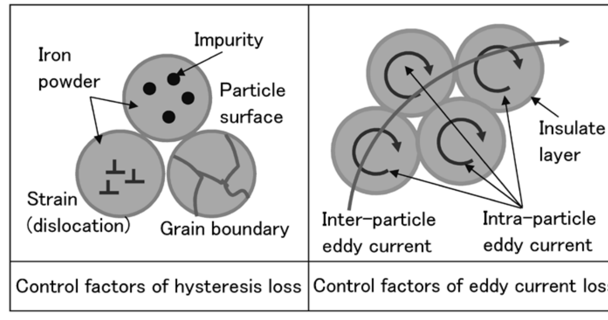

Fig. 1 Control factors of iron loss

increased as a whole loss. Therefore, in addition to inter-particle eddy current, intra-particle eddy current must also be suppressed. In the case of alloy powders, intra-particle eddy current is suppressed by increasing impedance by the use of additive elements, whereas, in the case of CP iron powder, it is difficult to control impedance with additive elements. Therefore, the only way of decreasing intra-particle eddy current is to decrease the particle size and thus restrict the flowing range of eddy current. Decreasing the particle size, however, increases the surface area, which can cause hysteresis loss to increase. Therefore, it is important to study both effects to determine the optimum particle size.

To this end, the effect of the particle size of iron powder on the core loss and powder characteristics was studied so as to determine the optimum particle size for achieving low core loss in the high-frequency region. The subsequent sections include the introduction of "MAGMEL MH20D" for high-frequency application, which was developed on the basis of the study results.

2. Investigative method

Kobe Steel's atomized CP iron powder was sieved to remove coarse particles providing raw iron powders having an average particle size of 30 μm to 85 μm (D50: the value of the particle diameter at 50% in the cumulative distribution obtained by sieving.) Processing liquid mainly comprising phosphoric acid was used to form an inorganic coating on the particle surfaces of these iron powders. Subsequently, it was coated with silicone resin to produce insulation-coated iron powder with an inorganic/organic double layer.[2)] Each of the coated iron powders was filled into a powder-lubricated die and the powder-filled die was heated to 303K to form ring compacts (ϕ45mm OD; ϕ33mm ID; 6mm H) under a pressure of 1,176MPa. These compacts were heat-treated at 873K for 1.8 ks in a nitrogen atmosphere. Each iron-loss measurement sample was prepared by forming a primary coil and a secondary coil, winding 50 and 10 turns of wire, respectively, on the corresponding heat-treated ring compact; while each BH-curve measurement sample was prepared by forming a primary coil and a secondary coil, winding 400 and 25 turns of wire, respectively, on the corresponding heat-treated ring compact.

The flow rate of coated powder was measured in accordance with the JIS Z 2502：2012, "Metallic powders-Determination of flow rate by means of a calibrated funnel." The BH curve of each sample was measured up to a maximum excitation magnetic field of 10 kA/m; while the core loss was measured for an excitation magnetic flux density of 0.1 T under a varying frequency of 1 k to 100 kHz.

3. Results and discussion

3.1 Effect of iron-powder particle size on magnetic characteristics

The eddy-current loss of a dust core consists of inter-particle eddy-current loss, due to eddy current flowing throughout the core, and intra-particle eddy current loss, due to eddy current flowing inside each particle (Fig. 1.) The inter-particle eddy current loss can be suppressed by providing insulation coating on iron powder particles, whereas intra-particle eddy current loss can be controlled by sizing the particle, i.e., changing the area where electric current flows. However, this changes the surface area of particles at the same time. The surface area of particles is one of the factors affecting hysteresis loss; hence both the eddy current loss and hysteresis loss must be taken into account in the effect of particle size.

Fig. 2 (a) shows the relationship between average particle size and core loss. It has been clarified that the core loss decreases with decreasing particle size. This trend is more pronounced at higher frequencies. On the basis of the frequency dependence of core loss, the eddy current loss was separated from hysteresis loss and the results are shown in Figs. 2 (b) and (c.) The eddy-current loss decreases with decreasing particle size, as in the case of core loss, whereas hysteresis loss changes only slightly with the change of particle size. This shows that the core loss decreases predominantly with decreasing eddy-current loss.

Fig. 3 shows the dependence of coercivity on particle size. The coercivity increases with decreasing particle size, indicating that decreasing particle size, i.e., increasing surface area of particles, is a factor inhibiting the migration of domain walls.

The coercivity is generally known to be proportional to hysteresis loss, and there is a discrepancy between the particle-size dependence of hysteresis loss shown in Fig. 2 and the particle-size dependence of coercivity shown in Fig. 3. This discrepancy can be explained on the basis of the excitation condition of each characteristic measurement. The excitation condition of core-loss measurement is 0.1 T in terms of excitation magnetic flux density. On the other hand, in the case of coercivity measurement, which is a static magnetic measurement, the excitation magnetic field is

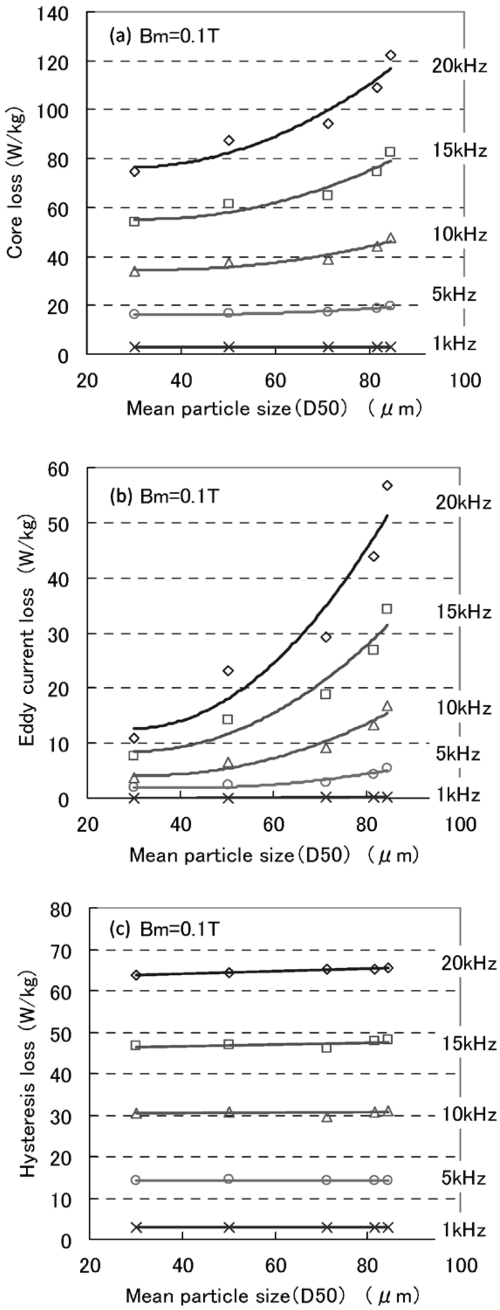

Fig. 2 Relationship between particle size and core loss
a) Core loss, b) Eddy current loss, c) Hysteresis loss

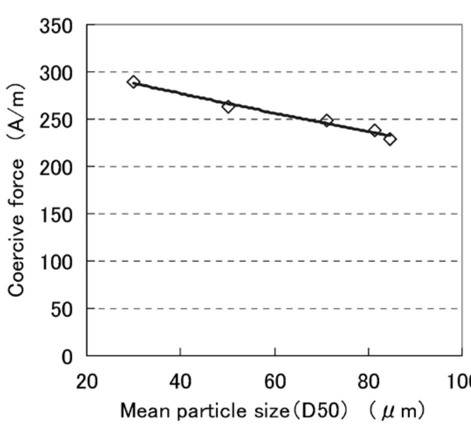

Fig. 3 Relationship between particle size and coercivity

10 kA/m. These excitation conditions are plotted on a BH curve, as shown in **Fig. 4**. The magnetic flux density for the coercivity measurement is approximately 1.4 T, which is greatly different from that of the core-loss measurement. This is indicative of a difference in the migration of domain walls: the domain walls barely migrate during the core-loss measurement; whereas, they migrate widely during coercivity measurement, since magnetization close to saturation occurs. It is believed that, when the migration of domain walls is small, the intra-particle factor inhibiting the domain wall migration governs; however, as the domain wall migration becomes greater, the surface begins to have a more significant effect. **Fig. 5** shows the particle size dependence of coercivity under different excitation conditions. As shown in this figure, no particle size dependence of coercivity is observed for the low excitation magnetic flux density of 0.1 T.

From the above, it is believed that, under the excitation condition in question (approximately 0.1 T), only the decreasing effect of eddy-current loss can be observed without the increase in hysteresis-loss due to decreasing particle size.

3.2 Effect of particle size of iron powder on powder characteristics

The flow rate is one of the key characteristics

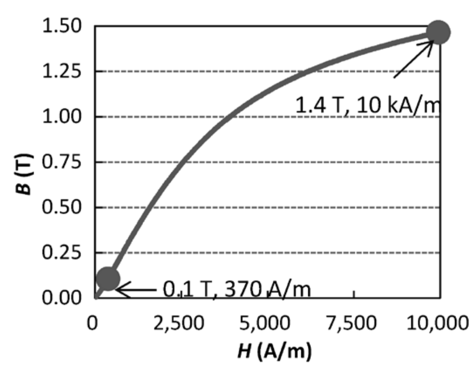

Fig. 4 Excitation condition

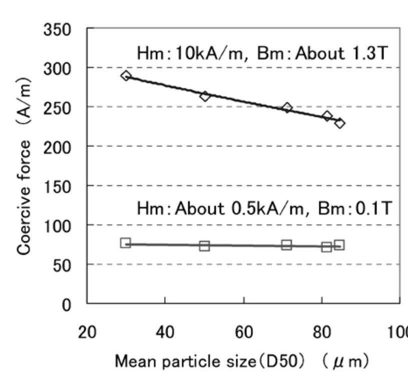

Fig. 5 Relationship between particle size and coercivity

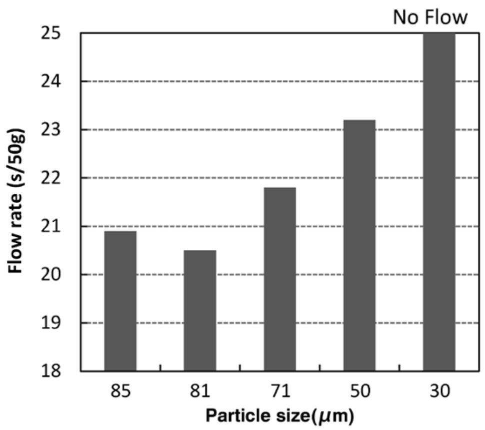

Fig. 6 Relationship between particle size and flow rate

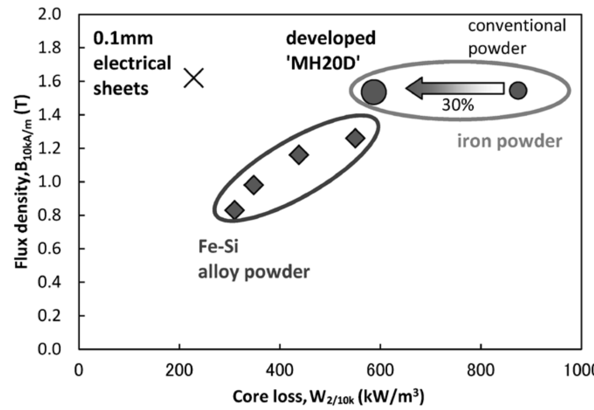

Fig. 7 Comparison of material characteristics

affecting the productivity of component production, involving storage, handling and die filling. In general, finer powder has a larger surface area, enhancing adhesion and cohesion while deteriorating the flow rate. This, therefore, is a trade-off relationship with the eddy-current loss described in the previous section. **Fig. 6** shows the relationship between the particle size and flow rate, in which the particle size was changed by sieving. The flow rate increases (the fluidity deteriorates) with decreasing particle size, and no flow occurred for the average particle size of 30 μm. On the basis of this result, the particle size of approximately 50 μm has been adopted as the practical minimum that allows the flow through the Hall flow meter, to achieve the balance between eddy-current loss and flow rate.

4. Summary

Targeting the high-frequency low magnetic-flux density region, a study was conducted on the particle size of CP-iron powder suitable for dust core. MAGMEL MH20D has been developed on the basis of the study, while exploiting "highly heat-resistant insulation coating technology"[2] and "crystal grain coarsening technology for powder."[3] **Table 1** summarizes the characteristics of a heat treated core, and **Fig. 7** compares the characteristics of MAGMEL MH20D with that of Fe-Si based alloy powder.[4] By combining these technologies, the core loss, which having been an issue, has been decreased by approximately 30%, while the high magnetic flux density, an advantage of CP iron powder, is maintained. This has realized core-loss characteristics that are comparable with those of some Fe-Si based alloy powders. The newly developed powder has been adapted to the reactors of power conditioners used in solar power generation.

Conclusions

It has been confirmed that the newly developed material can expand the applicability of CP iron powder to applications in which electrical steel sheets have conventionally been used. The advantages of dust cores over laminated cores include high yield, i.e., no material being left over due to punching, which contributes to reduced cost and resource saving. When compared with alloy powders, the newly developed powder has higher compressibility, which decreases compacting pressure by approximately 20% to 50%, saving energy cost. Although the application is currently limited to solar power generation systems, this powder is expected to be applied, for example, to inverters (general purpose, on-vehicle) using similar booster circuitry.

Table 1 Properties of 'MH20D' core

Grade	Density	DC Magnetic properties			AC Magnetic Properties			Mechanical Properties
		Flux Density $B_{10kA/m}$	Maximum Permeability	Coercive force	Core Loss $W_{1/10k}$	Hysteresis Loss $Wh_{1/10k}$	Eddy current Loss $We_{1/10k}$	Transverse Rupture Strength
	(Mg/m^3)	(T)		(A/m)	(W/kg)	(W/kg)	(W/kg)	(MPa)
MH20D	7.44	1.46	224	224	20.1	15.2	4.9	77

* Compaction: 1,176MPa with DWL compaction method at 403K
Heat treatment: 873K for 1.8ks in N_2

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