Brief Report

High-density Magnetic Composite for Reactor in Hybrid Vehicle

Takeshi Hattori, Masaki Sugiyama, Hidefumi Kishimoto and Takanobu Saito

Report received on Jan. 20, 2015

KEYWORDS Reactor, Powder Magnetic Core, High-density Powder Compaction, Particle Shape Control, High-heat-resistance Insulator Coating, Low Core Loss, High Magnetic Flux

1. Introduction

The reactor is an important component of the boost converter in the power control unit (PCU) of a hybrid vehicle (HV). The role of the reactor is to increase the output voltage of the HV system, while lowering costs by reducing the required battery capacity. The reactor is required for stably maintaining the inductance to boost the voltage of the system. The reactor is also needed to prevent overheating and achieve a low core loss. For these purposes, thin (t = 0.1 mm) electrical steel sheets with a low core loss have been used as core materials. However, a lower-cost core material is desirable because steel sheets are expensive.

This article focuses on a powder magnetic core, which is expected to reduce costs because the high-density powder compaction technique using net shaping[1] is capable of reducing manufacturing time and increasing the material yield. Using this technology, we developed a new type of powder magnetic core for a reactor with electromagnetic characteristics equivalent to those of electrical steel sheets, which is difficult to achieve with conventional powder magnetic cores.

2. New Powder Magnetic Core for Reactor

2. 1 High-density Powder Compaction

Fe-Si alloy particles were used as raw powder. By adopting the high-density powder compacting technique, the magnetic characteristics were improved (**Fig. 1**). In particular, the magnetic flux density of the core increased by 35%.[2] However, the reduction in the core loss was only about 7%, which fell short of our target. Thus, new process technologies were needed for a powder magnetic core with lower loss.

2. 2 Particle Shape Control

Water atomization is a technique for manufacturing powder to be used in powder compaction. In general, it yields irregularly shaped particles (**Fig. 2**(a)). The resulting complex particle cross sections reduce the size of the crystal grains, and increase the hysteresis loss.

Therefore, a modified water atomization technique was developed to produce particles with controlled pseudo-spheroidal shapes (Fig. 2(b)). Upon heat treatment, grain-coarsening occurred and the hysteresis loss of the particles was also greatly reduced.[2]

2. 3 High-heat-resistance Insulating Coating

The coating on the particles must have excellent insulating properties to suppress eddy currents between particles. In order to prevent an insulation breakdown of the coating during press molding and heat treatment, what is needed is an insulating material

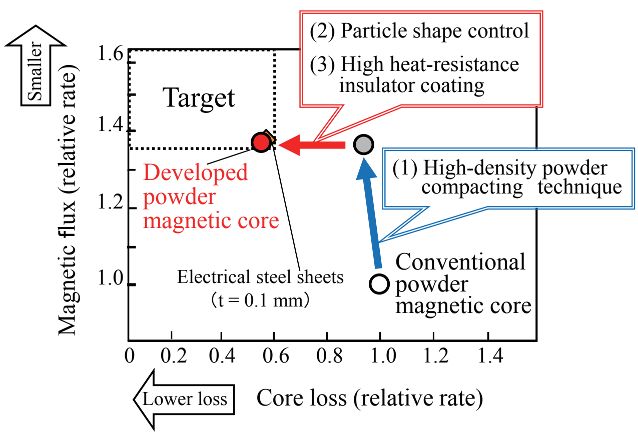

Fig. 1 Positioning of developed technologies.

that has both high flexibility and high heat resistance, and is capable of forming a very tight bond with the particles. In particular, a heat treatment at temperatures above 1000 K is required to obtain a powder core with a core loss comparable to that of an electrical steel sheet.

Thus, we focused on silicone resin as an insulating film. NMR analysis showed that upon heating above 1000 K, silicone resin formed a chemical structure with Si-O-Si bonds. On the other hand, we found that a uniform SiO_2 layer formed on the surface of Fe-Si particles as a result of heat treatment under a partial pressure of oxygen. Both the SiO_2 layer on the particles and the silicone resin with the Si-O-Si structure promoted stable electronic performance of the insulating coating.[(3)] Thus, a new insulating film that maintained its insulating properties up to a high temperature was developed using silicone resin and Fe-Si particles.

As a result, the total hysteresis loss and eddy current loss were reduced by 33% owing to the development of particles with controlled shapes and the high-resistance insulating coating.

3. Conclusion

A powder magnetic core with electromagnetic properties comparable to those of electrical steel sheets for a reactor was developed by adopting the following approaches:

(1) The high-density compaction technique increased the magnetic flux density.

(2) The shape of the Fe-Si magnetic powder particles was controlled to be spheroidal to decrease the hysteresis loss.

(3) The surface of the powder was coated with a newly developed SiO_2 insulator.

As a result, the magnetic flux density increased by 35%, and the core loss decreased by 40%. A reactor core with electromagnetic characteristics comparable to those of electrical steel sheets was developed, and its cost was greatly reduced. It is difficult to achieve this target using conventional powder magnetic cores. This is the first powder reactor core in the world to be installed in a HV (**Fig. 3**: the third-generation Prius that was launched in 2009).

References

(1) Kondo, M. and Okajima, H., "High Density Powder Compaction Using Die Wall Lubrication", *Advances in Powder Metallurgy & Particulate Materials*, Vol. 3 (2002), pp. 47-54.

(2) Sugiyama, M., Yamaguchi, T., Kishimoto, H., Okochi, S., Hattori, T. and Saito, T., "Development of High Density and Low-loss Powder Magnetic Core for Reactor in Hybrid Vehicles", *TOYOTA Technical Review*, Vol. 59, No. 229 (2013), pp. 75-80.

(3) Hattori, T., Sugiyama, M., Kishimoto, H. and Saito, T., "Development of High-density and Low-loss Powder Magnetic Core for Reactor in Vehicles", *Annual Congress* (*Autumn*) *of the Japan Society of Powder and Powder Metallurgy* (in Japanese) (2013), p. 80.

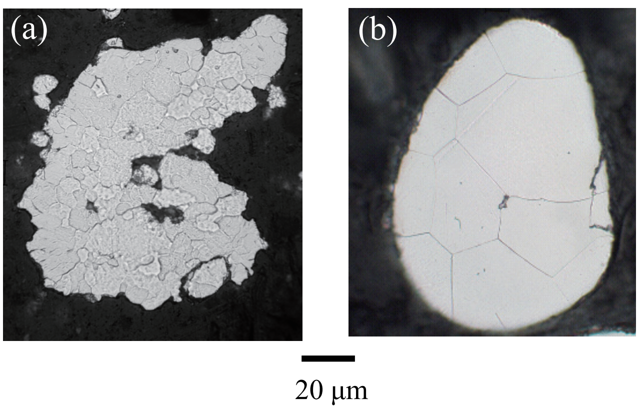

Fig. 2 Particle shape of atomized powders. (a) Water atomization. (b) Modified water atomization.

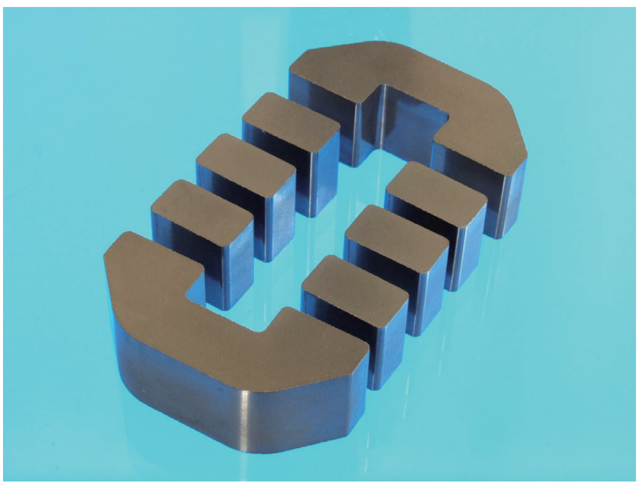

Fig. 3 Developed reactor core.

Fig. 1
Reprinted from TOYOTA Technical Review, Vol. 59, No. 229 (2013), pp. 75-80, Sugiyama, M., Yamaguchi, T., Kishimoto, H., Okochi, S., Hattori, T. and Saito, T., Development of High-density and Low-loss Powder Magnetic Core for Reactor in Hybrid Vehicles, © 2013 Toyota Motor Corporation, with permission from Toyota Motor Corporation.

Text
Partially adapted from TOYOTA Technical Review, Vol. 59, No. 229 (2013), pp. 75-80, Sugiyama, M., Yamaguchi, T., Kishimoto, H., Okochi, S., Hattori, T. and Saito, T., Development of High-density and Low-loss Powder Magnetic Core for Reactor in Hybrid Vehicles, © 2013 Toyota Motor Corporation, with permission from Toyota Motor Corporation.

Takeshi Hattori

Research Field:
- Magnetic Materials

Academic Societies:
- The Japan Institute of Metal
- The Magnetics Society of Japan
- Japan Society of Powder and Powder Metallurgy

Awards:
- MSJ Young Scientist Award (Takei Award), 2001
- JSPM Distinguished Paper Award, 2005
- JPMA Award Grand Prix, 2009
- The Ministry of Economy, Trade and Industry Manufacturing Industry Director Award, SOKEIZAI Center, 2010
- JSPM Award for Innovatory Development, 2013

Masaki Sugiyama*

Research Field:
- Powder Metallurgy

Academic Society:
- Japan Society of Powder and Powder Metallurgy

Awards:
- JSPM Distinguished Paper Award, 2005
- JPMA Award Grand Prix, 2009
- The Ministry of Economy, Trade and Industry Manufacturing Industry Director Award, SOKEIZAI Center, 2010
- JSPM Award for Innovatory Development, 2013

Hidefumi Kishimoto*

Research Field:
- Magnetic Materials

Academic Society:
- Japan Society of Powder and Powder Metallurgy

Awards:
- JPMA Award Grand Prix, 2009
- The Ministry of Economy, Trade and Industry Manufacturing Industry Director Award, SOKEIZAI Center, 2010
- JSPM Award for Innovatory Development, 2013

Takanobu Saito**

Research Field:
- Magnetic Materials

Academic Society:
- The Magnetics Society of Japan

Awards:
- JPMA Award Grand Prix, 2009
- The Ministry of Economy, Trade and Industry Manufacturing Industry Director Award, SOKEIZAI Center, 2010
- JSPM Award for Innovatory Development, 2013

* Toyota Motor Corporation
** Daido Steel Co., Ltd.