# Expectation to Magnetic of Electrical Motor, Power Electronics in Electrical Vehicle

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Commercial use of electrical vehicle is now expanded year by year for the reduction of environmental impact [1]. The electrical vehicle is driven by electrical motor drive system with an electrical motor and a power electronics technology [2]. The electrical motor is driven by magnetic force [3]. So the soft magnetic material is used as a motor core to obtain high magnetic flux density, and the hard magnetic material is used as magnetic field of the rotor [4].

NO (Non-oriented) silicon steel is mainly used as motor core due to good cost performance. However, to reduce the iron loss, lower iron loss material is commercially used as GO (Grain-oriented) steel, amorphous material and nano-crystal steel. They have a good magnetic performance as low iron loss and high magnetic permeability. When they are applied to the motor core and tribally manufactured, core loss reduction is measured [5-7]. Cost reduction is one of the main problems to be realized.

When the inverter excites the magnetic material for the motor drive system, the iron loss usually increases due to the carrier frequency and modulation index characteristics [8]. Ringing phenomena is observed in GaN-FET inverter excitation because high rising up voltage of fast switching operation makes a resonance with the load. So the ringing iron loss increases in high carrier frequency operation [9].

The power electronics circuit needs an inductor with soft magnetic material. So the magnetic material for high frequency operation is now a bottleneck technology to realize the power electronics realization

About 30 years old or so, high frequency magnetic material technology was more advanced than power electronics technology [10]. More than 1 MHz magnetic material and the device were researched and trail manufactured, though high frequency power device such as MOS-FET was under developing. However, since high frequency devices such as IGBT or GaN, SiC devices are researched and in practical use, air core is used as an inductor device or low frequency operation is used.

Ferrite is expected to be for high frequency, but it has small magnetic saturation or is weak for high temperature such as 100 degree or so. Metal powder with magnetization characteristics is developed, but it has small magnetic permeability due to demagnetization characteristics. Magnetic metal sheet with small thickness is expected due to high magnetic permeability. High density of power semiconductor and control one is advances now, so most of the components of the power electronics circuit are often shown to be the magnetic material [5].

Magnetics are important technology for the realization of power electronics society and EV society.

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# Magnetic domain structure and magnetic properties of soft magnetic materials

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Low-loss soft magnetic materials are used for transformers and motors as magnetic core materials. Because the higher the operational frequency enables miniaturization of the devices, recently, it has become necessary to reduce the loss of soft magnetic materials at high frequencies. For this reason, various soft magnetic materials have been proposed, including amorphous and nanocrystalline materials and molded cores using their magnetic powders[1)-5)].

The magnetic properties of these magnetic materials largely depend on the magnetic domain structure[6)-8)]. Therefore, it is important to observe the magnetic domain structure of magnetic materials to improve the performance of magnetic materials and devices. We have observed magnetic domains of various soft magnetic materials using magnetic Kerr effect microscopy[9)-12)]. In this paper, we report on the relationship between magnetic domain structure and magnetic properties of soft magnetic materials.

Figure 1 shows an example of magnetic domain observation of an oriented Si-Fe sheet used for a transformer. The dark and bright domains in this figure have magnetizations pointing upward and downward, respectively. Fig. 1(a) shows a stripe-shaped magnetic domain pattern parallel to the rolling direction. A motion of 180° domain walls was observed when a magnetic field along the rolling direction was applied. On the other hand, Fig. 1(b) shows the magnetic domain configuration of a Si-Fe sheet with a 50 μm × 50 μm square scratch on the sheet surface. It can be seen that magnetic wall motion was pinned at the edge of the scratch, as shown in the figure. It was found through the result that scratches on the surface of the magnetic material suppress magnetic wall motion and cause increased iron losses.

In order to reduce eddy current losses in soft magnetic materials at high frequencies, decreasing the thickness of the sheet is useful. However, it is known that the ratio of the measured value to the classical theoretical value of eddy current loss increases when the sheet thickness decreases below 0.20 mm in non-oriented electrical steel sheets due to changes in the magnetic domain structure[13)]. Figure 2 shows the domain structure of 0.35- and 0.15-mm-thick non-oriented Si-Fe sheet at a remanent state. Chemical etching was used for thinning the sheet from the underside to observe the same spot before and after thinning. Stripe domain configuration running parallel to the rolling direction was observed at the thick sheet of 0.35 mm. It was observed that the domain pattern changed to the stripe domain configuration along the transverse direction when the sheet thickness decreased to 0.15 mm, as shown in Fig. 2(b). The stripe domain observed at a small thickness of 0.15 mm is part of the closure domain structure created by the normal magnetization component to the surface. When the magnetization component inclines from the normal direction, the in-plane magnetic field causes the wall motion inside the sheet, which causes a large eddy current loss.

Figure 3 shows the magnetic domain configuration for 6.5% Si-Fe powders. Figs. 3(b) and 3(c) show enlarged images of a part of Fig. 3(a). Pinning of the magnetic wall occurred in the area circled in red, as shown in Fig. 3(b). When the applied magnetic field was increased, the magnetic wall moved, and depinning occurred, as shown in Fig. 3(c). The composition was examined at the locations of the pinning sites by SEM-EDX. At the pinning sites, Mn and S were detected in addition

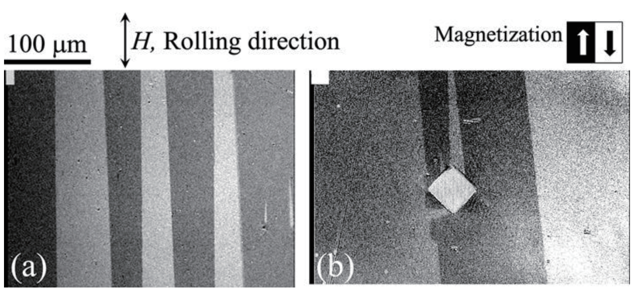

Fig. 1 Magnetic domains of an oriented Si-Fe electrical sheet.

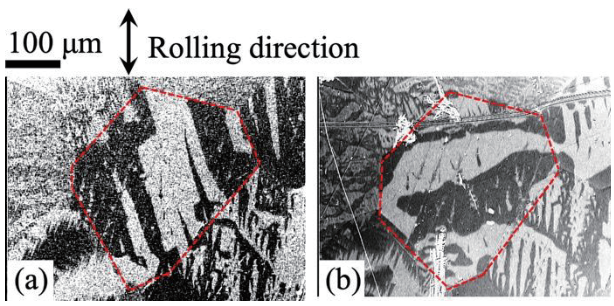

Fig. 2 Magnetic domains of a non-oriented Si-Fe electrical sheet.

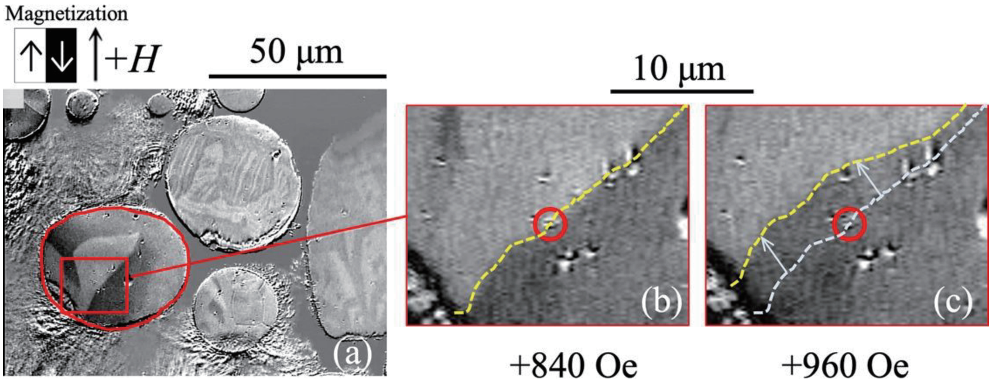

Fig. 3 Magnetic domains of 6.5% Si-Fe powders.

to Fe and Si. It was found that Mn-S included in the magnetic powder causes pinning of the magnetic domain wall.
In concluding, we have described that scratches, impurities, and changes in sheet thickness affect the magnetic domain structure of soft magnetic materials and cause an increase in their iron loss. In the future, it is expected that magnetic domain observation of various soft magnetic materials, such as nanocrystalline materials, will be further developed to achieve higher efficiency and lower loss in electric devices.

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# Basics of Power Electronics

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Power electronics is a technology that integrates mainly three fields which are devices, circuits, and control technologies. In power electronics technology, input power is converted to the output power form, which is expected by the load, by turning semiconductor switches on and off. The size, voltage, and capacity of power electronic applications are wide-ranging from large devices such as high voltage DC power transmission and frequency converters to small devices such as point-of-load (POL) converters mounted on a motherboard in a personal computer. The basic principle remains the same in any application, and power conversion is performed by turning the semiconductor switch on and off. Table 1 shows the types of power conversion circuits and typical examples of each circuit. Although the switch is schematically drawn in the figure, diodes, IGBTs (insulated gate bipolar transistors), and MOSFETs (metal-oxide-semiconductor field-effect transistors) are used in single or in combination.

The desired output is obtained in each circuit by controlling the switching period, duty ratio, and phase of switches. In addition, the switching period tends to be shorter, i.e., the switching frequency tends to be higher to reduce the size of the device and improve the quality of the output waveform.

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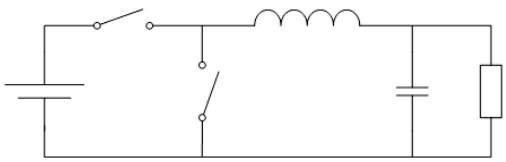
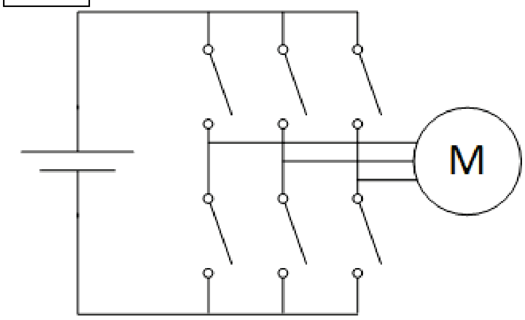
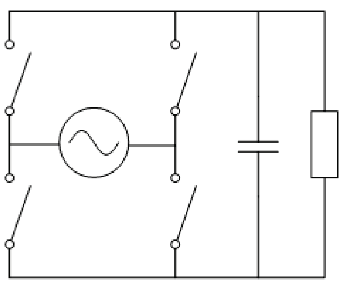
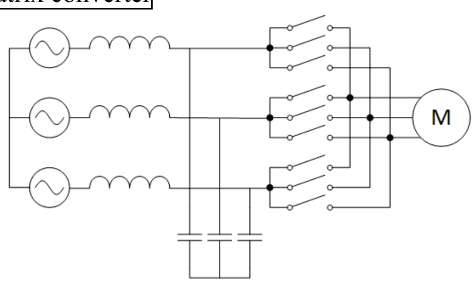
Table 1: Types of power conversion circuits and their typical examples.

| Input / Output | DC | AC |
|---|---|---|
| DC | DC/DC converter, chopper  Buck converter | Inverter   Three-phase inverter |
| AC | Rectifier  Capacitor input rectifier | Matrix converter   Three-phase to three-phase matrix converter |

# Magnetic properties expected of soft magnetic materials by motor designers

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Against the background of acceleration of worldwide decarbonization, it is predicted that there will be an acceleration of electrification, mainly in the automobile and aircraft fields in the future[1], and motors are attracting attention as a key part of this electrification. On the other hand, in terms of electric power demand across all industries in Japan, motors currently account for half of the total demand [2].

There are two main types of motors: induction motors(IM) and permanent magnet(PM) motors. The former is mainly driven at commercial frequencies (50 Hz and 60 Hz), while the latter is mainly driven by inverters capable of variable speed driving, and this is attracting attention as a motor for electrification. Therefore, it is necessary to consider the efficiency improvements in the motor based on the type and driving method of the motor. Therefore, in this lecture, we summarize the causes of motor loss according to the type of motor and the driving method and describe expectations for soft magnetic materials for each of the motor types.

Firstly, a schematic diagram of the loss breakdown of a commercial frequency-driven IM and an inverter-driven PM motor is shown in Figure 1. Figure 1 demonstrates the percentage of the total loss at 100 %. In the induction machine, primary copper loss mainly occurs in the stator conductor and secondary copper loss mainly occurs in the rotor conductor. In addition, the harmonic component of iron loss is also relatively high in inverter drives. Therefore, a different approach is required to improve the efficiency of each motor. Figure 2 shows the relationship between the magnetic properties of each motor ({ 1>B50) and the iron loss (W10/400). The overall demand for soft magnetic materials is high magnetic flux density and low iron loss.. However, as copper loss is the main cause of loss in commercial induction machines, the motor current can be reduced by increasing the magnetic flux density. In the case of permanent magnet motors for electrification, however, this is mainly iron loss, so materials that reduce iron loss are required.

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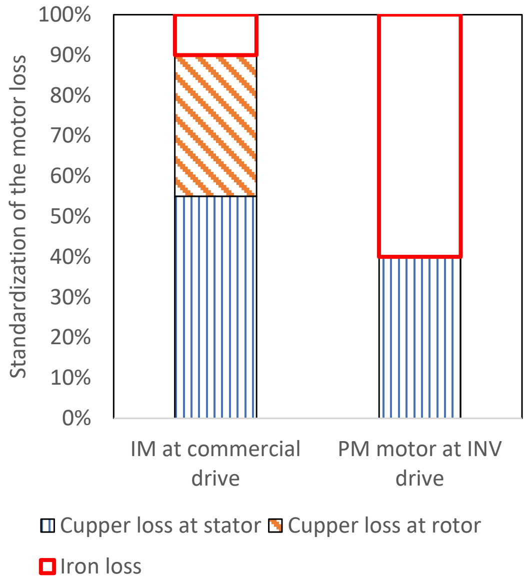


Fig.1 Loss breakdown of a commercial frequency-driven IM and an inverter-driven PM motor

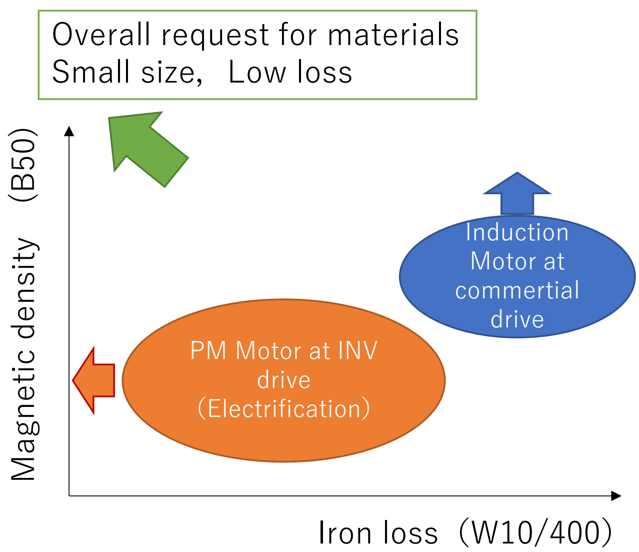


Fig.2 Relationship between magnetic properties of each motor

# Recent trend in soft magnetic material for power electronics

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Magnetic materials are roughly classified into both metallic magnetic materials and oxide magnetic materials by their composition. In addition, magnetic materials are also classified into both soft magnetic materials showing the smaller coercive force (Hc) and hard magnetic materials showing the large Hc in their magnetic properties.

Ferrite materials are well known as typical oxide magnetic materials. Since OP magnet and CuZn ferrite core were invented by Kato and Takei in 1930's, various kinds of hard/soft ferrites have been developed and used in many applications.

Generally, as shown in Fig. 1, ferrite materials show the low saturation magnetic flux density compared to the silicon steel such as metallic soft magnetic materials. However, ferrite materials with a higher electrical resistivity exhibit the excellent magnetic characteristics in high frequency. From the above reason, soft ferrites have been widely used as the core of inductor and transformer for high frequency application, and new materials are continuously being developed to contribute for the advancement of the power electronics.

MnZn ferrites and NiCuZn ferrites are known as representative materials of soft ferrite.

However, suitable applications are different because these ferrites show different magnetic characteristics. For example, as shown in figure 2, appropriate operating frequency range for each ferrite is differed by their permeability range. In addition, even for only MnZn ferrite, there are various materials with different features such as the temperature dependency and the high frequency characteristic. Therefore, it is important to choose suitable materials for applications considering magnetic characteristics of each magnetic materials.

On the other hand, power electronics have been required to handle increasingly large power with small volume in recent years. Thereby, metallic soft magnetic materials with a high saturation magnetic flux density are attracting attention, and the material development of that is being actively advanced.

In the presentation, recent topics of the development of ferrite materials and metallic soft magnetic materials for power electronics will be reported.

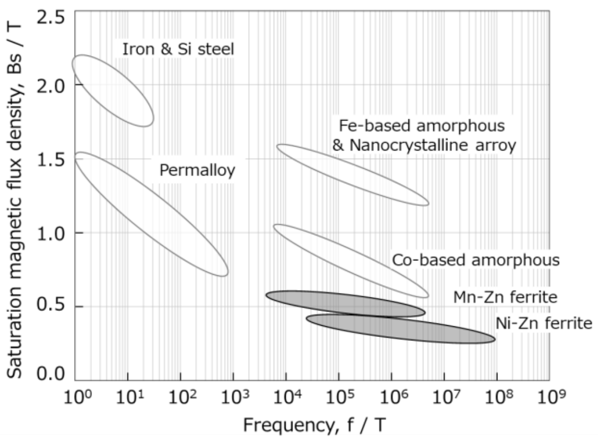


Figure 1. The saturation magnetic flux density and appropriate frequency range for representative soft magnetic materials

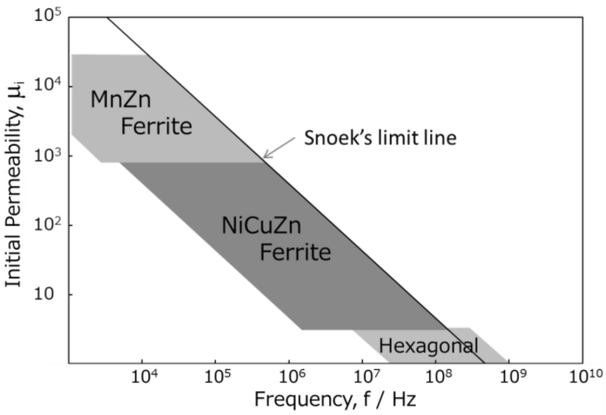


Figure 2. Schematic image of relationship between initial permeability range of ferrites and its appropriate operating frequency range.[1)]

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