Rectangular Magnet Wire for Electric and Hybrid Electric Inverter-Drive Motors

Shinya OTA*, Masaaki YAMAUCHI, Akira MIZOGUCHI, Kengo YOSHIDA, and Yasushi TAMURA

A surge current caused by a high-voltage inverter-drive motor system damages the insulation performance of magnet wires. Sumitomo Electric Industries, Ltd. has developed a novel magnet wire that has a uniform micro-closed cell structure in the insulation film. This paper discusses the excellent dielectric properties of the new magnet wire.

Keywords: magnet wire, motor, partial discharge, low permittivity, withstand voltage life

1. Introduction

Recently, the market for electrified vehicles, such as hybrid electric vehicles (HEVs) and electric vehicles (EVs), has been expanding rapidly due to the environmental regulations introduced by various countries.

The motor for electrified vehicles is driven by an inverter from the viewpoint of reducing size and increasing efficiency to improve the output density. The operating voltage and frequency have been increased. However, this has generated an inverter surge that affects the magnet wires. Partial discharges occur, causing deterioration of the insulation film, resulting in a shorter withstand voltage life for the motor.(1)

To extend withstand voltage life, it is necessary to suppress the partial discharges. To this end, efforts have been made to develop magnet wires coated with a low-permittivity film.

We have developed a new technology to uniformly create closed microcells in the film on a magnet wire and have succeeded in developing an innovative low-permittivity magnet wire, which has been confirmed to show excellent dielectric characteristics. The details are reported below.

2. Partial Discharge from Magnet Wires

2-1 Inverter surge voltage generated in magnet wires

Inverter surge voltage refers to a sharp voltage spike that is generated at the terminal of a motor due to the switching of an inverter (Fig. 1).

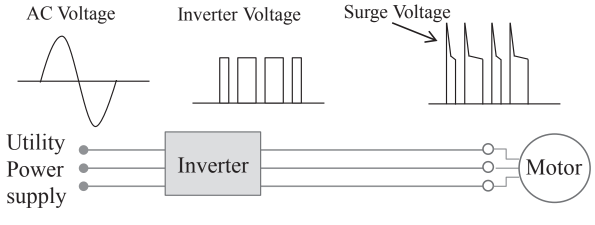


Fig. 1. Schematic diagram of the inverter surge voltage

The longer the wiring between the inverter and motor, the larger the inverter surge. The peak value may reach about double the inverter voltage.(2)

2-2 Deterioration of the film on magnet wires due to partial discharge

When a high voltage applied between magnet wires exceeds the partial discharge inception voltage (PDIV), a microdischarge (partial discharge) occurs on the surface of the film of the magnet wires.

When a partial discharge continues to be generated, the film is eroded and deteriorates, resulting in dielectric breakdown, as shown in Fig. 2.

To extend the withstand voltage life, it is necessary to use a magnet wire that can suppress partial discharges at high frequency and high voltage.

In general, PDIV is known to be correlated with the relative permittivity and film thickness, as advocated by Dakin (Equation 1). However, if the film thickness increases, the ratio of the cross section area of the conductor against the cross section area in the motor slot (space factor) decreases, leading to lower motor efficiency.

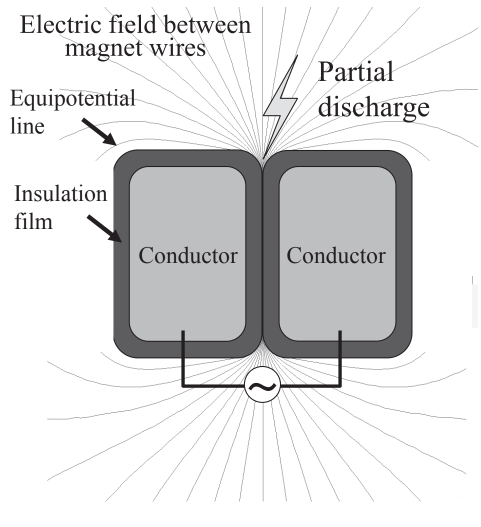


Fig. 2. Partial discharge and film deterioration of magnet wires

To improve PDIV while maintaining the space factor, it is necessary to reduce the relative permittivity of the film.

【Dakin equation】

$$V = \sqrt{2} \times 163 \times (2 \times t/\varepsilon_r)^{0.46} \quad \cdots\cdots (1)$$

V : partial discharge inception voltage [Vp]

ε_r : relative permittivity of the insulation film

t : thickness of the insulation film [μm]

3. Development of a Low-Permittivity Magnet Wire

We have developed and marketed polyimide (PI, relative permittivity: 3.0) magnet wires, which are coated with a PI film, for HEVs and EVs that require high thermal resistance, processing resistance, and electrical insulation.(3)

We systematically reviewed the correlation with the chemical structure of PI to reduce the relative permittivity of the PI film. However, we could not reduce the relative permittivity below 2.7.

A known technique to significantly reduce the relative permittivity of the insulation film is to introduce air whose relative permittivity is 1.0 to the film.(4)

We have reviewed the possibility of introducing microcells to the PI film on the magnet wire, and succeeded in developing a technology to introduce microcells uniformly while controlling their size. (In this paper, a magnet wire with cells introduced is referred to as a "magnet wire with microcellular coating," and the rate of microcells introduced is referred to as the "percentage of microcells.")

Figure 3 shows the correlation between the percentage of microcells and relative permittivity of a magnet wire with microcellular coating. We managed to reduce the relative permittivity with an increase in the percentage of microcells, as expected based on the theoretical calculation. We succeeded in reducing the relative permittivity to 2.2 by introducing about 30 vol% microcells and to 1.7 by introducing about 50 vol% microcells into a PI whose relative permittivity was 3.0.

In conventional magnet wires with microcellular coating, the microcells are likely to be connected as open microcells. Large microcells may reduce the electrical insulation and processing resistance.

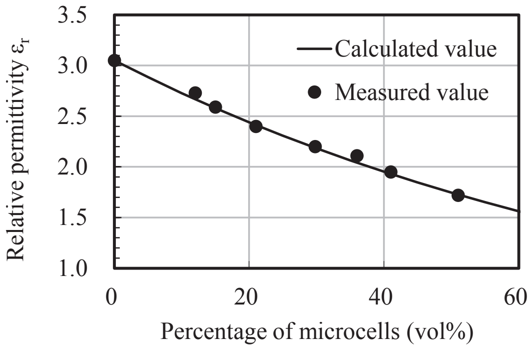
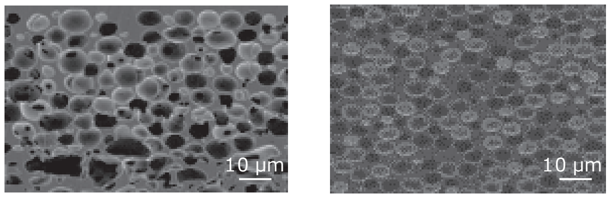


Fig. 3. Relative permittivity of magnet wires with microcellular coating

Notably, when the microcell size increases, the discharge inception voltage in the microcells is expected to decrease. For this reason, microcells should be uniformly created and their size should be controlled.(5)

We have developed a magnet wire that has microcellular coating with closed microcells uniformly created in the film on the magnet wire (Fig. 4).



a) Conventional magnet wire with microcellular coating

b) Newly developed magnet wire with microcellular coating

Fig. 4. Microscopic image of the cross section of the magnet wire with microcellular coating

Figure 5 shows the schematic diagram of a sample for measuring the dielectric breakdown voltage. To measure the dielectric breakdown voltage, we wrapped the center of a magnet wire with metal foil. We connected the conductor at the end of a magnet wire (where the film was delaminated) with the metal foil using a terminal, and applied an AC voltage to measure the dielectric breakdown voltage.

We found that the conventional magnet wire with microcellular coating was subject to dielectric breakdown at 4.9 kV. The dielectric breakdown voltage of the newly developed magnet wire with microcellular coating improved by up to 10.8 kV.

Electrical insulation is considered to have improved by suppressing the internal discharge with the introduction of closed microcells.

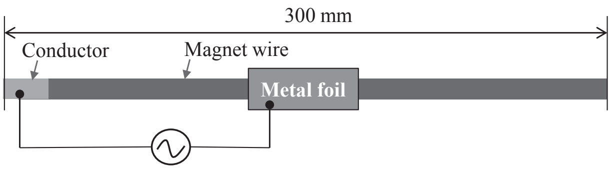


Fig. 5. Schematic diagram of a sample for measuring the dielectric breakdown voltage

4. PDIV of the Magnet Wire with Microcellular Coating

4-1 Measurement of PDIV

To measure PDIV, we used a sample with the flat surface of two rectangular magnet wires in close contact in parallel and secured ("a pair sample"), as shown in Fig. 6.

The film thickness of the magnet wires was 60 μm. The conventional PI magnet wires and PI magnet wires

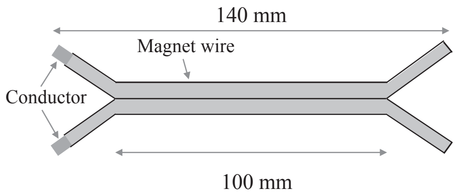


Fig. 6. Schematic diagram of a sample for measuring PDIV

with microcellular coating (percentage of microcells: 10, 30, 50 vol%) were used for measurement.

The measurement temperature was 25°C with a relative humidity of 50%. Measurement was repeated 10 times to calculate the mean value.

Figure 7 shows the PDIV experiment circuit diagram. To measure the current pulse of the partial discharge, a current sensing resistor was connected to a sample in series. Measurement was conducted via a high-pass filter that blocked the power supply frequency components.

An AC voltage of 60 Hz was applied to a sample by increasing it at the rate of 1.0 kV/min. The momentary voltage value when the discharge current was detected for the first time was regarded as PDIV.

The higher the percentage of microcells, the more the PDIV of the PI magnet wire with microcellular coating improved, as shown in Fig. 8. We confirmed that a PI magnet wire that has microcellular coating with a percentage of microcells of 30 vol% improved PDIV by 200 Vp or more compared to a PI magnet wire with a percentage of microcells of 0%.

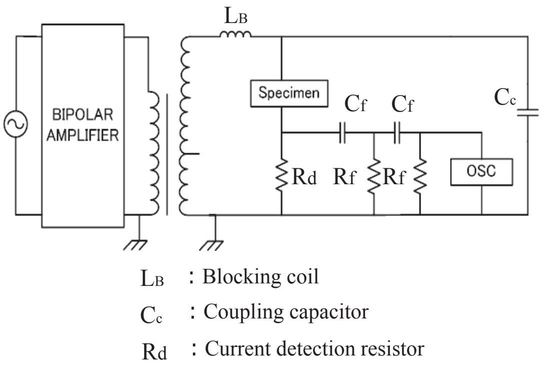


Fig. 7. PDIV measurement circuit diagram

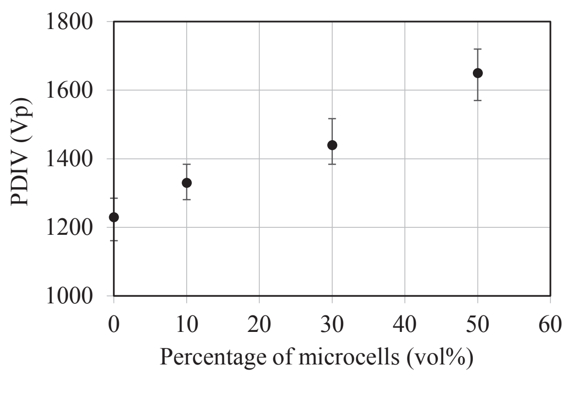


Fig. 8. PDIV measurement results of the PI magnet wire with microcellular coating (25°C)

4-2 Temperature dependence of PDIV

Figure 9 shows measurement results of the temperature dependence of PDIV. For both the PI magnet wire and PI magnet wire with microcellular coating, PDIV was confirmed to decrease due to the temperature increase. We confirmed that the PDIV decrease rate of the PI magnet wire was equivalent to that of the PI magnet wire with microcellular coating.

The decrease in PDIV due to temperature increase is attributable to the increased likelihood of a discharge caused by the decreased density of air between magnet wires.

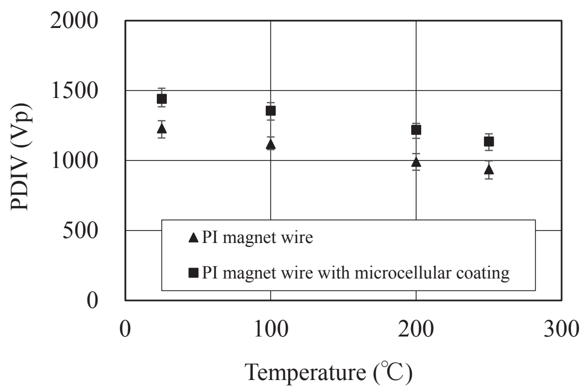


Fig. 9. Measurement results of temperature dependence of PDIV

4-3 Atmospheric pressure dependence of PDIV

The measurement results of PDIV dependence on atmospheric pressure are shown in Fig. 10. PDIV was confirmed to decrease due to decreased atmospheric pressure for both the PI magnet wire and PI magnet wire with microcellular coating. The PDIV decrease rate of the PI magnet wire was confirmed to be equivalent to that of the PI magnet wire with microcellular coating.

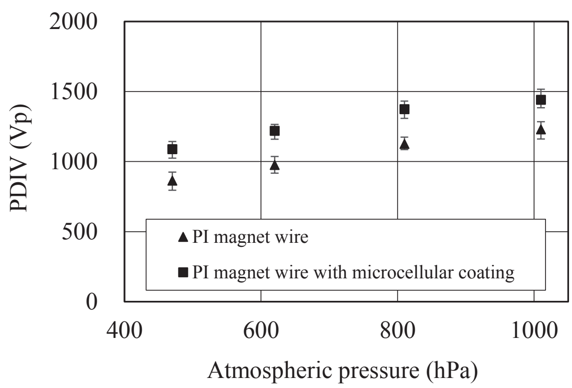


Fig. 10. Measurement results of atmospheric pressure dependence of PDIV

5. Withstand Voltage Life Test

As discussed above, when a voltage that exceeds PDIV is applied, a partial discharge occurs between magnet wires, causing the film to deteriorate and resulting in dielectric breakdown.

The time until dielectric breakdown occurs at each voltage applied is referred to as the withstand voltage life.

A pair sample of PI magnet wires and a pair sample of PI magnet wires with microcellular coating (percentage of microcells: 30 vol%) used in the PDIV measurement in 4-1 above were used to measure the withstand voltage life (Fig. 11).

The measurement temperature was 25°C with a relative humidity of 50%. A sine wave AC voltage of 10 kHz was applied, and the withstand voltage life was measured by changing the applied voltage.

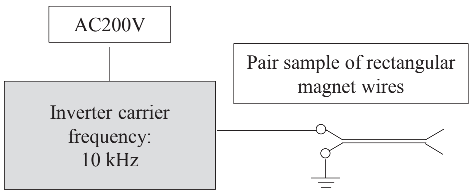


Fig. 11. Schematic diagram of withstand voltage life measurement

Figure 12 shows the correlation between the test voltage and the withstand voltage life of a magnet wire at the test voltage.

The points plotted using a blank triangle and square show the time when the test was finished because the samples were not subject to dielectric breakdown. We confirmed the appearance of the samples plotted using a blank triangle and square after testing, but no traces of a discharge were found on the films. We assume that dielectric breakdown does not occur even when a voltage is applied infinitely, (This is referred to as an infinite life region.)

At the test voltage of 1,600 Vp, the PI magnet wire and PI magnet wire with microcellular coating were subject to dielectric breakdown in 25 minutes and 402 minutes, respectively.

At the test voltage of 1,400 Vp, the PI magnet wire was subject to dielectric breakdown in 49 minutes, but the PI magnet wire with microcellular coating was not subject to dielectric breakdown even after 3,000 minutes. We judged that the PI magnet wire with microcellular coating was in the infinite life region.

The evaluation results are summarized in Table 1. The results show that the PI magnet wire with microcellular coating is less subject to dielectric breakdown compared to the PI magnet wire. We confirmed that the withstand voltage life of the PI magnet wire with microcellular coating improved.

Table 1. Evaluation results

		Conventional product (PI magnet wire)	Newly developed product (PI magnet wire with microcellular coating)
Insulation film material		Polyimide	Polyimide
Film thickness (μm)		60	60
Percentage of microcells (vol%)		0	30
Relative permittivity		3.0	2.2
PDIV (Vp)		1230	1440
Withstand voltage life (min)	1600 Vp	25	402
	1400 Vp	49	Non breakdown

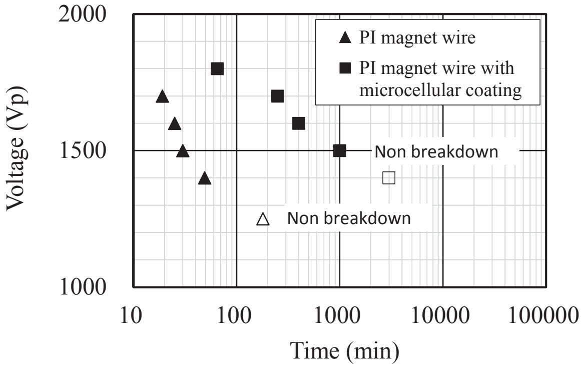


Fig. 12. Measurement results of the withstand voltage life (25°C)

6. Conclusion

We have developed a new technique to create many microcells in the film on a magnet wire, and succeeded in developing an innovative low-permittivity magnet wire.

The newly developed PI magnet wire with microcellular coating demonstrates excellent dielectric characteristics surpassing those of conventional magnet wires.

The operating voltage and frequency of industrial motors will continue to increase from the viewpoint of reducing size and increasing efficiency. The newly developed PI magnet wire with microcellular coating is expected to be used for various applications.

Technical Terms

*1 Relative permittivity: A value that shows the polarizability of an insulator. When the relative permittivity is low, the partial discharge inception voltage is high.

*2 Partial discharge inception voltage (PDIV): The voltage at which a discharge starts between magnet wires. If a discharge occurs, the insulation film deteriorates, and the motor life may be shortened.

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Contributors

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

S. OTA*

• Energy and Electronics Materials Laboratory

M. YAMAUCHI

• Group Manager, Energy and Electronics Materials Laboratory

A. MIZOGUCHI

• Group Manager, Energy and Electronics Materials Laboratory

K. YOSHIDA

• Group Manager, Sumitomo Electric Wintec, Inc.

Y. TAMURA

• Assistant General Manager, AutoNetworks Technologies, Ltd.