Rectangular Magnet Wire for HEV/EV Inverter-Drive Motor

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Steep surges generated by high-voltage inverter-drive motors are expected to cause significant damage on the insulators of magnet wires. Sumitomo Electric Industries, Ltd. has developed a novel magnet wire with uniform closed microcells introduced into the insulation. This paper discusses the excellent dielectric properties of the newly developed magnet wire.

Keywords: rectangular magnet wire, motor, partial discharge, low dielectric constant, microcell

1. Introduction

In recent years, the market for electrified vehicles, such as hybrid electric vehicles (HEVs) and electric vehicles (EVs), has been expanding rapidly amid efforts to comply with environmental regulations established by various countries around the world. The motors used in electrified vehicles are driven by inverters from the viewpoint of increasing output density through downsizing and efficiency improvement, and the operating voltage and frequency have been increased. As a result, inverter surges occur and enter the magnet wires. Partial discharges occur and deteriorate the insulation film, reducing the withstand voltage life of the motor.(1) To extend the withstand voltage life, it is necessary to suppress these partial discharges. As a measure for achieving this, the development of a magnet wire coated with a low dielectric constant film is underway.

In these circumstances, Sumitomo Electric Industries, Ltd. has developed a new technique for uniformly creating closed microcells inside the insulation film of the magnet wire, and has succeeded in developing an innovative low-dielectric-constant magnet wire. This paper reports the details of the new wire.

2. Partial Discharge from Magnet Wire

2-1 Inverter surge voltage generated in magnet wire

An inverter surge voltage is a sharp voltage spike generated at the terminal of a motor during the switching of an inverter (Fig. 1). The inverter surge rises as the wiring length between the inverter and the motor increases, and the peak value often reaches twice the inverter voltage.(2)

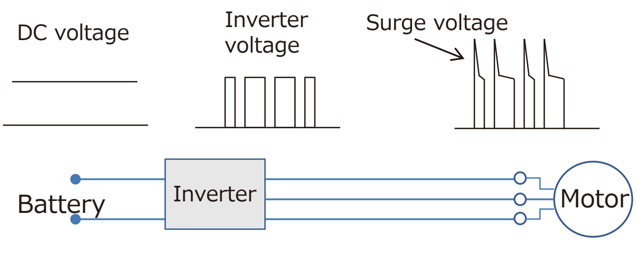


Fig. 1. Schematic illustration of inverter surge voltage

2-2 Deterioration of magnet wire film due to partial discharge

When the voltage applied between magnet wires exceeds the partial discharge inception voltage (PDIV)*1, a micro-discharge (partial discharge) occurs on the surface of the magnet wire film. If the partial discharge continues to occur, the film will erode and deteriorate, resulting in dielectric breakdown (Fig. 2).

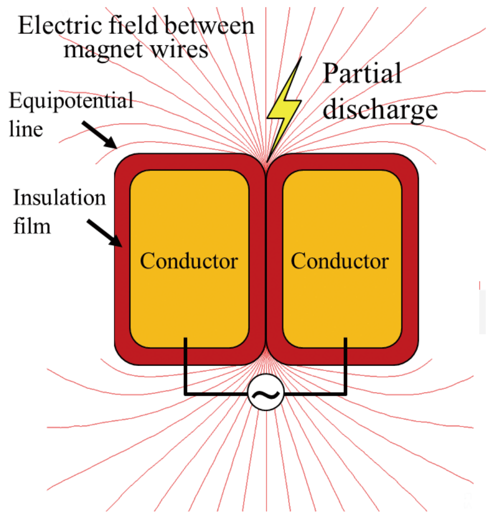


Fig. 2. Partial discharge from magnet wires and deterioration of film

To extend the withstand voltage life, the magnet wire is required to suppress the occurrence of partial discharge even at high frequencies and high voltages. It is generally known that the PDIV is correlated with the dielectric constant*2 and the thickness of the film (Eq. (1)), as advocated by Dakin et al..(3) However, the ratio of the cross-sectional area of the conductor to the cross-sectional area in the motor slot (space factor) decreases as the film is thickened, resulting in lower motor efficiency. To improve the

PDIV while keeping the space factor unchanged, it is necessary to reduce the dielectric constant of the film.

[Dakin's Eq.]

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

A: Constant
V: PDIV (Vp)
ε_r: Dielectric Constant of Insulation Layer
t : Insulation layer thickness (μm)

3. Development of Insulation Film

3-1 Development of base resin

The insulation film of magnet wires to be used in HEVs and EVs is required to have high heat resistance and insulation properties. The relationship between the glass transition temperature of an insulation resin, an index of its heat resistance, and its dielectric constant is shown in Fig. 3.

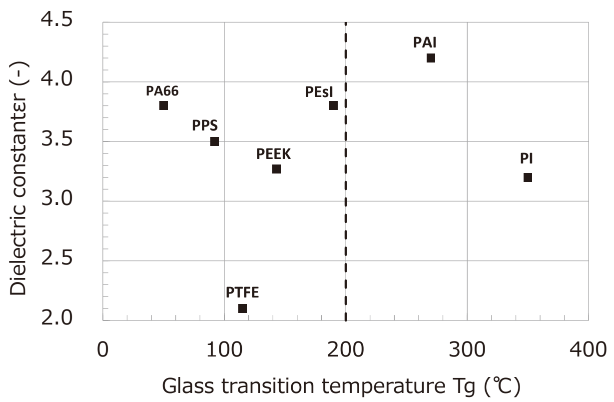


Fig. 3. Relationship between heat resistance and dielectric constant

The glass transition temperature (Tg) is the temperature at which the resin exhibits a rubber-like property that facilitates molecular motion. If the resin exceeds the glass transition temperature, its elastic modulus will decrease, increasing the risk of microcell formation in the insulation film during the welding process in motor manufacturing. The insulation properties of the resin will also decrease due to a decrease in volume resistance and an increase in dielectric constant. Since a drive motor heats to a high temperature of about 200°C when the vehicle climbs a hill or runs at high speed, a Tg of 200°C or more is desirable. Polyether ether ketone (PEEK), which is a super engineering plastic, polyphenylene sulfide (PPS), which is a thermoplastic resin, and polyester imide (PEsI) are generally considered to have high heat resistance. However, these resins were not considered suitable for magnet wire insulation films for drive motors, since their Tg values are lower than 200°C. Owing to its Tg of more than 200°C, amide-imide (PAI) has been used for the magnet wires of drive motors. However, in recent years, customer demand for long-term thermal durability and resistance to processing degradation has increased. To meet such growing demand, we have marketed polyimide (PI) magnet wires coated with PI film.[(4),(5)] PI is superior to PAI in performance.

3-2 Reducing the dielectric constant of PI

To increase the PDIV of magnet wires by reducing their dielectric constant, we systematically examined the correlation of the dielectric constant with the chemical structure of PI. However, the lowest dielectric constant we could achieve was about 2.7. In addition, the use of PI for insulation films was not easy due to a decrease in heat resistance. In this study, we focused on introducing air, whose dielectric constant of 1.0, into the film as a method of lowering the dielectric constant while maintaining proper heat resistance.[(6),(7)] When introducing microcells into the films of magnet wires for drive motors, it is necessary to select a proper method after taking into account the effect of microcells on the insulation properties of the film. For example, there are risks of the occurrence of partial discharge inside the formed microcells[(8)] and uneven insulation due to the non-uniform distribution of microcells. Further, the motor cooling oil may penetrate into the film through the microcells if they are not closed. For PI magnet wires, the insulation film is formed by curing polyamic acid varnish, a precursor, by heating (Fig. 4).

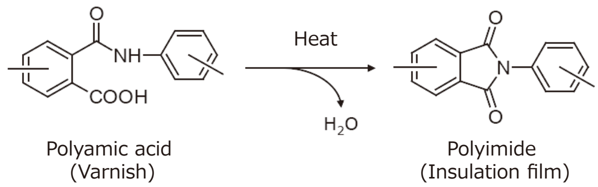
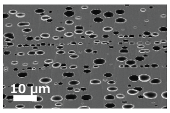
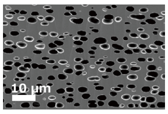
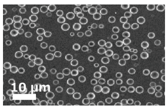


Fig. 4. Hardening reaction of polyimide

The phase separation method is a technique for forming microcells by mixing polyamic acid varnish with a liquid compound that is incompatible with the varnish and heating them in a separated state, thereby creating an insulation film. However, the state of microcell formation varies depending on the varnish mixing method and the baking conditions. Microcells tend to connect with each other and a difference in density occurs between the microcells formed in the longitudinal and thickness directions of the insulation film. Therefore, it is very difficult to control the size of microcells in the insulation film and the rate of their introduction in the insulation film. (Hereafter, a magnet wire with microcells introduced is referred to as a "microcell magnet wire," and the rate of introduction of microcells is referred to as the "percentage of microcell.") The thermal decomposition method is a technique for introducing microcells in an insulation film by using the heat generated in the formation of the film by mixing solid resin particles, which undergo a decomposition reaction when heated, with varnish. However, in microcell formation by the ordinary thermal decomposition method, as in the phase separation method, it is difficult to control microcell size, and cooling oil penetrates into the microcells since a microcell is connected and linked to the adjacent microcells. To overcome these problems, we reviewed the possibility of closing microcells by thermal decomposition using a microcell-forming material with an outer shell. Using a high heat resistance, non-thermal decomposition material as an outer shell makes it possible to introduce closed microcells while controlling their size. By controlling the amount of microcell-forming material, the percentage of microcell can be designed in response to the level of insulation required (Table 1).

Table 1. Comparison of microcell introduction methods

	Phase separation method	Thermal decomposition method (conventional)	Thermal decomposition method (developed)
SEM photo			
Microcellell size	1-5 μm Uncontrollable	1-5 μm Uncontrollable	1-5 μm Uniformly controllable
State of microcell	Possibility of linking (May become coarse)	Possibility of linking (May become coarse)	Closed
Microell distribution	Uneven	Even	Even

4. Development of Microcell Magnet Wire

4-1 Designing the film of microcell magnet wire

When determining the optimal microcell size, we took into account the risk of occurrence of electrical discharge inside the microcell. It is widely known that the relationship between discharge voltage and spatial distance is expressed by Paschen's equation (Eq. (2)).[9] The discharge voltage inside the microcell was estimated using this equation. The relationship between the discharge voltage and the distance between the electrodes, which was obtained when the pressure was assumed to be atmospheric, is shown in Fig. 5. As shown in this figure, the spark discharge voltage increases as the distance between the electrodes decreases from the minimum value of 12 μm. Since a voltage of about 1,000 to 2,000 Vp is applied to the drive motors, it is desirable to control the size of microcells in the insulation film to 12 μm or less, thereby keeping them closed and preventing them from becoming coarse. We have established a technology for producing magnet wires whose microcell size is controlled to 12 μm or less by the newly developed thermal decomposition method.

[Paschen's Eq.]

$$V_s = B\frac{pd}{K + log(pd)} \quad \cdots\cdots\cdots \quad (2)$$

V_s : spark voltage (discharge inception voltage) (V)
p : atmospheric pressure (mmHg)
d : distance between electrodes (mm)
B,K : constant

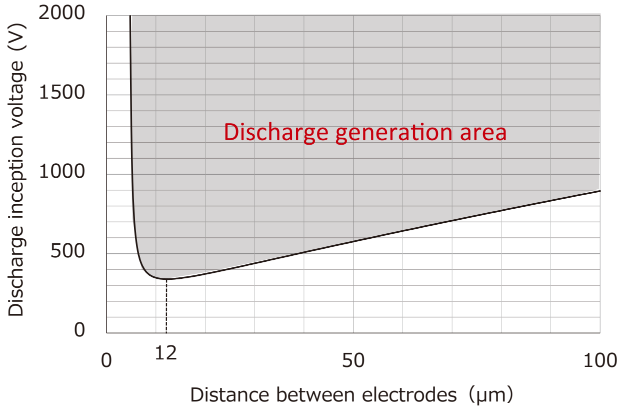


Fig. 5. Estimation of discharge inception voltage using Paschen's equation

The relationship between the percentage of microcell and the dielectric constant of a magnet wire is shown in Fig. 6. As theoretically calculated, the dielectric constant could be decreased by increasing the percentage of microcell. We succeeded in reducing the dielectric constant to 2.5 by introducing approximately 20 vol% microcells, and to about 2.0 by introducing approximately 40 vol% microcells into the PI, whose dielectric constant was 3.2.

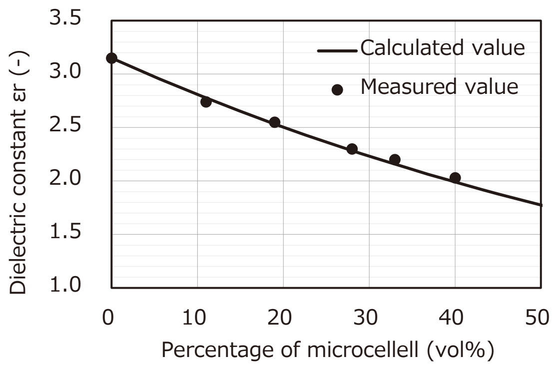


Fig. 6. Relationship between percentage of microcell and dielectric constant

4-2 Insulation properties of microcell magnet wire

To measure the PDIV, we prepared each sample by pairing two rectangular wires fixed with their flat surfaces aligned parallel to each other as shown in Fig. 7. Conventional PI magnet wires and microcell PI magnet

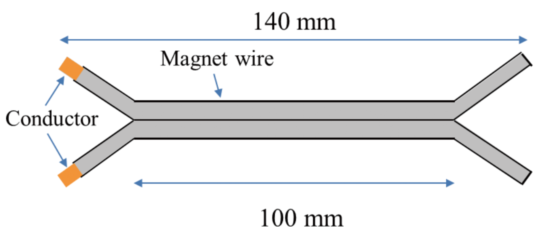


Fig. 7. Schematic illustration of PDIV measurement sample

wires (percentage of microcell: 15, 30, 40 vol%) were used for the measurement.

Measurements were conducted at temperature of 25°C and relative humidity of 10%, and were repeated 10 times to determine the average values.

As shown in Fig. 8, the PDIV of the microcell PI magnet wire increased as the percentage of microcell increased. It was confirmed that a microcell PI magnet wire with a percentage of microcell of 30 vol% improved the PDIV by 250 Vp, and a microcell PI magnet wire with a percentage of microcell of 40 vol% improved the PDIV by about 400 Vp, when compared with a PI magnet wire with a percentage of microcell of 0%.

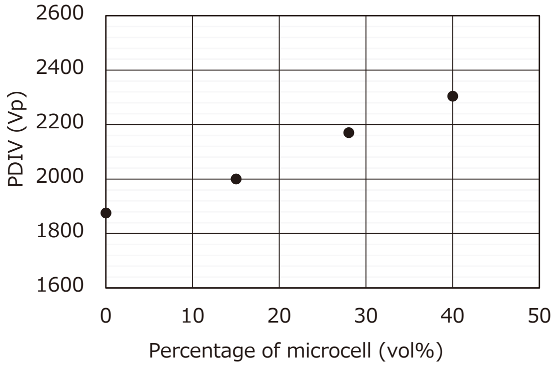


Fig. 8. Relationship between percentage of microcell and PDIV

5. Challenges for Microcell Magnet Wire

The insulation properties of a microcell magnet wire improve as the percentage of microcell increases. On the other hand, since the ratio of PI in the insulation film decreases, the stress concentration on the PI existing between the microcells increases when the wire is processed. Therefore, the mechanical properties (elongation at break) of the insulation film decreases as the percentage of microcell increases (Fig. 9). Since the insulation film can be stretched by 30% or more during the forming process in motor manufacturing, the insulation film of the magnet wire with a high percentage of microcell is required to be sufficiently stretchable to withstand the forming process. To improve the elongation at break of the insulation film, we worked to improve the elongation of the PI insulation film where stress was concentrated. In general, PI exhibits high elongation at break due to its strong, rigid molecular structure and cohesive structure caused by the strong intermolecular forces of imide bonds. In this study, we introduced microcells into PI after optimizing the molecular structure and the cohesive structure. As a result, we could achieve an elongation at break of 50% or more even when the percentage of microcell was 40% (Fig. 10). The improvement in elongation at break is expected to enable severe molding processes in motor manufacturing.

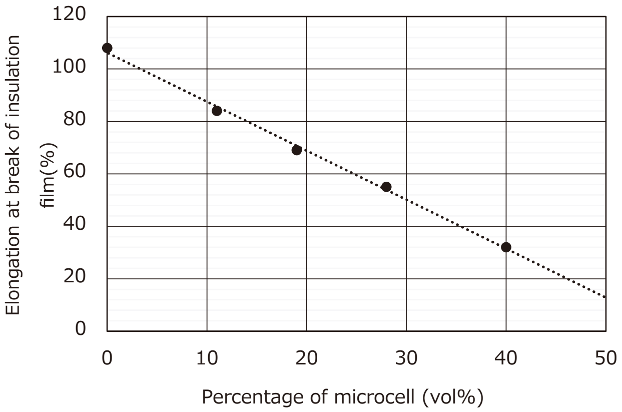


Fig. 9. Relationship between percentage of microcell and elongation at break of insulation film

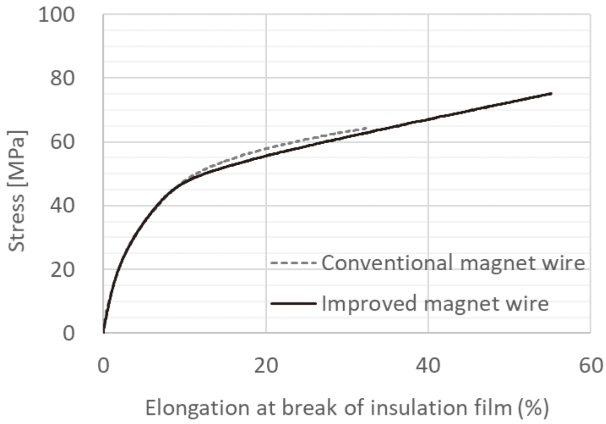


Fig. 10. Elongations at break of conventional and developed magnet wires

6. Conclusion

We have developed a new technique for forming closed microcells uniformly inside the insulation film of a magnet wire, and have succeeded in developing an innovative low-dielectric-constant magnet wire. The new magnet wire with microcells introduced into the PI insulation film exhibited excellent dielectric properties superior to those of conventional magnet wires. In addition, reducing the elongation at break of the film, which was a problem associated with microcell magnet wires, was alleviated by modifying the PI. The operating voltage and frequency of drive motors will continue to increase from the viewpoints of downsizing and improving efficiency. The developed microcell PI magnet wire is expected to be widely used in the future.

Technical Terms

*1 Partial discharge inception voltage (PDIV): The voltage at which a discharge starts between magnet wires. If a discharge occurs, the insulation film will deteriorate and may shorten the motor life.

*2 Dielectric constant: An index showing the polarizability of an insulator. The smaller the dielectric constant, the higher the partial discharge voltage.

References

(1) Inverter Surge Insulation investigating committee, "Feature articles for insulation influence on inverter surge," The Institute of Electrical Engineers of Japan, Vol.126, No.7, pp.419-427 (2006)

(2) Japan Electrical Manufacturers' Association,Insulation influence on movement for 400V inverter motor,pp.1-3(1995)

(3) T. W. Dakin .et al., "Effect of Electric Discharges on the Breakdown of Solid Insulation," AIEE Part I: Communication and Electronics, 73 (1954) pp.155-161

(4) J. Sugawara, et al., "History and Future Prospects of Magnet Wire Development," SEI TECHNICAL REVIEW No.84, pp.108-113 (April 2017)

(5) K. Okamoto, et al., "Analysis Technologies for Quality Improvement in Magnet Wires of Electrified Vehicles," SEI TECHNICAL REVIEW No.90, pp.22-26 (April 2020)

(6) H. Ueno, S. Okada, S. Ota, "A.Mizoguchi, M.Yamauchi, V-t characteristics of enameled wire under high-frequency AC voltage," The Institute of Electrical Engineers of Japan, Plasma · Discharge · Pulse power Joint Technical Meeting, ED-15-079 (2015)

(7) CMC Publishing CO.,LTD, "Latest polyimide materials and application technologies," pp.102-105 (2002)

(8) I. Tanaka, S. Okada, H. Ueno, S. Ota, A. Mizoguchi, M. Yamauchi, "Investigation of Partial Discharge in Cavity in Foamed Enameled Wire Insulation," The 2018 Annual Meeting of The Institute of Electrical Engineers of Japan, 1-129

(9) Asakura Publishing Co., Ltd., "High voltage engineering," p34

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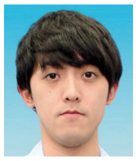

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