

Low Relative Permittivity of Magnet Wire Insulation Coating for HEV Motor

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ABSTRACT

An insulation coating that achieves a balance of heat resistance and insulating properties was developed for use in HEV motors. Technology was established that lowers the relative permittivity as low as 2.4, which is at the level of polyethylene and other such low-permittivity materials, while also having heat resistance with the high temperature index of 250°C by causing independent gas bubbles to be dispersed evenly in polyimide resin. This technology made it possible to maintain the insulating properties of conventional magnet wire while reducing the coating thickness by approximately 20% and increasing the cross-sectional area of the conductor by approximately 6%. As a result, losses in newly developed motors were successfully reduced by 5% relative to conventional motors.

1. Introduction

Due to the demand seen in recent years for reduced CO₂ emissions and higher fuel economy in vehicles when driving, the widespread adoption of electric-powered vehicles such as hybrid electric vehicles (HEV) and electric vehicles (EV) has progressed rapidly. Electrification is expected to accelerate further as fuel economy regulation becomes stricter in the future. The range of vehicle models to which this is applied has also broadened, from compact vehicles to large vehicles, minivans, SUVs, and other types of automobile. There is demand for drive motors to be made compact while maintaining both high torque and high power characteristics, particularly for installation in compact vehicles. However, the higher current needed for enhanced motor characteristics together with the more compact motor framework result in a lower heat capacity so that increased motor temperatures become an issue⁽¹⁾. In order to reduce the heat generated by the magnet wire, which is the heat source, it is effective to lower the resistance when current is applied by enlarging the cross-sectional area of the conductor.

In order to retain the motor framework as is while enlarging the cross-sectional area of the conductor, it is necessary to make the insulation coating thinner. However, this decreases the insulating properties of the coating, which are its main function. For the purpose of making the coating

thinner while also retaining its insulating properties, it is effective to reduce the relative permittivity of the insulation coating⁽²⁾.

The most effective known approach capable of reducing the relative permittivity is to increase the porosity of the resin. Causing the gas that is the component of the insulator with the lowest relative permittivity to be dispersed throughout the resin makes it possible to achieve a relative permittivity that cannot be obtained with the resin component alone. Increasing the porosity of the resin does not just heighten the insulating properties, it can also enhance a variety of other characteristics⁽³⁾⁻⁽⁵⁾, such as lightweight properties, sound-absorbing properties, heat insulating properties, shock-absorbing properties, and others. Although there have been numerous reports on research into the insulating applications of increased porosity⁽⁶⁾⁻⁽⁸⁾, there are no instances of practical application as insulation coating for magnet wire. In order to put it to this practical use, independent gas bubbles of several micrometers in size need to be dispersed evenly throughout the entire coating^{(9), (10)}.

Methods for increasing the porosity of resin can generally be classified into two kinds, physical approaches and chemical approaches. As a typical instance of the physical approach, the use of carbon dioxide or some other such supercritical fluid is a well-known method^{(9), (11), (12)}. Supercritical methods, however, require a high-pressure

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environment, which means that it will be a discontinuous product, making reduced productivity an issue⁽¹³⁾. On the other hand, chemical approaches generally use foaming agents that are thermally expandable, and the gas bubbles that are formed end up being large with adjoining gas bubbles forming continuous holes, so that the separateness of the gas bubbles cannot readily be maintained^{(9), (14)}. The physical approach using supercritical fluids and the chemical approach using foaming agents are, therefore, not suited for use in increasing the porosity of insulation coating.

Here, an insulation coating with increased porosity was put to practical use by applying a thermochemical method using a gas bubble forming material that has an outside shell. By applying this technology for use as insulation coating for magnet wire, the loss in a new model motor was reduced by 5% from previous motors. This paper describes the conceptual approach to insulation coating design for drive motors to be installed in vehicles, the design of gas bubble coating that is optimal for the developed motor, and the results from evaluation of the design as a motor characteristic.

2. Conceptual Approach to Insulation Coating Design

Drive motors to be installed in vehicles use inverters capable of highly precise control of the motor speed. However, the rapid switching in the inverter is accompanied by sharp spikes in the pulse voltage and mismatches between the inverter output impedance and motor input impedance. For these and other such reasons, high surge voltages from the inverter may be applied to the magnet wire. The peak value for the inverter surge voltage can at times be as much as about two times the usual inverter voltage⁽¹⁵⁾ (Fig. 1), so it is important to assure the magnet wire insulation.

The partial discharge inception voltage (PDIV) is

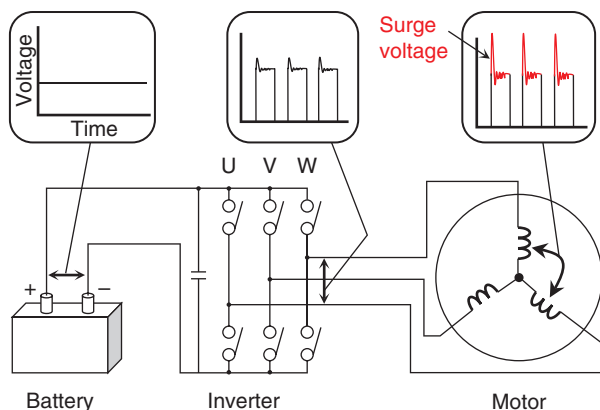


Fig. 1 Schematic diagram of inverter surge voltage

one of the characteristics that are important for assuring the insulation on the magnet wire. When the potential difference that occurs between wires exceeds PDIV, minute discharges called partial discharges take place in the space between insulation coatings. As shown in Fig. 2, when partial discharges continue to occur, the impact energy of the discharges causes erosion of the insulation coating, and there is a possibility that ultimately the vehicle may stop running when destruction of the insulation causes short circuits. The insulation coating, therefore, needs to be designed so that partial discharges do not occur even in environments that are challenging for the onboard motor, such as under high temperatures and at high elevations where the air pressure is lower.

Dakin's equation, shown in Eq. (1), is widely known as a guideline for such design. PDIV becomes a function of coating thickness and relative permittivity. In order to raise PDIV, it is effective to increase the coating thickness or to lower the relative permittivity, as shown in Eq. (1). Increasing the thickness of the coating will reduce the space factor of the conductor in the slot, which will lead to a reduction in the motor volume efficiency. For magnet wire used in the compact and highly efficient motors required to drive HEV, EV, or other such electric-powered vehicles, it is important to reduce the relative permittivity of the insulation coating.

$$PDIV = A \times (2 \times t / \epsilon_r)^{0.46} \quad (1)$$

A : Constant

ϵ_r : Relative permittivity

t : Thickness of coating

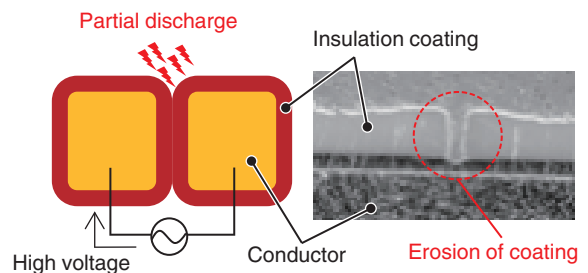


Fig. 2 Partial discharge of magnet wire and example of erosion of insulation coating

3. Low Relative Permittivity of Insulation Coating

3.1. Issues for Low Relative Permittivity

Figure 3 shows the relationship between the temperature index and the relative permittivity of the main

insulating resins. The temperature index is one indicator of the heat resistance of the magnet wire insulation coating⁽¹⁶⁾. Various characteristics are demanded for the organic parts in drive motors for HEV and other such vehicles, including heat resistance, oil resistance, and chemical resistance. Polyamide-imide (PAI), polyether ether ketone (PEEK), polyimide (PI), and other such insulating resins that are categorized as super engineering plastics are, therefore, commonly used as the insulation coating on magnet wire for drive motors. However, these have relative permittivity of 3.1 or higher, which is 30% or more higher than materials with low relative permittivity, such as polyethylene (PE) and polytetrafluoroethylene (PTFE), making their lower insulating properties an issue. PE and polypropylene (PP), on the other hand, are insulating resins that show low relative permittivity of 2.2 to 2.3. However, their heat resistance is low and they are not suited for use in vehicle drive motors, where they are exposed to high heat environments when driving up slopes, operating at high speeds, and so on. Furthermore, PTFE and other such fluorinated resins have lower adhesion and mechanical properties and so are not suitable for magnet wire, which requires adhesion to the conductor and processing resistance for bending.

An investigation was therefore made into the development of insulation coating that has low relative permittivity while also providing the heat resistance, adhesion, and other such characteristics needed for insulation coating on magnet wire. PI, which as shown in Fig. 3 has high heat resistance and comparatively low relative permittivity, was chosen as the resin to be used as a base for development of an insulation coating with low relative permittivity. A number of methods for lowering the relative permittivity of PI have been reported⁽¹⁷⁾, one of which is a chemical structural design according to the Clausius-Mossotti equation shown in Eq. (2) either to reduce the imide concentration or to give it a bulkier

structure. Although either method can lower the relative permittivity to around 2.7, however, it has been reported that this reduces the heat resistance that is one of the strengths of PI⁽¹⁷⁾. A lowering of relative permittivity by fluorine modification has also been reported⁽¹⁷⁾. As with the above, however, this conflicts with other characteristics, and the reduction in adhesion is a particular issue, so that this approach cannot readily be applied to the mass production of insulation coating for magnet wire.

$$\varepsilon_r = \frac{1+2(P_m/V_m)}{1-(P_m/V_m)} \quad (2)$$

P_m : Molar polarizability

V_m : Molar space occupied volume

3.2. Dispersion of Gas Bubbles for Lower Relative Permittivity of Resin

The relative permittivity cannot readily be lowered in the resin component while providing the characteristics considered necessary in magnet wire. Attention was focused, therefore, on the gas that is the component of the insulator with the lowest relative permittivity. Although there have been numerous reports to date^{(6), (8), (17), (18)} of methods for lowering relative permittivity by causing gas bubbles to form within the PI resin, there are no cases of this method being put to practical use for insulation coating in a drive motor. Figure 4 shows the methods attempted here to lower the relative permittivity of resin by gas dispersion, and summarizes them in terms of application to insulation coating on magnet wire.

The supercritical method is a manufacturing method that requires a high-pressure environment. Manufacturing, therefore, needs to be done in a batch furnace, so it is not suited to mass production. There is also the formation of gas bubbles by the use of hollow particles, which can be applied to the conventional magnet wire process. However,

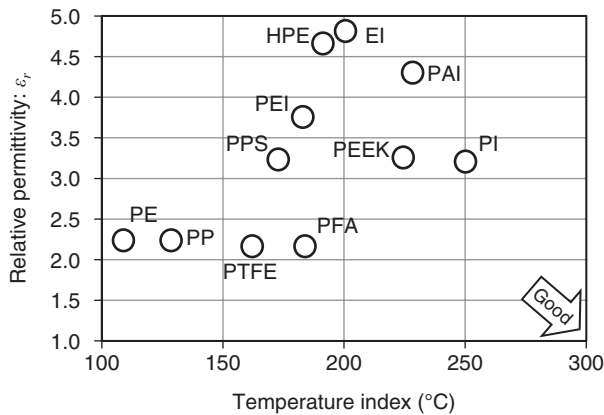


Fig. 3 Relationship between temperature index and relative permittivity of main insulating resins

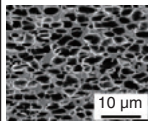
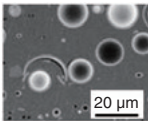
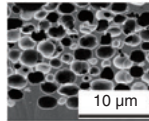
Item	Supercritical method	Hollow material method	Thermochemical method
SEM image			
Gas bubble size	1 - 5 μm (Large variation)	15 μm - (Large size)	3 μm (Controllable)
Gas bubble connection	Connected	Not connected	Connected
Varnish stability	Stable	Not stable	Stable
Continuous productivity	Not acceptable	Acceptable	Acceptable

Fig. 4 Methods and characteristics of gas bubble dispersion for insulation coating

polyamic acid, which is a basic ingredient of the varnish used for coating formation, is the precursor of PI and has a very different density from those gas bubbles so that the two tend to separate. This varnish, therefore, has issues with storage stability. There is also the common thermochemical method for forming gas bubbles. When the gas bubbles are formed, however, they make continuous holes that connect to adjoining gas bubbles. This means that there are questions as to whether the oil used to cool the motor will soak in and lower the breakdown voltage (BDV) of the insulation. An investigation was therefore made of resolving the continuous holes that are an issue with the common thermochemical method by using a gas bubble forming material with an outside shell so that the gas bubbles are made independent.

4. Optimal Design of Gas Bubble Coating

The following will discuss the porosity, the gas bubble diameter, and the uniform dispersibility of gas bubbles, which are key design elements for the purpose of application to mass production of the insulation coating for magnet wire to be used in on-board drive motors.

4.1. Porosity

The A. S. Windeler formula in Eq. (3) is commonly used as a theoretical formula for relative permittivity and porosity in the insulation coating as a whole.

$$\frac{\varepsilon_i - \varepsilon_r}{\varepsilon_i - \varepsilon_a} = \frac{F}{100} \cdot \frac{3\varepsilon_r}{2\varepsilon_r + \varepsilon_a} \quad (3)$$

ε_i : Relative permittivity of resin

ε_r : Relative permittivity of entire insulation coating

ε_a : Relative permittivity of gas (=1.0)

F : Porosity (%)

Figure 5 shows the relationship between the gas bubble ratio (porosity) of the gas bubble coating and the relative permittivity. It was confirmed that when the gas bubble

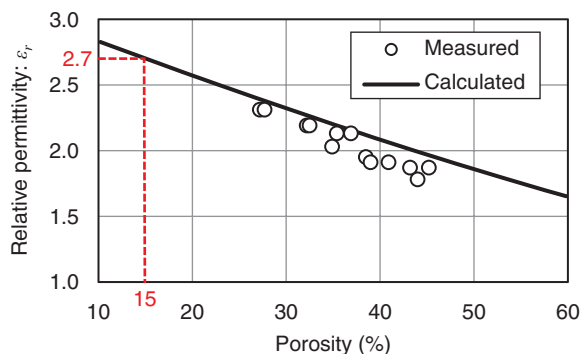


Fig. 5 Relationship between relative permittivity and porosity of PI

ratio increases, the relative permittivity decreases, just as aimed for, largely matching the theoretical formula. The loss reduction target value for the developed motor was used to determine target values for the cross-sectional area of the conductor and the coating thickness. The necessary insulating properties were also taken into account and the relative permittivity target value was set at 2.7 or lower. According to the theoretical formula, the porosity that achieves a relative permittivity of 2.7 or lower is 15% or higher.

Raising the gas bubble ratio is beneficial for the insulating properties, but the reduced processing resistance for bending becomes an issue. Figure 6 shows an example of simulation results for distribution of stress occurring in PI when tensile stress is applied to a PI gas bubble coating model with a porosity of 30% and gas bubble diameter of 3 μm. A concentration of stress is observed in the PI in the vicinity of the gas bubbles, and it is apparent that the stress is unevenly distributed. This concentration of stress becomes more conspicuous as the porosity increases, becoming a cause of reduced coating elongation.

Figure 7 shows the formed shape of the magnet wire

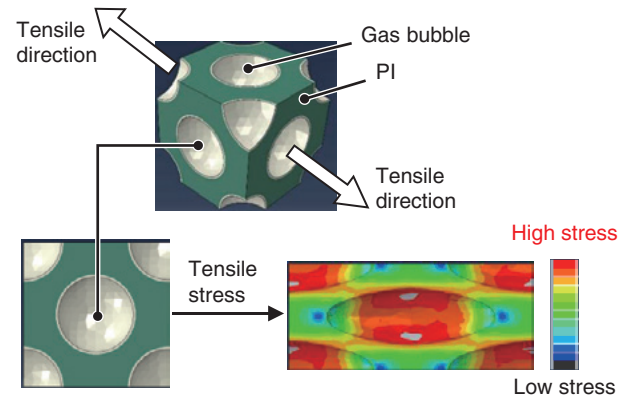


Fig. 6 Simulation results of elongation and stress distribution of bubble film

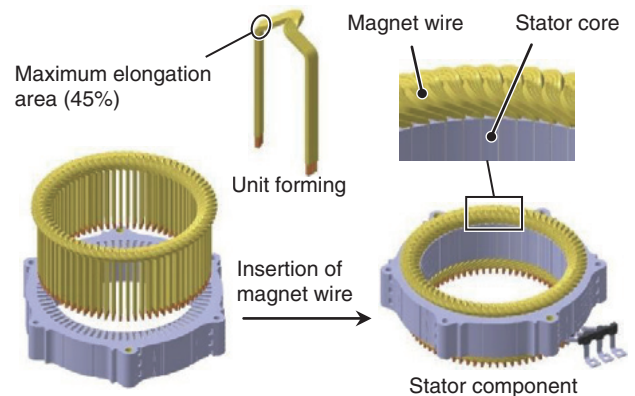


Fig. 7 Shape of magnet wire in stator component

in the stator component of the developed motor for which application of the gas bubble coating was investigated. In order to make the developed motor compact and highly efficient, a method of assembly⁽¹⁹⁾ was adopted that connects the conductors by making unit coils from four rectangular magnet wires formed into a U-shape, placing them together side by side, inserting them all together into the stator core, and joining them. As a result of this method, a large tensile deformation occurs in the gas bubble coating when forming into the U-shape. The maximum tensile elongation comes to as much as about 45%.

Taking this into consideration, tensile testing was carried out using samples with varying gas bubble ratios and the correlation between porosity and coating elongation was verified. Figure 8 shows the relationship between the porosity and elongation at break of the coating obtained through the present experimentation. As in the simulation, the two were found to be in an inverse relationship, with the elongation at break decreasing as the porosity increases. It was determined from these results that with a porosity of 33% or less, the magnet wire can undergo a maximum elongation of 45% during forming without breaking.

4.2. Gas Bubble Diameter

An investigation was made of the optimum gas bubble diameter with respect to the variation in the coating thickness and discharge in the gas bubbles. Equation (4) shows the relationship between discharge and spatial gap, for which the Paschen formula is widely used⁽²⁰⁾. Figure 9 shows the relationship between the electrode distance and the spark discharge voltage obtained using Eq. (4) at barometric pressure (1013 hPa). As can be seen from the graph, the spark discharge voltage has its lowest value when the electrode distance is 22 μm , since the spark discharge voltage starts to go high at smaller distances and spikes at around 8 μm . This means that at an electrode distance of 8 μm or less, discharge does not occur even under voltages as high as several thousands of volts.

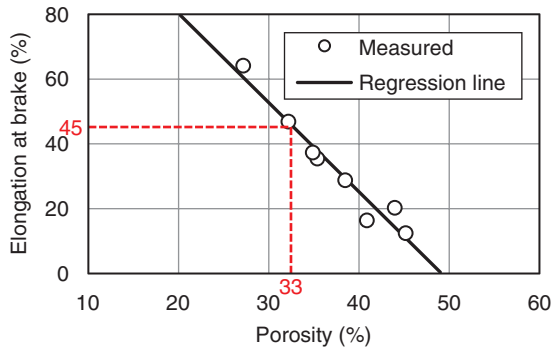


Fig. 8 Relationship between elongation of insulation coating and porosity of PI

$$V_s = \frac{B(Pd)}{\log(Pd) + C} \quad (4)$$

V_s : Spark discharge voltage (V)

P : Barometric pressure (hPa)

D : Electrode distance (μm)

B, C : Constant (Air: $B=94.5, C=0.095$)

Figure 10 shows schematic diagrams of the discharge generation mechanism in the discharge generation area (a) and at an electrode distance of 8 μm or less (b). As shown in Fig. 10 (a), an electric field is generated by the potential difference between electrodes, and discharge occurs when the initial electrons in that space are accelerated by the field so that they collide with oxygen or other such molecules in the air and electrons are ejected. The continuous occurrence of this phenomenon causes the discharge to grow. As shown in Fig. 10 (b), however, sufficient distance to allow the initial electrons to accelerate is not provided when the electrode distance is small, so the level of energy to cause ejection of electrons due to collision with molecules is not reached, and discharge does not occur. Yanaze et al. verified the relationship between gas bubble diameter and partial

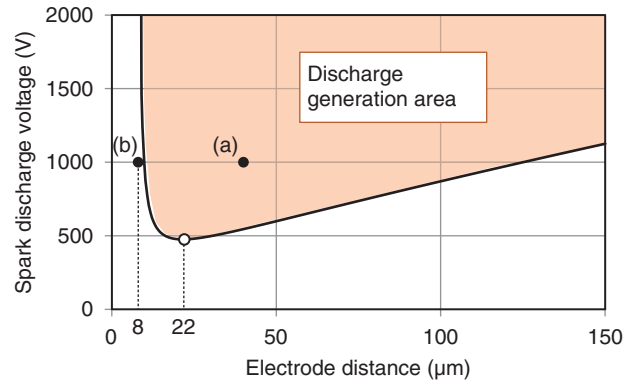


Fig. 9 Relationship between spark discharge voltage and electrode distance

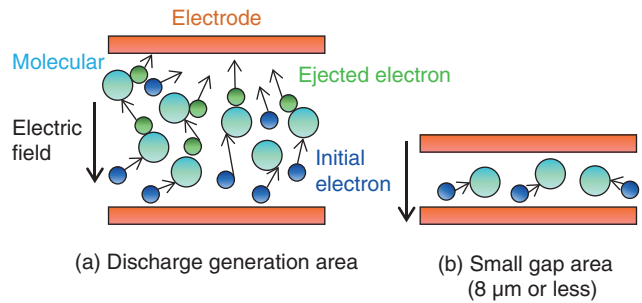


Fig. 10 Schematic diagram of discharge generation mechanism

discharge inside the gas bubbles and reported⁽²¹⁾ establishing that partial discharge does occur with a gas bubble diameter of 34 μm , but does not occur in gas bubbles at bubble diameters of 5 μm and 11 μm . These results support the conceptual approach of Eq. (4). In light of the above, it was reasoned that when the gas bubbles in the insulation coating have a diameter of about 8 μm or less, discharge does not occur inside the gas bubbles, and the relative permittivity can be reduced.

There is also the matter of applying the insulation coating, which in the interest of productivity is normally coated on the conductor in a thickness on the order of several micrometers. That process is repeated for the specified number of passes to obtain the required coating thickness. For that reason, when the gas bubble forming material has a diameter that is large in relation to the thickness of coating applied in a single pass, then the surface of the coating becomes rough and the variation in coating thickness becomes greater. In order to make the coating thickness more uniform, therefore, the gas bubble forming material, which determines the gas bubble diameter, is made so that it will have a diameter on the order of several micrometers.

4.3. Uniform Dispersibility of Gas Bubbles

The magnet wire used in a single developed motor amounts to several hundred meters in total length. If the gas bubbles in the coating become packed closely together, then it is possible that cracking will occur in the coating during forming, and under some conditions, partial discharge will occur in areas where there are, conversely, fewer gas bubbles. For that reason, it is desirable to have the gas bubbles dispersed uniformly in the coating. Figure 11 shows the processes of baking on the coating and forming the gas bubble coating. First, PI varnish that contains an

admixture of the gas bubble forming material that provides a base for the gas bubbles is coated onto the conductor. Next, the conductor is placed in a baking furnace where the PI varnish is hardened and progressive vaporization takes place due to the heat of the internal constituents of the gas bubble forming material. Ultimately, the PI that has completed hardening and the outside shell of the gas bubble forming material remain, forming the gas bubble coating. For this reason, the dispersibility of the gas bubble forming material in the PI varnish governs the uniform dispersibility of gas bubbles in the coating.

Figure 12 shows a schematic diagram of three different types of PI varnish with different degrees of dispersion of the gas bubble forming material, together with the particle size distributions, photographs of the surface appearance of gas bubble coating made as prototypes using those dispersions and distributions, and cross-sectional SEM images. The degree of dispersion increases from A to B and C, in that order. In C, the gas bubble forming material is in a uniformly dispersed state. With the varnish in A, aggregation of the gas bubble forming material is observed due to the particle size distribution, and the surface of the completed gas bubble coating is rough for that reason. Aggregation of the gas bubbles was also confirmed from the cross-section. With the varnish in B, peaks were observed that originated in secondary and tertiary aggregations due to the particle size distribution. Although this was an advance over A, the coating formed in B was observed to have partial aggregations based on surface appearance and cross-section SEM. With the varnish in C, a peak was observed that matched with the diameter of the gas bubble forming material due to the particle size distribution, and it was confirmed to be a monodispersion. The surface of the completed coating is smooth in appearance, as well, and uniform dispersion of the gas bubbles was also confirmed

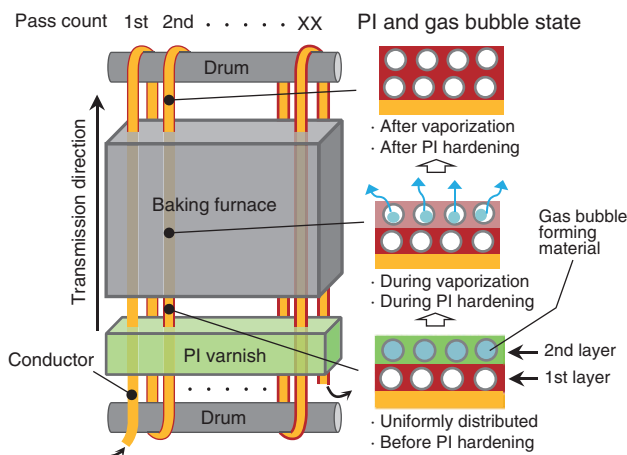


Fig. 11 Schematic diagram of developed magnet wire coating process and gas bubble formation

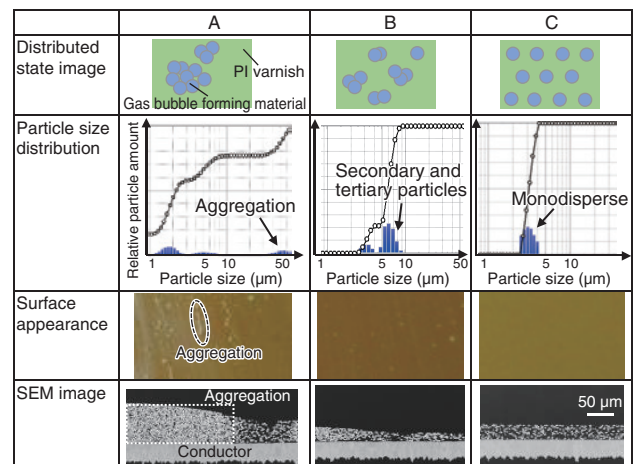


Fig. 12 Comparison of three types of PI varnishes with different degrees of dispersion

from the cross-sectional SEM image. In this way it was found that insulation coating with uniform dispersion of the gas bubbles could be obtained by controlling the dispersibility of the gas bubble forming material in the PI varnish.

Figure 13 shows a schematic diagram and cross-sectional SEM image of the developed coating as obtained from the results of optimal design. It is apparent that, due to the existence of an outside shell, there is uniform dispersion of gas bubbles that are several micrometers in size and independent, without links forming to nearby pores. Taking into account the elongation that occurs during processing of the magnet wire, material of a composition that allows for elongation was used for the outside shell.

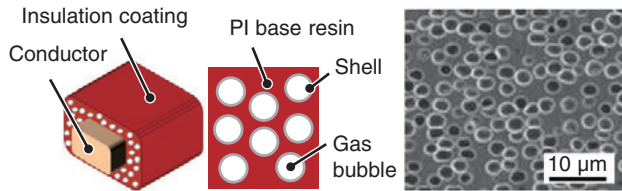


Fig. 13 Schematic diagram and cross section SEM image of newly developed insulation coating

5. Characteristics of the Developed Coating and Its Motor Loss Reduction Effect

5.1. Insulating Properties and Heat Resistance of the Gas Bubble Coating

Figure 14 shows the positioning of the relative permittivity and temperature index of the previous coating⁽¹⁹⁾ and the developed coating. Through uniform dispersion of independent gas bubbles in the PI, the relative permittivity of the PI was successfully lowered to 2.4 while retaining its higher heat resistance. This made it possible to develop an insulation coating that achieves a balance between heat resistance and insulating properties to an unprecedented extent.

5.2. Motor Loss Reduction Effect

Figure 15 shows the loss reduction effect of the developed motor. Relative to the motor using conventional technology⁽¹⁹⁾, the thickness of the magnet wire coating has been reduced by approximately 20%, the cross-sectional area of the conductor has successfully been increased by approximately 6%, and a loss reduction effect of 5% has been confirmed. With the additional adoption of technology for low loss control and other such techniques together with current reduction by the amount of the torque increase from optimization of the magnetic circuits, losses in the motor as a whole were successfully reduced by a total of 14%.

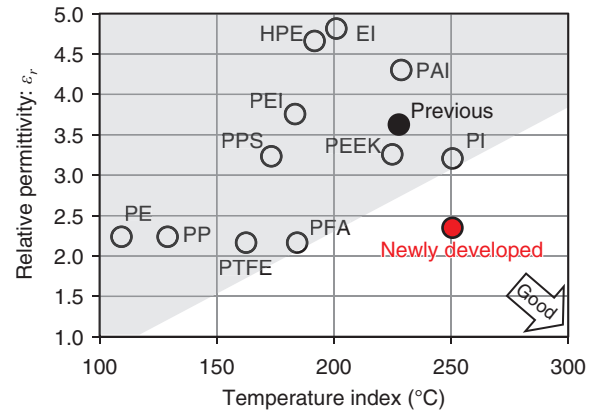


Fig. 14 Positioning of relative permittivity and temperature index of developed insulation coating

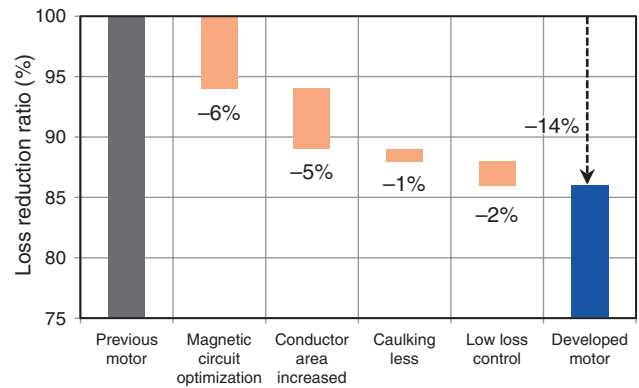


Fig. 15 Loss reduction effect of developed motor

6. Conclusion

- (1) When applying gas bubble coating to insulation coating for magnet wire, the use of a thermochemical method that utilizes gas bubble forming material that has an outside shell successfully yielded a gas bubble coating with independent gas bubbles that are several micrometers in size and dispersed evenly throughout.
- (2) By applying this gas bubble coating to the magnet wire in a new model motor, the motor loss was reduced by 5% from previous motors.

This is the first known successful application of this technology for practical use as insulation coating for magnet wire. The motor in which this technology was adopted is installed in the FIT e:HEV that went on sale in February 2020.

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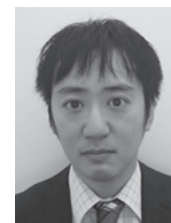
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