

# Magnet Wires for Driving Motors in Electric Vehicles

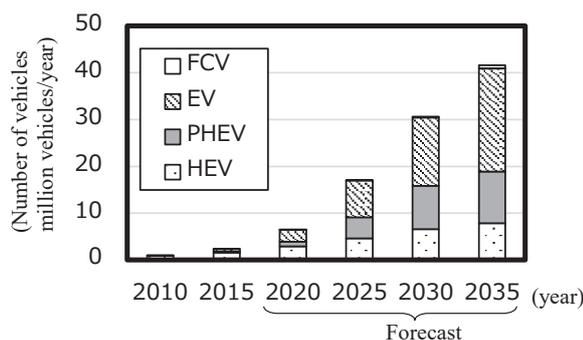
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The electrification of vehicles has been advanced rapidly with the aim of reducing environmental impact. This paper summarizes the transition of motor design technology and its future development trends with a focus on driving motors for electric vehicles as a benchmark. We also report on the current status of our efforts towards the development of rectangular wires that contribute to the improvement of motor performance. In our efforts, we have worked to enhance the insulation performance of the film coating for magnet wires and reduce their size variation.

Keywords: electric vehicles, motor, magnet wires

## 1. Introduction

To cope with environmental issues, it has been required to reduce the environmental impact such as air pollution and resource depletion and to reduce CO<sub>2</sub> emissions for prevent global warming. Against this backdrop, the Paris Agreement was adopted, and various regulations including ZEV,\*<sup>1</sup> CAFE,\*<sup>2</sup> and LCA\*<sup>3</sup> have been established. Notably, CO<sub>2</sub> emissions from the transport sector are high, following the energy conversion sector (e.g., power plants) and the industrial sector. Most CO<sub>2</sub> emissions are from vehicles. In order to meet the regulatory standards, the number of electric vehicles (EVs) such as hybrid electric vehicles (HEVs), plug-in hybrid vehicles (PHEVs), and battery electric vehicles (BEVs) has been increasing rapidly. The pace of increase is expected to keep accelerating into the future (Fig. 1). Therefore, we did research on the trend of driving motors for EVs. This paper presents a report on our magnet wires that are used for these vehicles.



(Source: Fuji Keizai Through Analysis and Research on HEV/EV-related Market (2019))

Fig. 1. Number of EVs

## 2. Changes in Driving Motors for EVs

### 2-1 Trend of driving motors

In order to push EVs on the public, it is essential to improve vehicle performance, increase fuel efficiency, and reduce the cost. For driving motors, technologies such as

those that increase torque and efficiency and simplify machine assembly have been under development.

Photo 1 shows the appearance of driving motor stators for HEVs and EVs that we researched. While various motor systems are used, when torque per weight (Nm/kg)

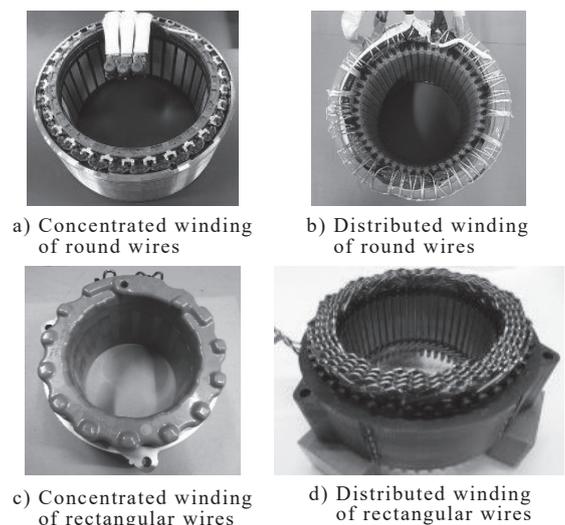


Photo 1. Driving motors for EVs (stator)

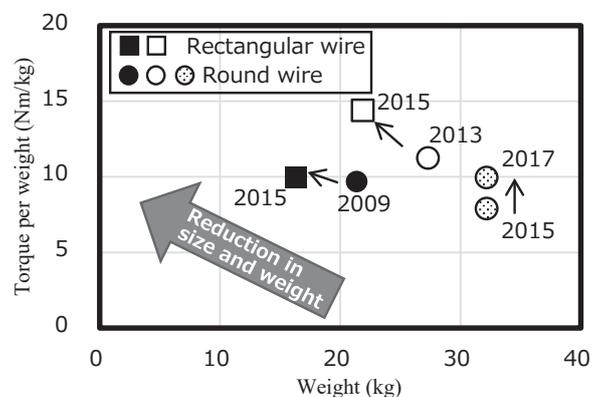


Fig. 2. Torque density of driving motors for EVs

is used as an index, the size and weight of motors used by the same automaker have been reduced (as shown by the arrows in Fig. 2). Notably, improvements have been made in motors that use rectangular wires.

## 2-2 Trend of motor coils

In terms of the coils of driving motors, the distributed winding method of round wires (whose cross section is round) and the concentrated winding method of rectangular wires (whose cross section is rectangular) used to be mainstream winding methods. Recently, the method trend is moving to the distributed winding method for rectangular wires as the technology advances.

Regarding the disadvantage of distributed winding motors (i.e., the coil end height is higher than that of concentrated winding motors), the coil end height is reduced to a level equivalent to that of concentrated winding motors by inserting a rectangular wire, which is divided into specified segments, into the iron core and then welding the edge for assembly. Also, the use of rectangular wires has significantly improved the space factor,<sup>\*4</sup> as shown in Fig. 3. This achieves not only downsizing of the size, but also reductions in weight and loss due to reduced amount of copper being used.

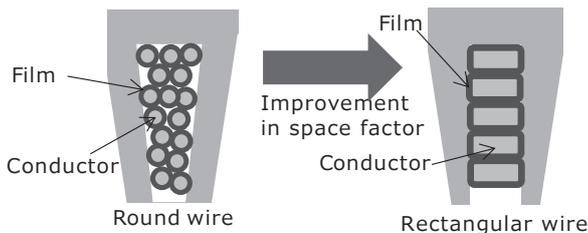


Fig. 3. Schematic diagram of the cross section of a motor core slot

## 2-3 Requirements for magnet wires

In line with the advancement of motors, magnet wires must meet the following requirements:

- 1) Higher space factor: rectangular shape, reduced film thickness inconsistency, lower permittivity<sup>\*5</sup> and thinner films
- 2) Higher voltage: thicker films, lower permittivity
- 3) Downsizing of the coil end: processing resistance, heat resistance, welding resistance
- 4) Higher rotation: conductors with lower eddy current loss
- 5) Easier assembly: improved core insertability

Inverter drive systems are used for driving motors for EVs. For some motors, the motor operation voltage has been increased by twice or more from the initial voltage.<sup>(1)</sup> At the coil end, it is necessary to ensure insulation of magnet wires corresponding to the interphase voltage. Insulating members, such as interphase paper, were used in conventional products, but the increased thickness of the insulation film reduces such insulating members, making it possible to achieve downsizing and cost reduction. Sumitomo Electric Industries, Ltd. has achieved uniform distribution of insulation film thickness for rectangular

wires, and developed a low-permittivity structure film whose insulation performance is higher than that of conventional film. The characteristics are excellent in terms of the resistance to degradation of wire treatment.

Meanwhile, the motor rotation has been increased to achieve downsizing and high power output.<sup>(2)</sup> For some motors, their rotation has been almost tripled from that of early products. High motor rotation requires an increased drive voltage.<sup>(3)</sup> The high insulation performance films that we have been developing, as mentioned earlier, contribute to increase the rotation.

## 3. Motors in the Future

As discussed in Section 1, the number of EVs is expected to increase rapidly. In particular, it is important to achieve advancements in technology to respond to various conditions under which the large number of EVs are used, changes and diversification of systems, and the need for price reduction. EVs are generally classified into two types: high-power output premium type and low- and medium-power output general-purpose type. For motors of the latter type, the operating voltage is 400 V or less, while the operating voltage of 800 V can be used for motors of the former type. In order to further increase the voltage in the future, it is critically important to improve the insulation performance of magnet wires. We have been focusing on the development of high-voltage rectangular wires. Also, it has become necessary to ensure global supply of the wires as standardization of motors proceeds due to the use of modules such as e-Axle.<sup>\*6</sup> Against this backdrop, we have been conducting a study on components.

## 4. Our Motor Magnet Wires

In the trend of the developments for improving the EV driving motor performance as previously discussed, the followings are our efforts to improve the characteristics of magnet wires. Regarding wire types, we use rectangular wires rather than the conventional round wires. In order to increase the space factor, we have worked on (i) the development of a processing method to reduce the inconsistency in film thickness and (ii) the use of film materials that achieve the same insulation performance as that of thinner films.

### 4-1 Improvement in film thickness distribution inconsistency

As above discussed in section 2, switching from a round wire to a rectangular wire improves the space factor, achieves reduction in size and weight, and increases the performance of motors.

Generally, in the case of a rectangular wire, the space factor is increased by enlarging its conductor area per wire. However, when there is an inconsistency in film thickness, even if a film with the same insulation characteristics is used, the outer diameter of a magnet wire is determined by the maximum film thickness (not by the minimum film thickness that guarantees insulation), resulting in a lower space factor (Fig. 4). It also increases consumption of film materials, leading to higher costs.

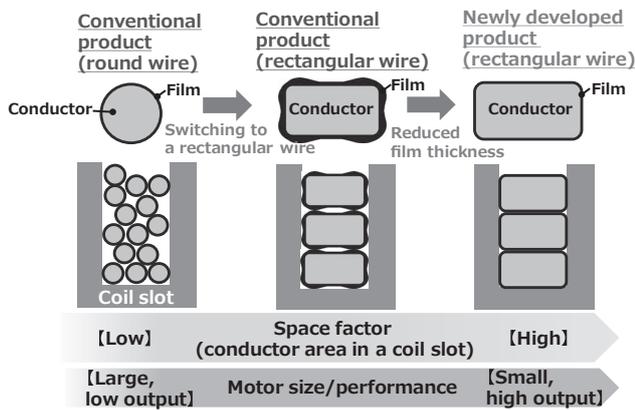


Fig. 4. Improved space factor in a slot

We reduced the inconsistency in film thickness of a rectangular wire and succeeded in achieving uniform distribution of film thickness, as shown in Photo 2.<sup>(4)</sup>

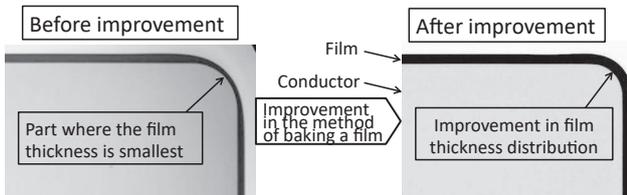


Photo 2. Improved film thickness inconsistency differences<sup>(4)</sup>

#### 4-2 Selection of film materials to reduce film thickness

A magnet wire used for high-voltage driving motors requires not only high heat resistance and resistance to degradation of wire treatment, but also insulation performance that can suppress partial discharge (higher PDIV\*<sup>7</sup>).

In early driving motors, esterimide, which is characterized by low permittivity to achieve higher PDIV, and amidimide, which is slightly inferior in terms of permittivity but superior in terms of heat resistance, were used as film materials.

For further improvement in motor performance, we developed and marketed a magnet wire using a polyimide film. As shown in Fig. 5, a polyimide film is superior to the above-mentioned film materials in terms of resistance to degradation of wire treatment,<sup>(4)</sup> while achieving low permittivity and high heat resistance.

It should be noted that polyimide is superior in performance, but was expensive. This was one of the obstacles in commercializing the product. We succeeded in lowering the price of the magnet wire and marketing a price-competitive rectangular wire for driving motors of EVs.

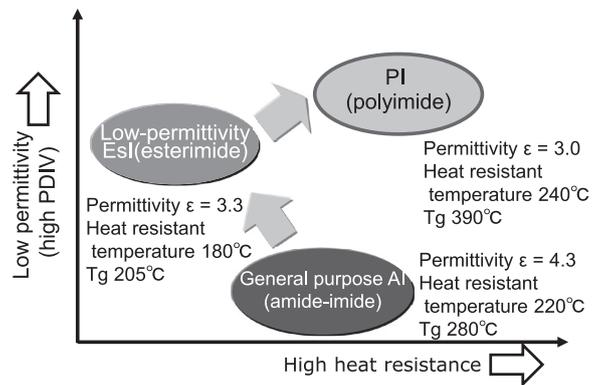


Fig. 5. Selection of magnet wire film materials

### 5. Improvement in Performance of a Rectangular Wire

We have been able to launch a rectangular wire using a polyimide film that contributes to improved performance of driving motors and succeeded in helping improve the performance of EVs. Moreover, we are currently working to further improve the performance of magnet wires.

In order to improve the space factor, we have worked on the development of a film material that can reduce film thickness with the same insulation performance. Its concept is to develop a film material whose permittivity is far lower than that of polyimide. We attempted to lower permittivity by denaturing the chemical structure of polyimide, which is the base material. However, the permittivity could be reduced only to 2.7 (permittivity of polyimide: 3.0).

It is known that permittivity of materials can be reduced by introducing air, whose permittivity is almost one, into films.<sup>(5)</sup> As an approach to lower the permittivity of a film, we worked on a technique that introduces microcells into a polyimide film of a magnet wire.<sup>(6)</sup>

Figure 6 shows the correlation between the percentage of microcells and the relative permittivity of a magnet wire with microcellular coating under development (a magnet wire with microcells introduced to its polyimide film).

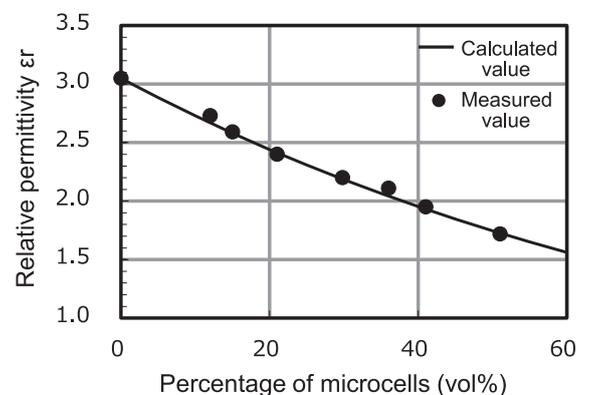


Fig. 6. Relative permittivity of magnet wire with microcellular coating<sup>(6)</sup>

In a magnet wire with microcellular coating, microcells may be connected to form large, open microcells, which may reduce the dielectric characteristics and processing resistance and may ultimately decrease motor performance.

We developed a magnet wire with a new microcellular coating to which closed microcells are introduced (Photo 3).<sup>(6)</sup>

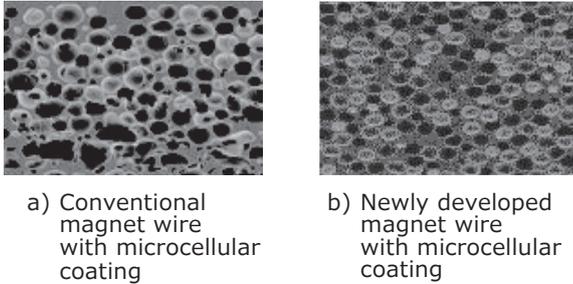


Photo 3. Cross section of film on magnet wire with microcellular coating<sup>(6)</sup>

We compared insulation characteristics between the magnet wire with the new microcellular coating and a magnet wire with the conventional microcellular coating. In magnet wires with almost the same film thickness, the magnet wire with the conventional microcellular coating was subject to dielectric breakdown at 4.9 kV, while the dielectric breakdown of the magnet wire with newly developed microcellular coating was improved up to 10.8 kV. The insulation performance was improved by forming closed microcells in the film.

It was also confirmed that PDIV was improved by introducing microcells into the film. Using measurement samples that two rectangular wire strips were secured back-to-back, we measured PDIV with different percentage of microcells.

The measurement results at 25°C are presented in Fig. 7. The higher the percentage of microcells becomes, the more the PDIV is improved. It was confirmed that the PDIV of a wire with a percentage of microcells of 30 vol%

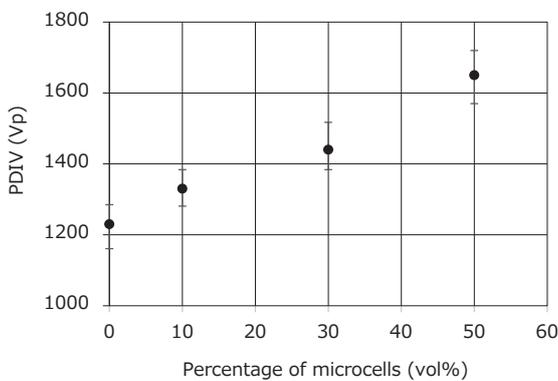


Fig. 7. PDIV measurement results of magnet wire with microcellular coating<sup>(6)</sup>

was improved by 200 Vp compared to that of a polyimide magnet wire with a percentage of microcells of 0%.

Comparison of the characteristics of the newly developed magnet wire with microcellular coating and the polyimide magnet wire is summarized in Table 1. For the magnet wire with microcellular coating whose percentage of microcells is 30 vol%, the relative permittivity can be reduced to 2.2, compared to 3.0 for the polyimide magnet wire. In terms of the PDIV of a magnet wire with the same film thickness of 60  $\mu\text{m}$ , the discharge inception voltage has improved by 200 Vp or more due to the decrease in relative permittivity. To attain the same PDIV value of 1,230 Vp, the polyimide magnet wire requires a film of 60  $\mu\text{m}$  thickness, while the magnet wire with microcellular coating requires a film of 44  $\mu\text{m}$  thickness. This means that the film thickness can be reduced by about 30%, which contributes to improving the motor space factor.

Table 1. Characteristics of magnet wire with microcellular coating (comparison with polyimide magnet wire)

	Conventional product (polyimide magnet wire)	Newly developed product (magnet wire with microcellular coating)	
	Polyimide	Polyimide	
Insulation film material	Polyimide	Polyimide	
Film thickness ( $\mu\text{m}$ )	60	60	44
Percentage of microcells (vol%)	0	30	←
Relative permittivity	3.0	2.2	←
PDIV (Vp)	1230	1440	1230

## 6. Conclusion

To establish our roadmap to develop magnet wires, we collected benchmarks of driving motors used in EVs and monitored the development trend of motors and parts used.

Based on the roadmap, our efforts have been made to develop a magnet wire and contributed to achieving higher performance for driving motors by switching from a round wire to a rectangular wire and improving the performance of the rectangular wire. We remain committed to improving the characteristics of magnet wire to achieve ever higher motor performance.

### Technical Terms

- \*1 ZEV: ZEV is an abbreviation of Zero Emission Vehicle. It refers to BEVs and fuel cell vehicles (FCVs) that do not generate emissions at all.
- \*2 CAFE: CAFE is an abbreviation of Corporate Average Fuel Efficiency. The CAFE standards are fuel efficiency regulations for vehicles based on average fuel efficiency by taking into account the number of vehicles shipped by each respective automaker.

- \*3 LCA: LCA is an abbreviation of Life Cycle Assessment. This method evaluates the total CO<sub>2</sub> emissions from vehicle production, energy generation, driving, disposal, and recycling, among other factors.
- \*4 Space factor: Space factor is the ratio of the cross section of a magnet wire conductor to the cross section of a slot into which the magnet wire is stored in a motor core. The larger the space factor becomes, the higher the motor output per size becomes.
- \*5 Permittivity: Permittivity is a value that shows the polarizability when an insulator is subject to an electric field. When permittivity is low, electrical discharge is less likely to occur, resulting in higher PDIV\*<sup>7</sup>.
- \*6 e-Axle: e-Axle is a module that integrates a drive motor, an inverter, and a transmission.
- \*7 PDIV: PDIV is an abbreviation of Partial Discharge Inception Voltage. It is also known as corona onset voltage.

#### References

- (1) Investigating R&D Committee on a trend of Electric Motors for EV/HEV, The Institute of Electrical Engineers of Japan Technical report, A Technology Trend of Electric Motors for EV/HEV, No. 1394
- (2) S. Fushiki, et al. TOYOTA Technical Review, Vol. 62 (April 2016). pp. 61-70
- (3) JMAG Motor design study group, Introduction to Permanent Magnet Synchronous Motor Design, pp. 224, JSOL (2016)
- (4) J. Sugawara, et al. SEI TECHNICAL REVIEW, No. 84 (April 2017).
- (5) 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)
- (6) S. Ota, et al. SEI TECHNICAL REVIEW, No. 88 (April 2019)

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