Potential for Improving Motor Performance Using Thermosetting Molding Materials

Shinya Yamamoto Hirofumi Kuroda Takahiro Harada
Wataru Kosaka Atsunori Nishikawa
SUMITOMO BAKELITE CO., LTD., Tokyo, Japan E-mail: nea@ml.sumibe.co.jp

ABSTRACT: This paper presents an effort to realize motor that lead to high efficiency & high performance by applying various plastic materials as solutions for motor in the trend of promoting EV. We have confirmed that it is possible to reduce stator coil temperature, and motor NV by applying a water channel in the slot with stator coil encapsulation, and a Phenolic housing.

KEY WORDS: Cooling, Stator, Rotor, Housing, Thermosetting, Magnet Fixation Epoxy molding compound,

1. INTRODUCTION

Toward the realization of a decarbonized society, the spread of electric vehicles is accelerating in the automotive field.(1) In particular, the electric powertrain (e-axle), which integrates a motor, inverter, and gearbox, is one of the key components for downsizing, weight reduction, and higher efficiency. However, how to deal with the heat caused by the high performance of the above components has become a major issue, and a new approach that differs from conventional technology is required. (2)-(9)

As a manufacturer of high-performance resin materials, we are promoting the development of technologies to solve the above-mentioned problems of electric axles by taking advantage of the features of high-performance resins, such as light weight, insulation, environmental resistance, shape flexibility, and strength.

These efforts include power modules in inverters, phenolic housings, etc. In this article, we will introduce innovative key technologies using thermosetting resins that we have applied in drive motors, and describe a series of evaluations and efforts using plastic motors manufactured with these technologies.

Table.1
Basic specifications of the motor under consideration

Item	*SPEC*
Motor type	IPM
Coil type	Flat/Distributed
Power (continuous)	60-80kW
Power (Max)	150kW
Torque (Max)	300Nm
Rotation speed (Max)	15000rpm

2. OVERVIEW OF Plastic motor

2.1. Specifications of the Plastic motor

In this study, we designed and manufactured a plastic motor by integrating key technologies of each component based on the motor specifications shown in Table.1, considering the capacity of the main drive motors applied to recent electric vehicles.

2.2. Technical points of each component

2.2.1. Direct cooling structure of Stator

For the stator, one of the key components in the IPM motor, a high thermal conductivity epoxy molding compound materials was applied. This materials can fill narrow areas even under low-pressure conditions, (10) and by encapsulation molding the slots in the stator core, between coils, and at the coil ends, a stator with excellent insulation and heat conductivity can be obtained.

The properties of the epoxy molding compound materials are shown in Table.2. Epoxy molding compounds are resin materials that have been proven in many cases in the

Table.2
Typical Property of Applicable materials

Typical Properties		*SPEC*
Thermal Conductivity	[W/(m・K)]	3
Thermal Expansion	[1/℃]	1.0×10^{-5}
Flexural Strength	[N/mm²]	190
Flexural Modulus	[N/mm²]	300×10^{2}
Specific Gravity	-	2.82
Specific heat	[J/(kg・K)]	881

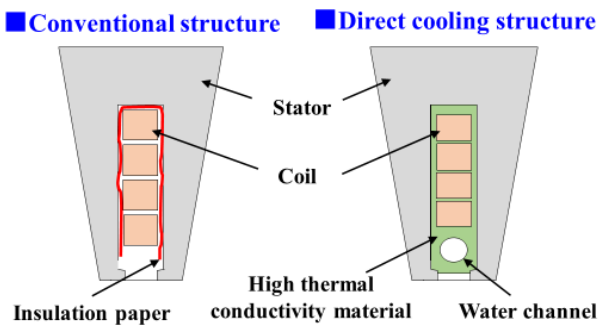


Fig.1 Conventional structure and direct cooling structure

encapsulation of semiconductor packages. They are used to protect electronic components from external mechanical external forces, external environments caused by temperature, heat, and chemicals, and to ensure electrical insulation. [10]

In addition, the encapsulation molding of semiconductor packages also needs excellent low melt viscosity properties to fill the material at low pressure so as not to break the bonding wires. In the present stator encapsulation molding, these materials enables molding of narrow sections of coils and stators without causing deformation of the coils and stators. Furthermore, as shown in Fig.1, a cylindrical water channel is placed in the inner diameter of the stator core slot to allow water to flow during motor drive, effectively cooling the heat from the coils and achieving an innovative cooling performance. (11)

2.2.2. Rotor Magnet Fixing Method by molding

We have adopted a magnet fixing method using epoxy molding compound materials as in the stator case, instead of the conventional method using glue.

In this method, a magnet is fixed by injecting material into the flux barrier section from the outside using a mold. (12)

The advantage of this method over the conventional gluing method is that it reduces the time required to fix the magnet, and it is both highly productive and reliable. As one of the reliability checks, we simulated a magnet fixation method using epoxy molding compound materials. A simulation model was used in which a section of the rotor (45 degrees) was created. We used the above model to compare with the conventional gluing method, after inputting the stresses generated in the rotor bridge section at a rotational speed of 20,000 rpm. The results are shown in Fig. 3.While the stress around the bridge area is 90 MPa with the conventional gluing method, the magnet fixing method using the epoxy molding compound material applied in this study has

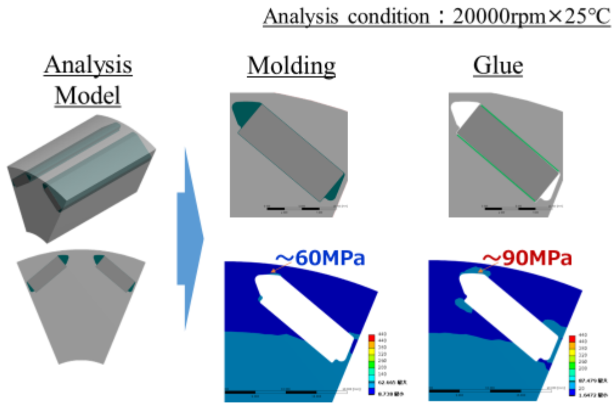


Fig.3 Rotor simulation results

resulted in a stress reduction of nearly 30 MPa. It is considered that the stress on the rotor is reduced due to the reinforcing effect of the bridge area by filling the flux barrier with molding materials. Based on the simulation results, we actually manufactured a rotor and conducted spin tests to check the effect of the rotor on the actual products. The test was conducted by conducting a spin test from a low RPM range, measuring the amount of outer diameter deformation of the rotor bridge due to centrifugal force, and gradually increasing the RPM to compare the change in deformation with the conventional glue method. The results are shown in Fig. 4.

In the magnet fixing method using glue, deformation of the rotor was observed from 20,000 rpm. On the other hand, the magnet fixing method using epoxy molding compound materials resulted in deformation from 23,000 rpm. This shows that the magnet fixing method using molding reduces the deformation of the magnet area in the rotor. This result proved that the magnet fixing method using epoxy molding compound materials is the most optimal method for fixing magnets in rotors that rotate at high speeds.

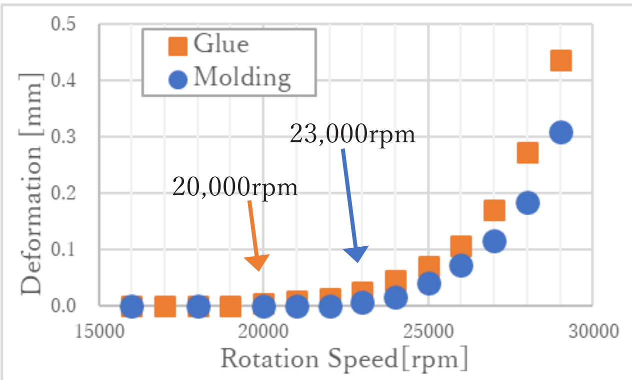
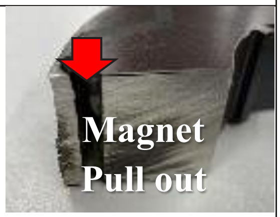


Fig.4 Rotor spin test results

Table.3 Result of easy disassembly material study

	Conventional products	Developed products
Appearance check		
After rotor cutting		

As a new approach, we are also working on the development of magnet fixation materials that are easy disassembly. With conventional magnet-fixing molding materials, it was necessary to burn off that material at 700°C or higher to remove the magnets from the rotor. The newly developed molding material has the same performance as conventional molding materials when the motor is in use, but the resin denatures at 300-400°C and the magnets can be easily removed.

Table 3 shows an example of the results of an easy- disassembly material study. A neodymium magnet without magnetization was set in the rotor core, and magnet fixation molding was done using two types of materials: conventional molding material and easily disassembled molding material. After that, heat treatment was done at 300°C x 30 min and observed the condition around the magnet at room temperature after cooling.

In the easily disassembled material, separation occurred at the interface between the magnet and the rotor core, and it was confirmed that the magnet could easily be pulled out after cutting around the magnet._This confirmed that the newly developed material has excellent easy disassembly properties for recycling magnets.

2.2.3. Motor housing with excellent NV properties

From the viewpoint of weight reduction and contribution to carbon neutrality, plasticization of large metal parts is a high priority, and the demand for such plasticization is increasing. (13) Currently, most of the materials used for housings, including engines as well as drive motors, are generally steel or aluminum materials. However, in this study, a plastic motor housing using phenolic molding compound material was manufactured and applied to a series of evaluations.

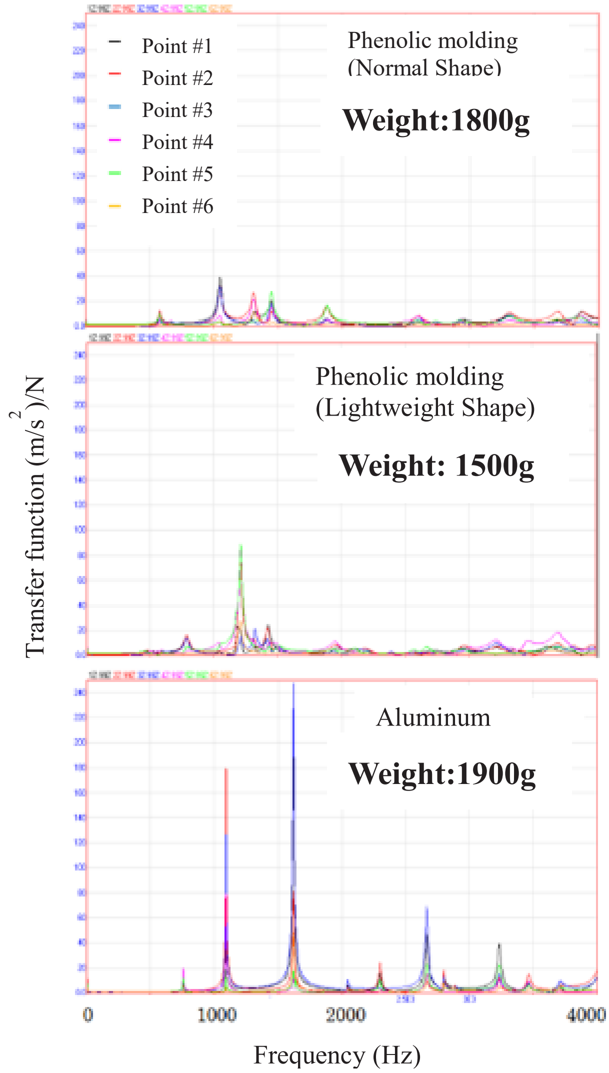
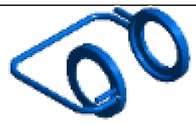
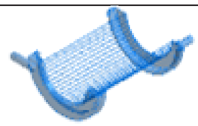


Fig.4 Housing Cover hammering test results

As electric vehicles such as BEVs become more widespread, the requirements for noise and vibration are expected to increase. For the above issues, plastics, including thermosetting materials, generally have excellent damping properties compared to metal parts, so reviewing the applicable materials along with the design may lead to a solution to the issues.

In this study, we manufactured a molded housing using phenolic molding compound materials and conducted hammering tests. An aluminum housing was also manufactured for comparison, and the differences between the two were confirmed. Fig. 4 shows the results of hammering tests conducted on motor housing cover parts that have similar geometries for phenolic and aluminum products. For the phenolic products, a comparison was conducted between the normal shape, which is 5% lighter than the aluminum product, and the lightweight shape, which is 20% lighter than the aluminum product. It was found that both phenolic products were highly effective in reducing vibration compared to the aluminum product.

Table.4 Motor assembly used in temperature rise test

A.	B.	C.
Conventional	Plastics-applied	
Outside water-cooled	Water-cooled coil end only	Water cooling of coil end and inside slot
		

3. Test results of assembled products

3.1. Temperature rise test with motor assembly

After each component was assembled, a water flow test was conducted using a DC power supply to ensure that the cooling effect was as expected before bench test was conducted, and the temperature change at the coil end was measured. As shown in Table 4, two types of plastics motors were tested with and without water channels in the slots to confirm their effectiveness.

3.1.1. Temperature rise test results

Comparative results of temperature rise tests are shown in Fig. 5. The measurements shown in the graphs are the actual measured data at the coil end when 300 A of DC power is applied to any of the motors.

For the conventional motor, the coil end temperature was found to be above 100°C after 250 seconds into the test. However, the motor with only the coil end of the product water-cooled still had a coil end temperature of nearly 90°C after 1800 seconds into the test. This shows that stator encapsulation using high thermal conductivity epoxy molding compound materials is effective in suppressing coil temperature rise.

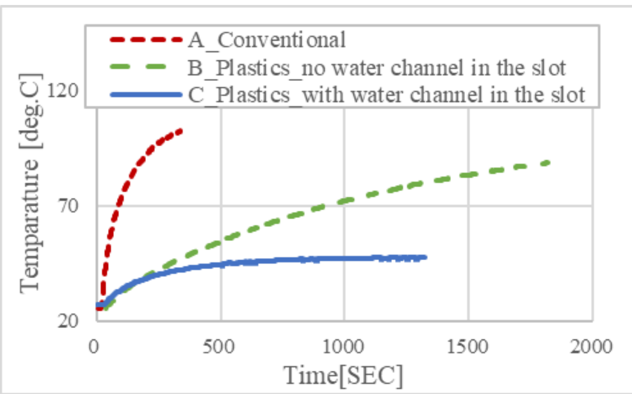


Fig.5 Results of stator temperature rise test using DC power supply

Fig. 6 Plastics-applied stator during bench test

Furthermore, it was confirmed that the plastics-applied motor using the water channel in the slot of the stator reached a steady state of about 45°C around 480 seconds after start. This suggests that a breakthrough cooling performance has been obtained, and it has been demonstrated that the motor structure using the coil encapsulating materials applied in this study has a very high cooling performance.

3.2. Bench testing of Plastics-applied motor

The assembled plastics-applied motor was mounted on a bench tester and driven under various load conditions to obtain various sound pressure, vibration, and temperature data. The plastics motor during the bench test is shown in Fig. 6.

In addition, conventional motors manufactured using existing technology were also tested for comparison and verification. The plastics-applied motor used in this test has a stator that is water-cooled only at the coil end as shown in Fig. 5-B. The plastic housing is a phenolic molding of normal shape.

3.2.1. Results of sound pressure level

Sound pressure during operation under each driving condition was measured with a sound-collecting microphone located near the bench tester. The results are shown in Fig. 7.

The sound pressure level of the plastics-applied motor was lower than that of the conventional motor under all conditions, although the rotational speed was varied from 2500 to nearly 10,000 rpm to drive both the conventional motor and the plastics-applied motor. Especially at 1000 rpm, the plastics motor showed a reduction in sound pressure level of about 20 dB compared to the conventional motor. The following factors are thought to be the reason why the sound pressure level of the plastics-applied motor is lower than that of the conventional motor. The second is

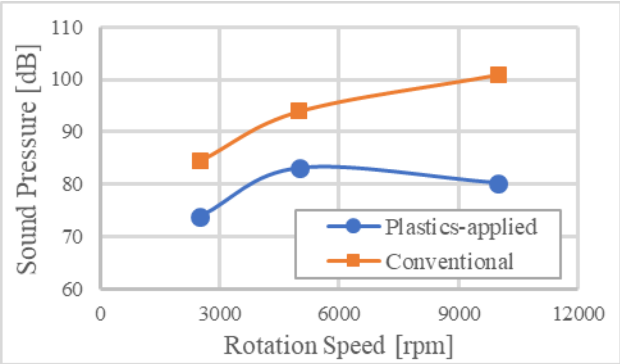


Fig. 7 Results of sound pressure measurement

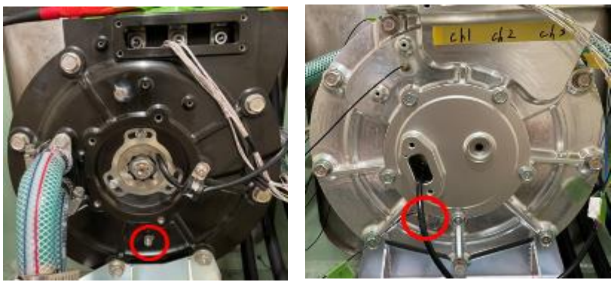


Fig.8 Acceleration sensor mounting position

presumably the damping effect of the vibration transmitted from the shaft by the plastic housing using phenolic molding compound materials.

3.2.2._Vibration acceleration measurement results

In the bench test, not only sound pressure but also vibration at various points of the motor were measured using acceleration sensors. And the plastics-applied motor was then compared to a conventional motor.

Fig. 8 shows the position of the acceleration sensor during the bench test, and Fig. 9 shows the measured vibration acceleration of each motor under each driving condition. The above measurement point is directly above the housing cover parts that was measured during the hammering test. And the measurement was taken at the location farthest from where the motor was mounted during the bench test.

In the region lower than 6 kHz, the vibration acceleration level of the plastic-applied motors generally tended to be low. In addition, in the high speed range (1000 rpm, 75 Nm condition), the vibration acceleration level of the plastics-applied motor tended to be low in the total area.

3.2.3. Results of motor temperature comparison

In the bench test, temperature sensors were installed at each motor location to measure coil temperatures during the test. Fig.

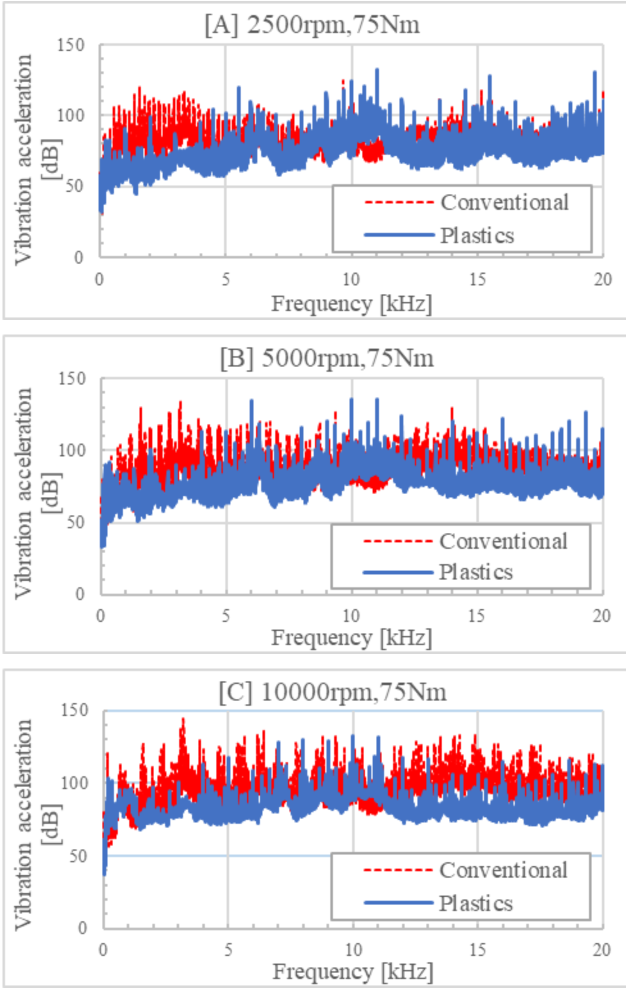


Fig.9 Vibration acceleration measurement results from bench test

10 shows the temperature transition during operation at the same location for the conventional motor and the plastics-applied motor.

The cooling water used in the tests was controlled by a chiller, with a temperature of 25°C and a flow rate of about 16 L/min. The temperature rise time to 100°C at high load (10000 rpm, 75 Nm) is about 3 minutes and 40 seconds for the plastics-applied motor with coil end cooling only, compared to 2 minutes and 20 seconds for the conventional motor, an improvement of more than 50%.In addition, the measurement of the plastics-applied motor this time showed that the stator core temperature remained higher than the coil end temperature. This indicates that coil encapsulation using high thermal conductivity materials effectively functions to conduct heat to the stator core, and it was confirmed that the technology applied in this study leads to suppression of coil temperature.

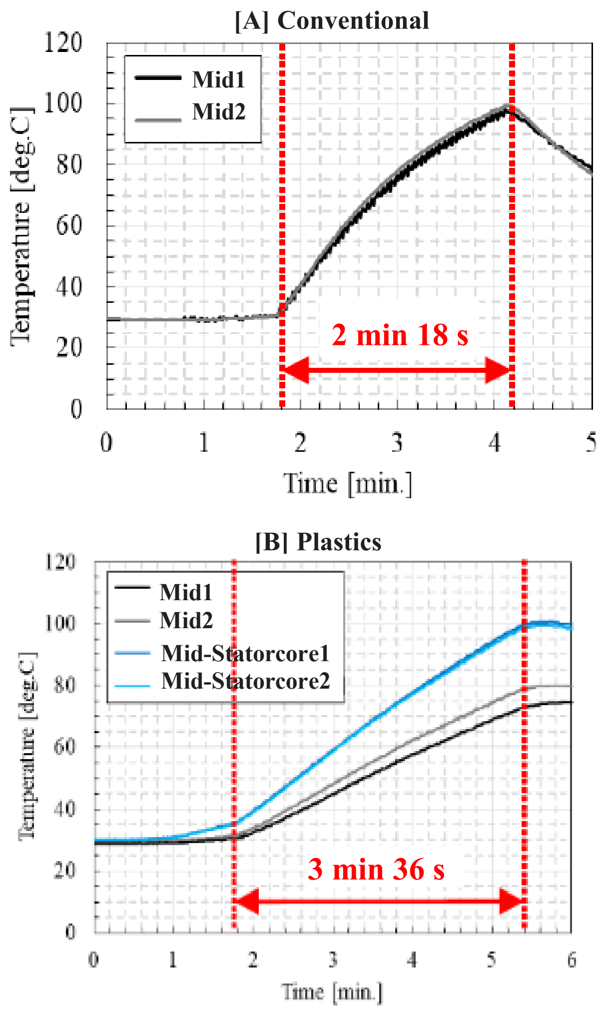


Fig. 10 Coil temperature transition in bench test

4. CONCLUSIONS

This paper suggests a plastic motor with excellent cooling performance and NV properties instead of a conventional metal motor, and describes the technical points of each component and the evaluation results of the motor assembled with those components.

We were able to confirm a drastic reduction in the sound pressure level during motor operation in bench tests by using a unique structure in which the coil is encapsulated with high thermal conductivity material and a water channel is provided in the slot, a method of strongly fixing the magnet in the rotor using encapsulating material, and a plastic housing with excellent damping properties.

We have also confirmed that the coil temperature rise in the motor can be reduced by heat dissipation through encapsulation molding of high thermal conductivity materials and by water channels in the slots._This confirms that this motor structure is suitable for higher rotation speed and higher efficiency.

This series of studies is the result of an evaluation using a concept model to confirm the potential of Thermoset plastics. For future realization, it will be necessary to continue establishing mass production methods and verifying design shapes based on the characteristics of Thermoset plastics. We will continue this study to contribute to the electrification of various fields.50% longer for the plastic motor than for the metal motor.

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