

Development of a Plastic Mold Technology for Bus Rings in a DC Brushless Motor

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ABSTRACT

To improve the layout and increase the mass productivity of Hybrid Electric Vehicles (HEV) drive motors, integrated molding of high voltage distribution parts using plastic insulation material was investigated as a method to reduce the number of parts and increase ease of assembly. The enlargement of part dimensions, occurring with the change to molding plastic from the former cure coat-type fluoropolymer insulator material, was minimized and waterproofing performance was increased. Selection of materials on the basis of measurements of heat strain in plastic molded parts and full molding using floating over molding ensure waterproofing. Study of the design basis for high-voltage insulation clarified the minimum insulation distance, enabling the development of an integrated bus ring molding technology, which allows mass production without increasing the dimensions of the parts.

1. Introduction

As part of the continuing effort to address automotive environmental issues, expectations have been high concerning the market penetration of hybrid electric vehicles (HEV hereafter) as technology to further improve fuel economy.

In order to work towards true market penetration of HEV, it is necessary to resolve issues of making the systems additional to those of a conventional gasoline vehicle, such as a driving motor and battery, etc., smaller and lighter, and improving mass productivity of these systems.

In addition, the motor drive voltage (generally 200 V or more) for HEV, EV and FCV is higher than the voltage of a conventional gasoline vehicle's electrical component (12 – 24 V). Therefore, the reliability of insulation against the high voltage of the electrical components is very important, and when insulation is guaranteed using plastic molding, the selection of plastic material and the structure design of the molding are important in determining the quality of insulation. Therefore, a study was made, working towards making the unit smaller and improving mass productivity, by

reducing the number of parts through integrated mold forming of the multiple bus rings, having a current distribution function used to drive the DC brushless motor, with plastic insulation material. In addition, studies were performed on integrated molding structures and molding technologies. Bus ring integrated plastic mold technologies were developed with high insulating reliability. This is a report on those technologies.

2. Development Aims

Figure 1 shows the structure of the DC brushless motor being used in the IMA (Integrated Motor Assist) system for the Honda Insight. The motor uses three copper conductors (bus rings) to distribute three-phase current to 18 stator coils used for motor drive.

The bus rings are required for not only an electrical distribution function, but also for inter-phase insulation and external insulation, so a cure coat type of insulation material is used. In the cure coat type of insulation material, generally an epoxy cured coating is used, but because of the engine bay

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high temperature environment around the motor for HEV, a highly heat resistant fluoro-polymer cured resin coating was used.

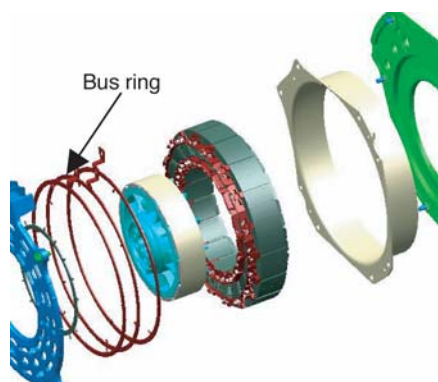


Fig. 1 Motor components and bus ring

The fluoro-polymer cured resin coating is not only high in raw material cost, but also, as shown in Fig. 2, it is easy for the coating to become thinner at the corner edges and in areas of burrs of the pressed copper conductors. Furthermore, because of coating imperfections, such as pin holes, conductivity contaminants, coating film separation, etc., it is necessary to have rigorous quality control in order to maintain insulation performance. Therefore, yield is poor and it is difficult to expand the scale of manufacture.

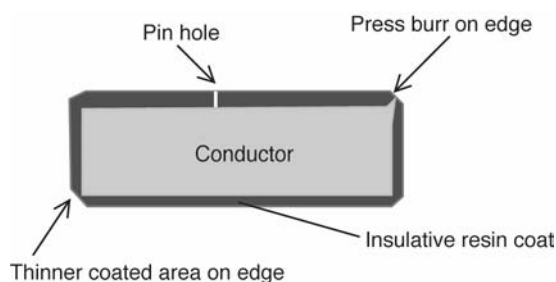


Fig. 2 Typical concerns of resin coated bus rings

In this development project, a study was done to see if it were possible to expand the scope of manufacturing through the use of copper conductors, over-molded with plastic insulation material, as insulation material instead of cured resin coating.

3. Technological Issues in Changing to Plastic Molding

3.1. Technological Issues in Changing to Plastic Molding

When over-molded with plastic and used as insulation material, by improving yield, an expansion of manufacturing scale can be expected. Yet the following technological issues must be addressed.

(1) Thinning of the insulation layer

With a cure type insulation layer, everything is fine as long as the minimum thickness necessary for insulation is maintained (10's of μm). However, in contrast, with plastic molding, it is necessary to have a thickness of approximately 1 mm in order to maintain plastic flow during forming. Therefore, when using three bus rings

together, additional space of 5 or 6 mm is needed in the stacking direction, in comparison with the cure type resin insulation material coatings.

(2) Durability and reliability against heat cycles

With cured resin coating, a comparatively flexible plastic coating is thinly formed on the conductor surface. Therefore, the plastic coating follows the thermal expansion of the copper conductor and it is able to absorb thermal strain. In comparison, when using plastic molding, the thermal expansion difference from the copper conductor cannot be absorbed because the molded plastic is hard and the layers thick. This means there is cracking of the molded plastic due to thermal cycles creating a water penetration passage and resulting in a drop in insulation performance. In particular, weld lines, which are one type of plastic forming flaw or imperfection, give low strength characteristics and easily form the point of origin of thermal cycle cracking.

3.2. Methods for Responding to These Issues

In order to resolve these issues, the following countermeasure methods were studied.

(1) Achieving a smaller size through integrated molding

Rather than plastic molding the three copper conductors separately, work to make it more compact with integrated plastic molding of the three conductors. At the same time, while coming up with ideas for an integrated molding structures and forming methods, maintain insulation reliability by firmly establishing principles for design of insulation against high voltage.

(2) Maintaining durability and reliability against heat cycles

The optimum plastic material is selected by directly evaluating thermal strain that occurs in the plastic during thermal cycles and comparing it with material strength characteristics. In addition, through forming method proposals and molding structure ideas, structurally prevent water penetration and avoid a drop in strength characteristics, which can be caused by flaws or imperfections such as weld lines.

4. Studies of Structure and Forming Method Proposals

4.1. Studies of Forming Method Proposals

When integrated, the major functions of the plastic molded parts are insulation between the integrated copper conductors and insulation from external parts. Accordingly, in order to maintain insulation performance, it is essential to accurately maintain the thickness of the molded plastic between the conductors and around the outside. Conductors are subject to a large plastic filling pressure during plastic molding. Therefore, as shown in Fig. 3, there is a conductor position misalignment which causes the insulation performance to drop.

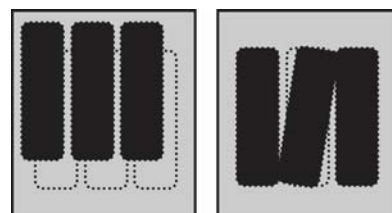


Fig. 3 Position shift in resin mold

Generally, in order to prevent insert part position misalignment during molding, forming manufacturing ideas are used, as shown in Fig. 4.

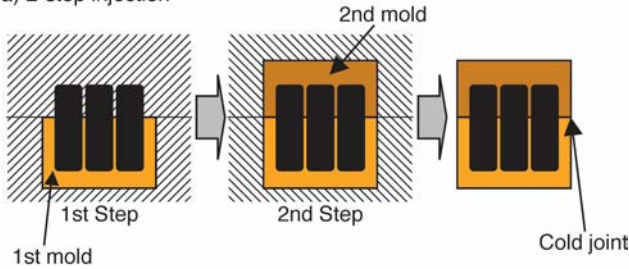
- The mold is formed in two separate stages (two-step injection).
- Conductor misalignment is prevented by holding them inside the mold using a mold holding pin.

Use of the two-step molding shown in “a” has the advantage of being able to firmly support the insert part. However, even when using the same plastic material for the 1st and 2nd injections, at the time of the 2nd injection the 1st mold has already cooled to a solid state, and at a position away from the injection gate, it is easy to have an incomplete interface fusion (cold joint). A cold joint on the outer surface of a part is a cause of loss of insulation function, due to water penetration.

In contrast, when using a holding pin, no cold joints are created. But in order to guarantee full waterproofing performance, it is necessary to add a process, such as waterproof potting application, etc., in the holding pin tracks, as shown in Fig. 4b.

A method that gives a seamless mold not requiring an additional waterproofing process is floating over mold, which removes the holding pin in the forming process. However, because the holding pin is removed before the plastic filling is complete, it becomes difficult to balance plastic filling pressure during the molding of complex shapes and to maintain insert position accuracy.

a) 2-step injection



b) using holding pin

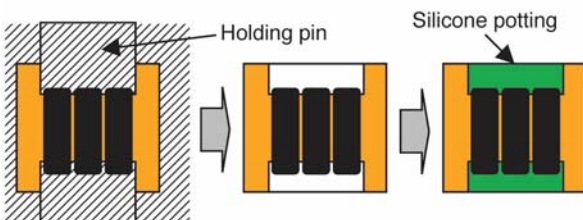


Fig. 4 Schematic drawing of full mold method

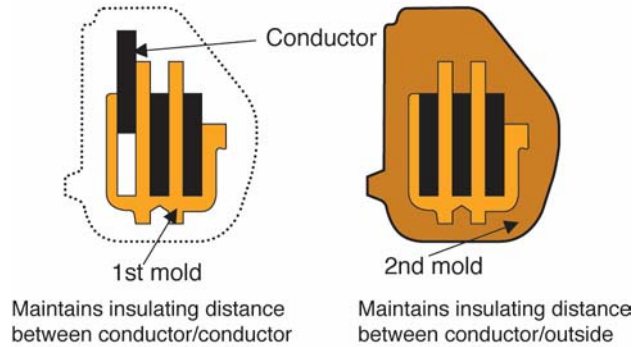
Therefore, this development project combines two-step injection (a) and float over mold (b), as shown in Fig. 5.

- The copper conductor is held by a previously formed 1st mold, and in addition to maintaining the accuracy of relative positions between phases, there is an over-mold over the whole (two-step molding).
- By molding over the 1st mold that holds the copper conductors, using floating over molding, no cold joints are created on the external surface and waterproofing

performance is maintained (floating over mold).

This structure and the forming method proposal separate the functions to be guaranteed.

(1) 2-step molding



(2) Floating mold

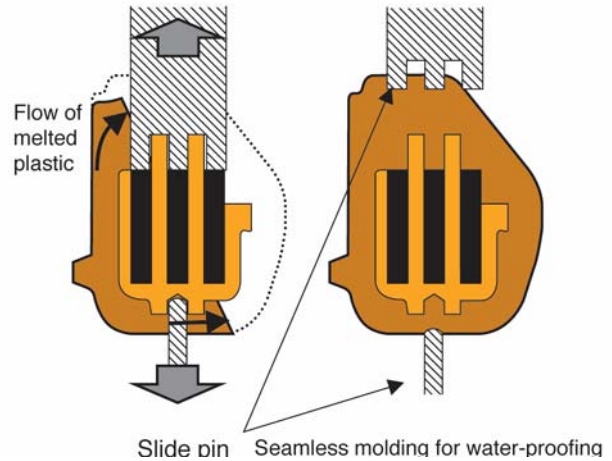


Fig. 5 Seamless molding method for a bus ring

4.2. Molded Bus Ring Structure

The basic structure of the plastic molded bus ring is shown in Fig. 6. Three copper conductors are bent into a cylindrical shape. After securing insulating distance between conductors held by the 1st mold (holder), waterproofing performance and insulation between the conductors and the outside are secured with a 2nd mold (over-mold).

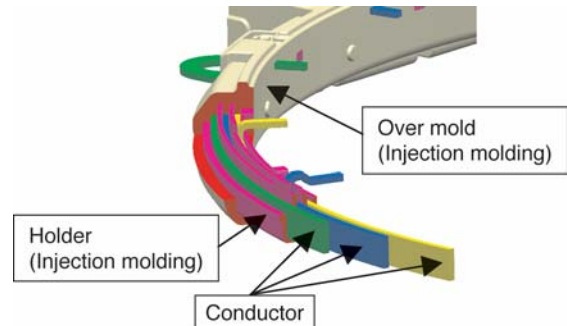


Fig. 6 Structure of a plastic molded bus ring

5. Selection of Optimum Material

5.1. Selection of Study Materials

In this development project, because the part usage environment temperature is high (150 °C or higher), and because shape accuracy and stiffness are necessary for the parts during assembly, the mold materials studied included PBT reinforced with glass fibers (PBT-GF hereafter), PPS reinforced with glass fibers (PPS-GF hereafter) and PPS reinforced with glass fibers and minerals (PPS-GF/M hereafter). The PPS-GF/M is a special grade with low thermal expansion anisotropy.

The thermal expansion coefficients for these materials are given in Table 1.

Table 1 Thermal expansion coefficient of investigated materials

		PBT-GF	PPS-GF	PPS-GF/M
Thermal expansion coefficient (10 ⁻⁶ /K)	Flow direction	35	15	19
	Transverse to flow direction	80	51	29

5.2. Evaluation of Thermal Stress

Plastic molded parts formed with metal inserts have thermal stress generated due to differences in thermal expansion when there is a temperature change. To select materials, the thermal strain is evaluated and a comparison is made of fatigue strength characteristics of the materials. With material such as metals showing isotropic thermal expansion behavior, a simple method for evaluating thermal strain is to use a self-temperature compensated strain gauge, compensating for a certain level of apparent strain occurring due to simple thermal expansion. However, with plastic insulation material, there is a large difference in thermal expansion behavior between the plastic flow direction and the direction perpendicular to the flow direction. In the case of plastic with anisotropic filler such as glass fibers, etc., the anisotropy is heightened, making it difficult ordinarily to correct apparent strain due to thermal expansion.

Even in this development project, in order to reduce the difference in thermal expansion with the copper conductor, studies were done on ordinary glass short fiber filler material and of glass filler + mineral filler material, called improved anisotropy material. However, even with the improved anisotropy grade, as shown in Table 1, there is anisotropy in the thermal expansion behavior.

Therefore, in this development project, two bus rings were formed under the same conditions, one being cut and used as a reference for free thermal expansion and the other being used for thermal strain evaluation in the part shape. By measuring them at the same temperature, it was possible to measure the thermal strain while eliminating the thermal expansion effect of the material itself.

The measurement method is shown in Fig. 7.

- A strain gauge is attached to one of the bus rings, and another strain gauge attached to the same area of the other bus ring, which has been cut. With the strain gauge on the cut bus ring as reference, the two-gauge method was used to create a bridge.
- The temperature was changed so that the temperature of the two bus rings became the same and a temperature to

strain (measured strain) diagram was obtained.

- At normal temperature, the completed part bus ring's cut release strain was measured and the temperature to strain diagram was shifted to calibrate, so that it passed through the measurement points, and the temperature to strain graph (calibrated strain) was obtained.

The temperature to strain diagram thus obtained shows the absolute value of thermal strain generated due to thermal expansion differences, at each temperature.

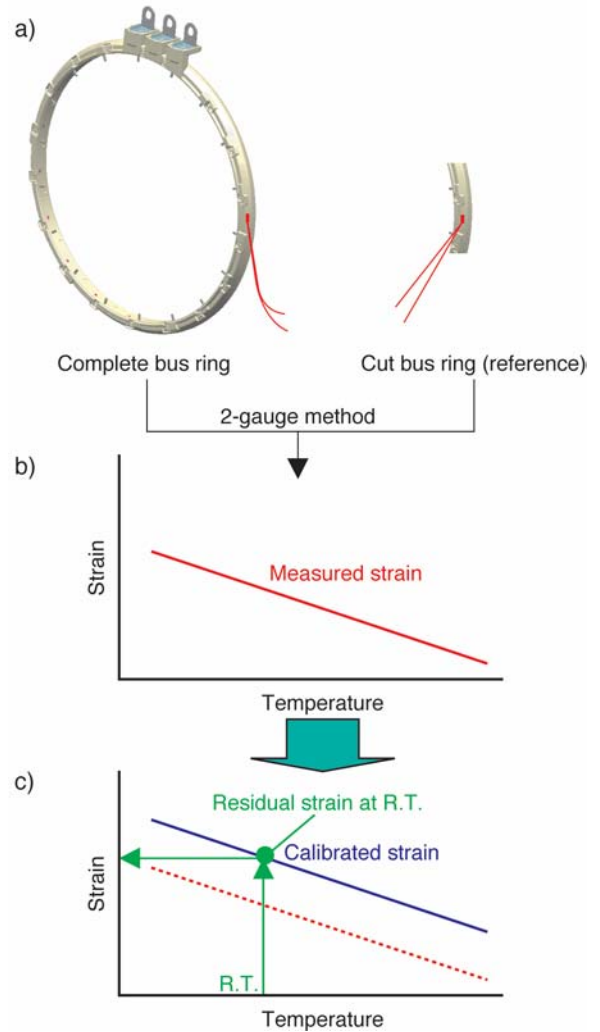


Fig. 7 Thermal strain measurement method

An example of bus ring thermal strain evaluation results obtained in this way is shown in Fig. 8.

Thermal strain occurring in bus rings is predicted from the thermal expansion behavior. It was confirmed that thermal strain is roughly zero near the temperature where plastic flow stops, and as the temperature lowers, it increases in a roughly linear manner. Accordingly, it is thought that bus ring heat cycle life is controlled by fatigue strength on the low temperature side, when thermal strain value is large and plastic elongation after fracture is low.

In addition, making predictions by comparing material thermal expansion rate, compared to the PBT-GF material, the PPS-GF ordinary grade material's thermal strain is approximately 30% smaller and the PPS-GF/M improved anisotropy grade material's thermal strain approximately 40% smaller.

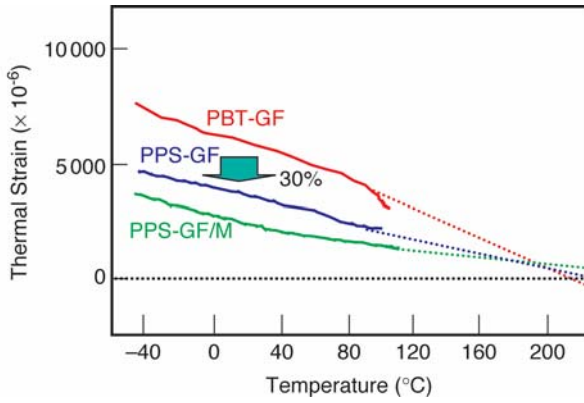


Fig. 8 Temperature dependence of thermal strain

Since this part's guaranteed low temperature limit is -40°C , when selecting material, the bus ring thermal strain amount at -40°C and the fatigue strength at the target cycles established are measured, and comparisons are made.

As shown in Fig. 9, with the PBT-GF material, thermal strain is generated that is roughly equivalent to test piece material strength. Ordinarily, because an actual formed part has forming flaws or imperfections such as weld lines that show lower physical properties than material test piece strength characteristics, the safety ratio of the actual formed part is expected to be less than 1. In contrast, with the PPS-GF ordinary injection molding grade and the PPS-GF/M improved anisotropy grade material, it is predicted that the thermal strain is sufficiently small in comparison with the fatigue strength (strain value), and heat cycle life can sufficiently be maintained.

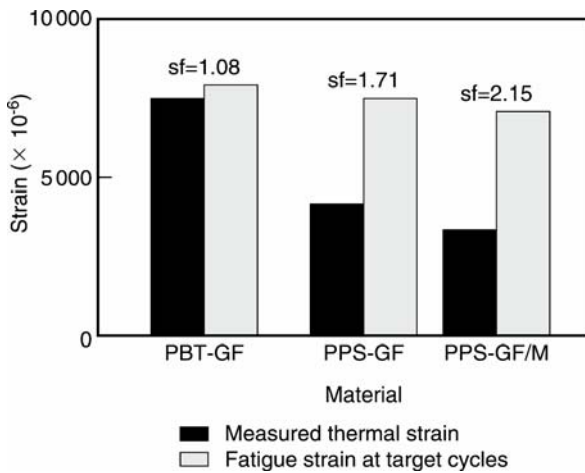


Fig. 9 Thermal strain and fatigue strain

Figure 10 shows the actual heat cycle life of bus rings molded with the various plastics.

The PPS-GF ordinary injection molding grade material and the PPS-GF/M improved anisotropy grade material, which have little thermal strain and a sufficient safety ratio against material strength, were confirmed as having at least three times the heat cycle life of the PBT-GF material, even with actual formed parts.

From these facts it was learned that ordinary PPS-GF injection molding grade material could be applied as molded plastic material.

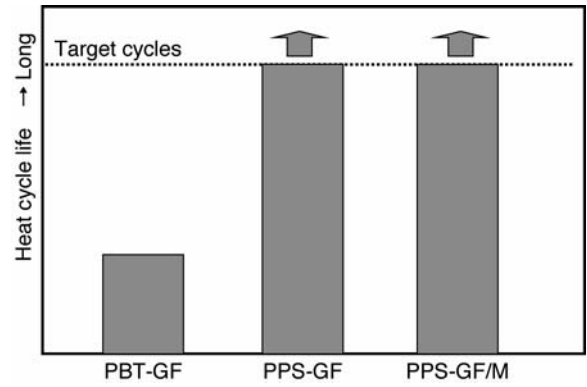


Fig. 10 Heat cycle life of bus ring

6. Insulation Design Technology

In order to achieve both insulation reliability against high voltage and a reduction in part size, insulation design principles were created.

With this structure, as shown in Fig. 11, the following two dielectric breakdown paths can be imagined.

- Dielectric breakdown at interface between 1st and 2nd mold
- Dielectric breakdown in the plastic thickness direction

Concerning these two dielectric breakdown paths, mold tests were carried out, and from the relationship between the insulation distance against the various dielectric breakdown paths and the dielectric breakdown voltage, the required insulation distance was determined.

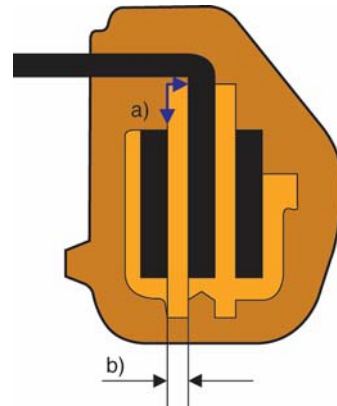


Fig. 11 Insulating distance a)interface, b)bulk

Figure 12 shows the relationship between the plastic material's bulk and surface insulation distance and the dielectric withstanding resistance, for the molded plastics studied.

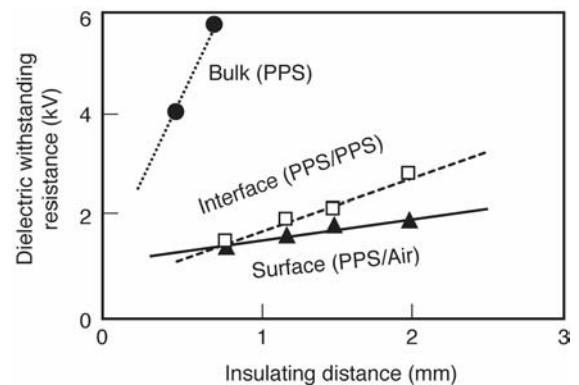


Fig. 12 Dielectric withstanding resistance

Generally, plastic surface resistance is lower than the internal plastic parts, due to the effect of water absorption in the plastic surface and electrostatic concentration on the vapor side⁽¹⁾, caused by differences in dielectric constant. The results of model tests also showed that plastic bulk insulation resistance is much greater than the insulation resistance of the plastic interface and plastic surface. And in terms of insulation design, a key point is to establish the insulation distance against the surface resistance at the interface.

In particular, concerning the insulation guarantee at interface “a)” it is necessary to establish a distance that guarantees insulation even when there is no interface fusion because it is not possible to expect fusion across the entire interface even when using the same plastic.

From these facts, it was learned that the distance between the copper conductors along the interface between the 1st and 2nd molds (creepage distance for insulation), as shown in Fig. 13, is the design value that guarantees insulation.

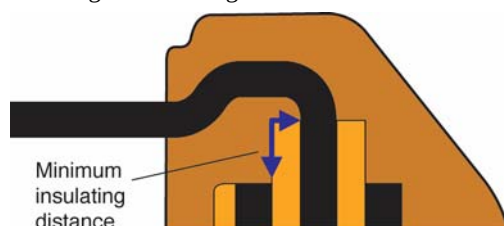


Fig. 13 Minimum insulating distance

7. Plastic Integrated Molding Technology

In this development project, the following principles were applied when making integrated molding of the three conductors.

- (1) Guaranty inter-phase insulation between the conductors in the structure
- (2) No exposure of the interface on the surface for waterproofing performance

In order to actualize these, floating over mold technology was applied, so that the 1st mold guarantees inter-phase insulation and the 2nd mold insulates against the outside and maintains waterproofing performance.

7.1. Overview of Floating Over Mold

Floating over mold is a technology that forms a seamless, multi-layer structure.

- (1) The first mold is inserted into the 2nd molding die and supported by holding pins.
- (2) At an appropriate time during the 2nd mold plastic filling process, the holding pins are removed and the support pin tracks are filled with molding plastic. This gives a plastic molded part without joints.

An overview of the floating over mold process is given in Fig. 14.

Because a high plastic filling pressure (generally 10 – 30 MPa or more) is applied to the 1st mold and the copper conductors during the 2nd mold filling, it is necessary to prevent deformation of or position misalignment of the copper conductor and the 1st mold during 2nd mold forming.

In this development project, in order to support the shapes of the 1st mold and the copper conductors, and to maintain position accuracy in the 2nd mold, the 1st mold is supported by slide pins from above and below, in the direction that divides the 2nd mold die.

The process can roughly be divided into three steps.

- a) The 1st mold and the copper conductors are set into the 2nd mold die, and supported.
- b) Injection of the 2nd mold plastic.
- c) At an appropriate time, the slide pins supporting the 1st mold are removed, and the slide pin tracks are filled with insulation plastic.

7.2. Establishing the Timing for Holding Pin Removal

Figure 15 shows the relationships between degree of cavity plastic filling after the start of filling, holding pin removal timing, copper conductor shift amount, and holding pin removal track weld line actual strength.

If the timing of the 1st mold holding pin sliding is early in comparison with the 2nd mold plastic filling, the 1st mold hold is insufficient and during the 2nd molding the 1st mold and the copper conductors shift due to injection pressure. This gives rise to variation in the 2nd mold thickness and to the mold warp accompanying it.

If the removal is late, there is a drop in temperature and pressure of the plastic that flows to fill the tracks of the pins removed, and this is a cause of filling flaws or imperfections around the pins and of weld line strength drop.

Accordingly, the timing of pin removal must be controlled after a certain level of plastic filling in the cavity and within the range of primary filling pressure.

In this development project, by optimizing the gate position and number of gates, according to CAE flow

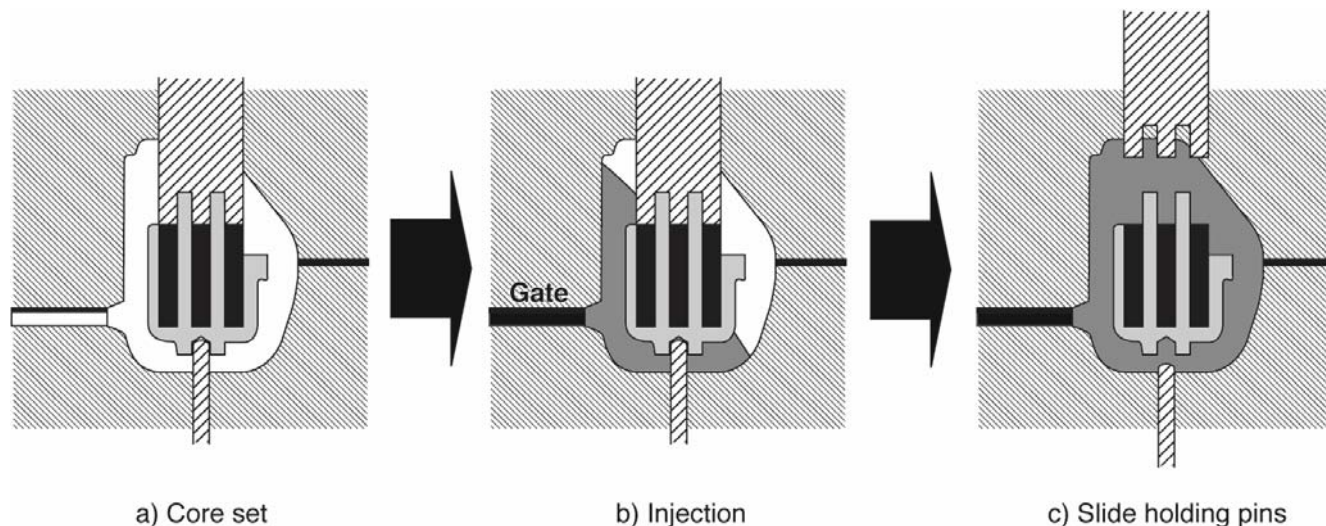


Fig. 14 Seamless injection molding process

analysis, and by establishing the removal timings for upper and lower pins separately, it was possible to simultaneously achieve stability of the 2nd mold thickness distribution and to maintain reliability of the strength of the weld line along the tracks of the pins.

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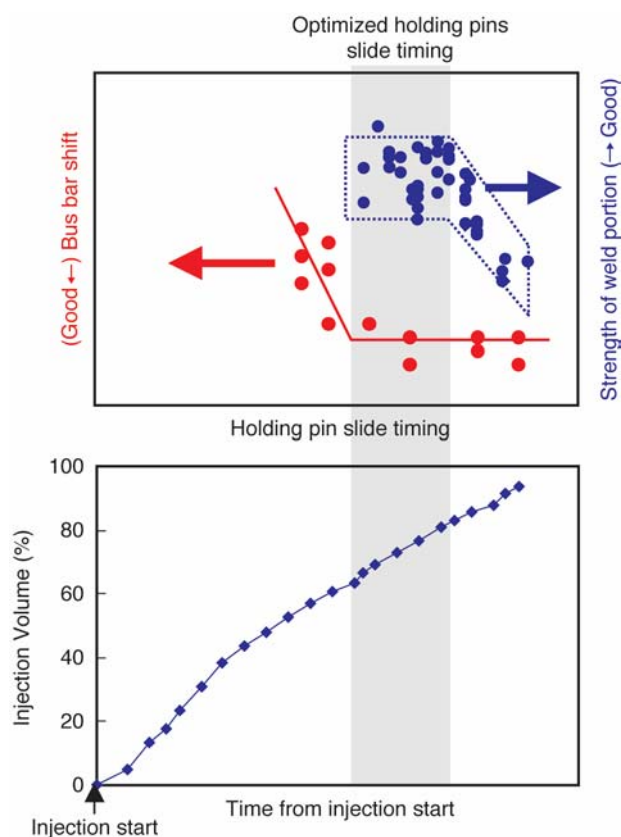


Fig. 15 Holding pin slide timing chart

8. Summary

Bus ring plastic integrated molding technology was developed in order to simultaneously achieve mass productivity advancement and a smaller size of a DC brushless motor.

- (1) It is now possible to select material by evaluating the thermal strain occurring in the plastic molded bus rings and comparing it with material fatigue strength characteristics.
- (2) Design technology for insulation against high voltage was firmly established, maintaining insulation reliability and at the same time achieving a smaller size.
- (3) Through the utilization of float over mold technology and the optimization of holding pin removal timing, it was possible to simultaneously achieve improvement through the integration of multiple parts, to shorten assembly time⁽²⁾, and to maintain waterproofing reliability and strength reliability.

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