Development of a Metal-Core Wiring Board J/B for Vehicles

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ABSTRACT Toyota's Land Cruiser is positioned in the firm as one of the Lexus brands, so that a drastic equipment upgrading was carried out --although it was defined as a minor change-- in the model change the car underwent in August 2002.

With regard to the junction block (hereafter denoted as J/B), the requirement for installation space inevitably became much more stringent due to the dilemma of increased electrical components and in-vehicle livability. To solve this problem, the authors have developed, through realization of high-density components mounting, an innovative J/B with a metal-core wiring board that can be installed in a space equivalent to the conventional. This report describes the development.

It is believed that this development will contribute to solving the problem of installation space that is expected to grow in severity in future.

1. INTRODUCTION

Recently, functions in automobiles tend to be enhanced to upgrade user-friendliness, so that the number of wire harnesses and electric components that support this tendency behind the scenes also increases even more.

On the other hand, car users require a large indoor space and comfortable livability, rendering it even more difficult to secure ample space for installing electric components. Accordingly, in addition to components downsizing, some of the components conventionally installed indoors are going to be transferred into the engine room, making it necessary that these components should be upgraded in terms of low heat generation and/or heat resistance to cope with the harsh environment. Moreover, car manufacturers strongly demand weight reduction aimed at improving fuel consumption as well as reduction in developmental investments and shortening the time for development.

Against this background, we have sought for a new J/B configuration, unlike the conventional busbar J/B or wiring J/B, and have arrived at the solution of a metal-core wiring board J/B. Below will be reported its development.

In the area of J/B for automobiles, there is a technological tendency to replace mechanical relays conventionally used with semiconductor switches, which is aimed at function upgrading together with downsizing and weight reduction. In view of this tendency, the use of wiring board in this development is probably advantageous.

Whereas certain precedents for the installation of wiring boards within engine rooms are known so far, they use a factitiously prepared environment resembling that of indoors. Thus, there are no precedents for the present case where J/Bs are installed directly in the engine room to control, in particular, large electric currents.

2. DEVELOPMENT OF METAL-CORE WIRING BOARD J/B

2.1 Background

J/Bs are generally used to streamline the electric wiring in automobiles. Conventionally, J/Bs are renovated at the time of full model change of a car to accommodate themselves to body form changes and upgrading of equipment specifications. At the time of minor model change, meanwhile, there would be a small-scale upgrading of equipment in a short period of time without changing the body form and J/Bs.

However, it was decided to substantially upgrade the equipment of the Land Cruiser --on which a new J/B was to be installed, although this was a minor change car, in view of customers' needs and trends of rival cars, and thus Toyota presented the following goals for the development of the J/B.

1) Reliability of ranking first in the world
2) Improvement of functionality and scalability in support of large-scaled car electronics
3) Compatibility between accommodation to large-scaled car electronics and ease of production

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Table 1 Comparison between existing and required specifications.

Item	Existing specification	Required specification	Difference
Number of circuits	153	206	+53
Number of fuses	27	32	+5
Number of relays	14	21	+7
Installation space (mm)	L160×W250	L160×W250	±0

A metal-core wiring board J/B was thought to be effective in realizing a J/B with reduced size, weight and development time period, so that in response to car manufacturers' needs, its development program began earlier to differentiate ourselves. The development at this time succeeded this program and accelerated its progress in order to finish ahead of schedule.

2.2 Required Specifications of J/B

Table 1 shows a comparison between the existing and required specifications of J/B.

2.3 Development Goals of J/B

The development goals were established as shown below based on the customer's requirements such as weight reduction, development cost reduction and shortening of development period, together with those shown in Section 2.2.

1) Size: equivalent to that of existing J/B
2) Mass: minus 30 % over the conventional busbar J/B
3) Productivity upgrading
4) Quality upgrading
5) Reduction of mold investment: minus 50 % over busbar J/B
6) Reduction of development time period: minus three months for electrical circuitry over conventional busbar J/B

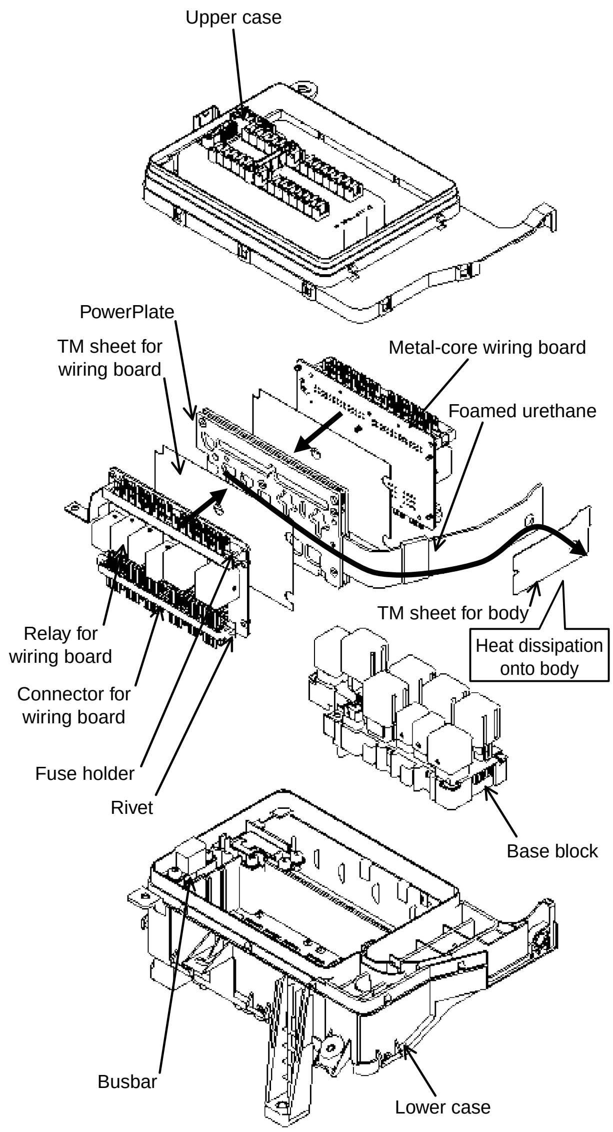

Figure 1 Exploded perspective view of developed product.

2.4 Structure of Metal-Core Wiring Board J/B

Figure 1 shows the exploded perspective view of a metal-core wiring board J/B, excluding the upper and lower covers.

The developed J/B consists of the upper and lower covers, case, base block and a PowerPlate® Assembly --a major component developed this time. The PowerPlate Assembly includes a PowerPlate, i.e., a heat-dissipating plate, on both side of which metal-core wiring boards mounted with relays and the like are assembled using a TM sheet, i.e., a heat-conductive sheet as an intervening layer. The metal-core board efficiently equalizes the heat generated by electric components such as relays; the TM sheet conducts the generated heat to the PowerPlate with a minimal loss and provides electrical insulation as well; and the PowerPlate transports the conducted heat instantaneously to the heat-dissipating side, thereby dissipating the heat to the car body via TM sheets.

In the following Sections, major constituents of the development will be described including the metal-core wiring board, TM sheet, PowerPlate and thermal simulations.

3. METAL-CORE WIRING BOARD

3.1 What is Metal-Core Wiring Board?

Metal-core wiring board is a wiring board with a metal sheet for its core layer. Its general features are heat equalization, mechanical strength and shielding performance, and heat equalization is most remarkable among these.

The schematic structure of a metal-core wiring board is shown in Figure 2.

Ordinary printed circuit boards using glass-epoxy substrates have disadvantages such that, because the circuit pattern layers are insulated by the insulation layer electrically as well as thermally, the heat generated by the mounted components and the circuitry is likely to be concentrated causing temperature rises, and that bulk dissi-

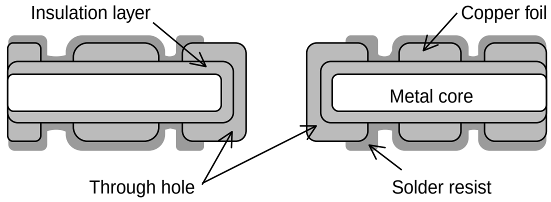

Figure 2 Schematic cross section of metal-core wiring board.

pation of the heat is difficult to be done because the heat sources are diffusely distributed. On the other hand, the metal-core boards can easily be configured to effect bulk dissipation of heat, because the heat generated by the components and circuitry concentrates on the metal core.

Figures 3 and 4 compare the thermal performance of glass-epoxy board and metal-core board. It is seen that the metal-core board can suppress temperature rises better than glass-epoxy board under the same electric current, and that it can suppress local temperature rises as well. Metal-core boards are finding major applications in suppression of temperature rises due to components with large heat generation such as CPUs and power transistors.

Metal-base board is another board known for its heat-equalizing performance. Whereas the structure of a metal-base board is such that layered circuits are laminated on a metal sheet via an insulation layer, mounting of components is limited to one surface only. In contrast, because a metal-core board has a structure such that the circuit patterns on both surfaces of the board are connected using through holes, the board permits components mounting on the both surfaces. In addition, the board permits solder mounting of components having lead wires, thus allowing for a large degree of freedom in circuitry design.

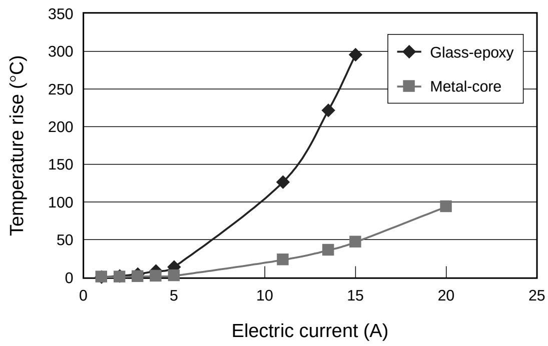

Figure 3 Temperature rise vs. electric current load of metal-core board and glass-epoxy board. Conductor width is 1 mm.

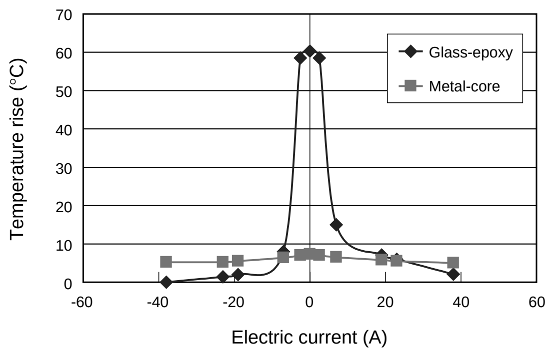

Figure 4 Temperature distributions of metal-core board and glass-epoxy board. Conductor width is 3 mm, electric current is 25 A.

3.2 Application to Wiring in Automobiles

Because the installation space for the J/B is limited, the components had to be mounted in high density, which inevitably resulted in the following requirements:

- Making the circuit pattern finer, leading to downsizing
- Gathering and dissipation of heat

We directed our attention to the heat equalizing property of metal-core board, and adopted the board to satisfy the above mentioned requirements. With respect to the core material, we selected aluminum that weighs about one third of copper for its lightness.

With conventional technology, circuit configuration using a lamination of busbar and insulation would be a solution. What is problematic with this is that the circuit pattern becomes large in size in order to suppress temperature rises in individual circuits, and also to make the over-current resistance satisfactory. In particular, in terms of the over-current resistance, the circuit patterns can not be downsized since the pattern width is subject to the current capacity of upstream fuses even in case of small-current circuits. In addition to the use of heavy copper alloys for the conductor, large circuit patterns result in increased mass, making it difficult to meet the customer's requirement of weight reduction. Moreover, with respect to dissipation of heat generated by the circuitry and mounted components, it is very difficult to gather the heat from distributed places to one place, so that these heat sources have to be dealt with individually.

On the other hand, because its wiring pattern and metal core are thermally connected while they are electrically insulated, the metal-core wiring board enables circuit wiring with a minimized wiring pattern width, so that the J/B can be downsized due to the following reasons:

- Local temperature rises on the circuit pattern can be suppressed because the heat is equalized.
- The heat shock due to overcurrents is absorbed and alleviated by the heat capacity of the metal-core.

However, irrespective of the reduced temperature differences within a board, the board in totality rises in temperature due to such factors as the interaction of heat generated from each circuit pattern and the heat concentration caused by high-density wiring, so that it became necessary to provide some means of heat dissipation. Thus, taking advantage of its heat-gathering and -conducting property, the metal-core board was connected with a PowerPlate, which was subsequently jointed to a heat-dissipating plate on the outside, to dissipate the generated heat to the exterior thereby lowering the overall temperature.

Through these means of weight reduction, we were successful in reducing the mass of the new automotive J/B with heat-dissipating components by 37 % over the conventional busbar J/B.

Figure 5 Conceptual model for connection of metal surfaces with and without using TM sheet.

4. TM SHEET (HEAT-CONDUCTIVE INSULATION SHEET)

4.1 What is TM Sheet?

The TM sheet is a heat-conductive insulation sheet comprised of acrylic rubber including a highly heat-conductive compound. This was an essential material as a heat-dissipating component of the developed J/B, but it was anticipated that the harsh environment in the engine room would degrade the rubber sheet considerably. We were successful, however, in developing the sheet with satisfactory characteristics by optimizing the compound ingredients and their compounding ratio.

Below will be described the main features of a TM sheet.

1) Superior heat-conductivity
   High heat conductivity is achieved due to the use of a compound with high thermal conductivity. Moreover, whereas metal surfaces generally have microscopic irregularities resulting in small effective areas for heat conduction as shown in Figure 5 (a), the TM sheet is flexible enough to absorb irregularities and fill the gap thus suppressing heat resistance as shown in Figure 5 (b).
2) Superior electrical characteristics
   Electrical insulators are also compounded in the TM sheet, so that electrical characteristics such as withstand voltage and insulation performance have been achieved without deteriorating its thermal performance.
3) Excellent workability and adhesiveness
   Since the TM sheet is adhesive in itself, it can be easily fixed on the surface simply by removing the protective film.
4) Siloxane free
   Since the TM sheet uses acrylic rubber, it has no fear of generating low molecular-weight siloxane. Conventional heat-conductive sheets made of silicone materials often cause problems such that low molecular-weight siloxane contained in the material is volatilized at high temperatures. This material adheres to the electrical contacts of relays and switches to produce silicon dioxide --an electrical insulator-- and eventually causes defective electrical contacts.

4.2 TM Sheet on the Wiring Board Side

As illustrated in Figure 1, the heat generated on the wiring board is conducted to the PowerPlate for outside heat dissipation, so that the heat resistance in-between should be as small as possible. Generally speaking, small heat resistance leads to small electrical resistance, making it difficult to assure sufficient electrical characteristics such as withstand voltage and insulation performance between these two parts. If the wiring on the board is electrically connected with the PowerPlate, troubles such as errors in automobile control may arise. Thus, it is necessary to satisfy a basically contradictory requirement of insulating electrically the board from the PowerPlate but simultaneously combining thermally them together.

We have been successful, as mentioned in Section 4.1, in obtaining low thermal resistance while maintaining sufficient electrical characteristics, and applied the technology to the connection of board with PowerPlate.

4.3 TM Sheet on the Car Body Side

The end of the PowerPlate is connected to the car body, which is utilized as a heat radiator. If these are connected directly, since the former is made of aluminum and the latter mild steel, there is a possibility of pitting of the PowerPlate leading to malfunctions due to the contact corrosion between different metals. From the standpoint of thermal performance also, the use of TM sheet is very effective.

However, unlike the wiring board side, the TM sheet on this side is exposed to the exterior when the J/B is shipped, raising concerns about sticking of dust. So, it was decided that the TM sheet to be adhesive on one side only, and that the adhesive surface to be attached on the PowerPlate. Except for this single-sided adhesiveness, the TM sheet on this side has the same characteristics as that for the board side described in the preceding Section.

5. PowerPlate®

5.1 What is PowerPlate?

The PowerPlate has been employed as a device for transporting the heat generated by the components mounted on the board to the outside of the J/B.

The PowerPlate is a heat-dissipating device consisting of a hollow plate of aluminum, in which a small amount of volatile liquid called working fluid is sealed after the space is evacuated of air at an ultra-high vacuum. Just like normal heat-pipes, the device can efficiently transport heat, in the lengthwise direction as well, by the latent heat of the working fluid, which repeatedly vaporizes and condenses as a result of the temperature difference between the evaporator and condenser sections.

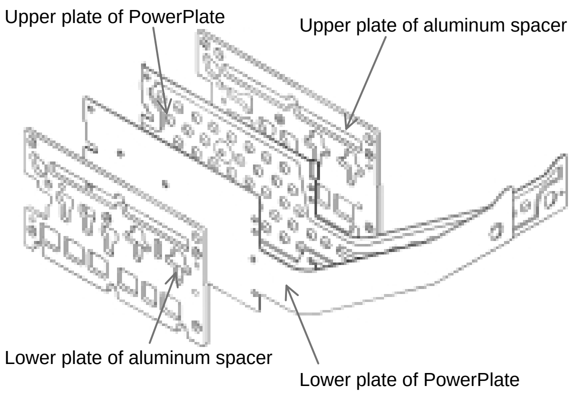

Figure 6 Exploded perspective view of PowerPlate.

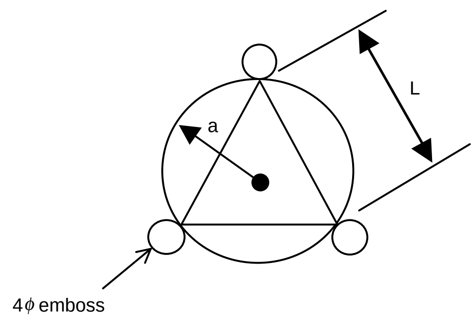

Figure 7 Strength calculation model.

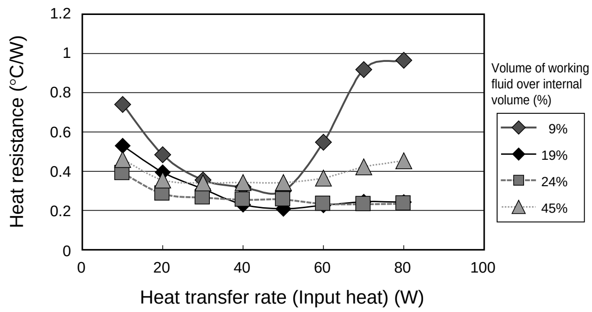

Figure 8 Relationship between heat transfer rate and heat resistance with working fluid volume as a parameter.

5.2 Structure

Figure 6 shows an exploded perspective view of the developed PowerPlate.

The PowerPlate comprises four stamped sheets of aluminum, which are laminated and bonded together by brazing.

The heat-absorbing portion of the PowerPlate is provided with a space to avoid interference with the terminals of board-mounted components having leads, and except for that, the dimensions of the PowerPlate are almost equivalent to those of the wiring board so as to efficiently absorb the heat that is equalized over the board. The heat-emitting portion is designed to closely contact the car body, so that the heat is directly dissipated into the body thus suppressing temperature rises in the J/B.

5.3 Selection of Working Fluid

Furukawa's conventional PowerPlates of aluminum used R123, i.e., a CFC substitute for its working fluid. Since this material belongs to global warming substances, however, we have newly adopted cyclopentane in consideration of environmental concerns. This material raises no global warming problems, while offering sufficient performance as a volatile refrigerant.

5.4 Mechanical Strength

Because the J/B is installed in the engine room of a car, the surface temperature of the metal-core board is expected to reach 140°C maximum in some places under the worst conditions of the scorching sun in the summer. The vapor pressure of cyclopentane is 969 kPa at this temperature of 140°C, while its boiling point is 49°C at atmospheric pressure, so that the PowerPlate has to have a sufficient strength against this inner pressure.

In the strength study, the calculation model shown in Figure 7 was used, i.e., a disk with a fixed perimeter under a load of uniform distribution [1].

When an inner pressure p acts uniformly on this model, the deflection of disk w and the tensile tension σ both become a maximum at the center reaching:

$$w(\max) = pa^4/64d$$
$$\sigma(\max) = 3a^2p/4h^2$$

where, a is the disk radius, d the shape factor, and h the sheet thickness.

Letting the sheet thickness h be 1 mm, w is 0.0096 mm and less --a negligible value-- in the range of a≤8 mm. Thus, considering only the tensile stress σ due to the inner pressure is enough to calculate the load on the disk, and a result of a≤8 mm is obtained based on the yield strength of A3003 aluminum at 140°C, which is 34.8 N/mm^2.

The actual PowerPlate used has a margin of strength over the calculated value mentioned above, since it is reinforced with a 3-mm thick spacer integrally soldered in addition to the peripheral ribs appropriately arranged. Whereas the interval of ribs was set to 7 mm to minimize influence on the thermal performance, it has been confirmed that this structure permits the device to be practically used in the environment up to 160°C.

5.5 Thermal Characteristics

Heat resistance and maximum heat transfer rate are two important factors to represent the thermal characteristics of the PowerPlate. Figure 8 shows their relationship.

The J/B at this time has an input heat of about 20 W generated by the board-mounted components. Against this heat, we have made the channel cross section of the PowerPlate for vapor passage as large as possible and optimized the volume of working fluid, thus achieving a heat transfer rate of 80 W or higher for horizontal installation. For the actual heat transfer rate of 20 W, the heat resistance slightly increases to 0.4 W/°C --a sufficiently low value, thereby proving its ample performance as a heat-dissipating device for a metal-core wiring board J/B.

5.6 Long-Term Reliability

One of the problems with respect to the long-term reliability of PowerPlate is generation of hydrogen gas and ingress of air through microscopic defects. The hydrogen gas and air may act as incondensable gases to hinder the heat transportation of the working fluid based on vaporization and condensation, thereby causing degradation of the thermal performance of PowerPlate.

The hydrogen gas within the PowerPlate is generated mainly by a chemical reaction where the moisture molecules adhered to the inside walls chemically react with aluminum due to thermal activation, as shown below:

$$2(Al)+3(H_2O)=Al_2O_3+3(H_2)$$

To prevent this reaction, the moisture inside the PowerPlate is completely vaporized by high-temperature processing at the time of brazing, and furthermore, the products are stored in a vacuum drying furnace until just before the sealing of working fluid. Thus, the inner surface of PowerPlate is assured to be completely dry.

The ingress of air is often caused by leaks due to the difference between the internal and external pressures, when microscopic defects are present at the welds formed by brazing. Because welding of aluminum is likely to be accompanied by defects, and because it is basically difficult to assure to be free of defects merely through controlling the welding process, leak tests are carried out throughout all the products. The test instrument measures leak volume of the working fluid in a vacuum environment, converts the volume into that of ingress air at normal temperature and pressure, and judgement is done whether or not the thermal performance of the product can be assured for at least 10 years.

6. THERMAL SIMULATION

6.1 Outline

Recent years have seen concentration of heat-generating components on J/Bs, making it essential to incorporate heat dissipation into the structural design. Thus requirement for thermal simulation is increasing day by day. It is required that thermal simulation at the time of structural design can respond to design changes quickly and that the results be accurate enough for practical design objectives. We have conducted thermal simulations of the metal-core wiring board J/B developed here to confirm its design[2].

6.2 Simulation Results

Figure 9 shows the surface temperature distributions of the J/B board obtained by thermal simulation, and Figure 10 shows a comparison between calculated and measured temperatures.

It can be seen that the difference between calculated and measured temperatures are around 3°C. Given this accuracy, it may be concluded that the simulation can accurately predict the thermal performance of products at an early stage of design, enabling provision for countermeasures beforehand, and that this is an effective tool for J/B designs.

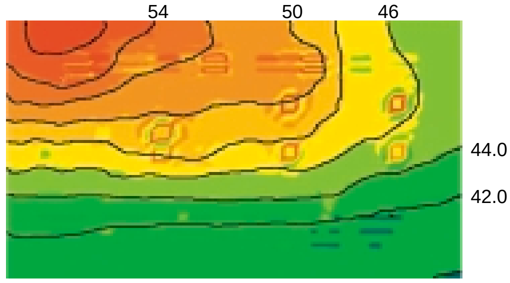

Figure 9 Temperature distributions calculated by simulation.

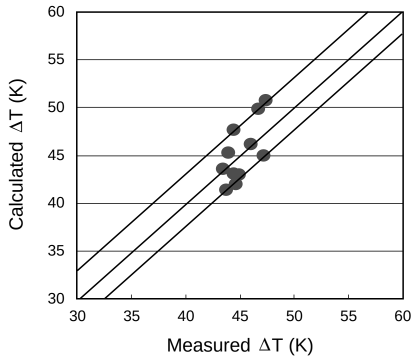

Figure 10 Comparison between calculated and measured temperatures.

7. ACHIEVEMENTS OF METAL-CORE WIRING BOARD J/B

7.1 Features of Developed J/B

The overall features of the metal-core wiring board J/B developed here are summarized as follows:

1) Using aluminum for the core, the weight of the metal-core board has been reduced.
2) With respect to the fuse holder, a slope has been provided to discharge water entering through the opening for mini-fuse insertion, thereby improving leak-current resistance.
3) Taking advantage of ease of wiring on the board, the fuses have been arranged in such a way that the plus and minus potentials do not take adjacent positions at the time of IG-ON and -OFF, thereby improving leak-current resistance against water.
4) Removable rivets have been used to joint the PowerPlate with the wiring board, thereby improving recyclability of PowerPlates made of aluminum.
5) A sliding mount structure has been employed to joint the base block with the lower case, thereby improving ease of components mounting and serviceability.
6) With respect to the relays on the board, only the terminals for plug-in relays have been changed, in order

Table 2 Achievements of metal-core wiring board J/B developed.

Item	Conventional product *1	Developed product	Achievement
Size	(L160×W250) +(L50×W150)	L160×W250	-(L500×W100) (-19%)
Mass *2	100%	63%	-37%
Number of connector joints	12	4	-8 (-67%)
Automated process ratio	70%	90%	+20%
Investment in molds *2	100%	46%	-54%
Development time period	6 month	2.5 month	-3.5 month

*1: Assuming bus-bar structure for the conventional product.
*2: Represented in relative values.

to reduce the time period of development as well as the cost.

7) In an effort to reduce developmental costs, the same size as for the current product has been realized, enabling appropriation of the lower cover of the current product.

7.2 Performance of Developed Product

In terms of leak-current resistance against water, it has been proved at water spray tests that the leak current has been suppressed to one hundredth of the criterion value, so that sufficient long-term reliability has been assured through preventing solder precipitation and fracture of circuit patterns due to leak currents.

Table 2 shows the achievements of the metal-core wiring board J/B developed here with respect to the development goals.

8. CONCLUSION

Whereas the new components used in this development such as metal-core wiring board, PowerPlate and TM sheet are commercially available, they proved to be insufficient to withstand the harsh environments of automobiles and in particular of engine rooms, raising a number of problems. In an effort to solve these problems, the authors put together the wisdom and power of those concerned to improve the product. Thus, it is the authors' greatest pleasure that they could manage to launch this metal-core wiring board J/B into the marketplace.

We plan to further study and solve the remaining tasks of: 1) Compatibility with Pb-free process, 2) Additional downsizing and weight reduction, 3) Cost reduction and 4) Upgrading thermal analysis technology, thereby becoming successful in establishing new technologies that differentiate ourselves from other companies.

Lastly, the authors would like to express their gratitude to those individuals who were of assistance in this development including those in Toyota Motor Corporation, ARACO Corporation and Furukawa Electric.

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