Packaging Technology of 3rd-Generation Power Module for Automotive Applications

GOHARA, Hiromichi*　TAMAI, Yuta*　YAMADA, Takafumi*

ABSTRACT

The development and popularization of hybrid and electric vehicles has been accelerating in recent years. These new vehicles demand miniaturized, light-weight and higher-output power module in order to improve fuel efficiency. Fuji Electric has developed high heat dissipating cooling unit for direct water-cooled structures, an ultrasonic bonding technology for electrodes and copper terminal, and new long-life solder that applies both precipitation strengthening and solid-solution strengthening. By applying these technologies, the 3rd-generation power modules for automotive applications that utilize RC-IGBT dies achieve greater reliability, about 30% smaller footprint and thinner structure compared to the previous generation.

1. Introduction

Recently, advances in energy saving and the tightening of regulations on CO_2 emissions have prompted the automobile industry to accelerate the development and dissemination of hybrid electric vehicles (HEVs) and electric vehicles (EVs). Inverters used for power control in HEVs and EVs are mounted in a limited space and they need to undergo a weight reduction and efficiency improvement for a low fuel consumption. In addition, power modules that accommodate the output of batteries and motors are demanded.

In order to meet these demands, Fuji Electric has been working on technological development for power modules that can achieve a significant improvement in power density. As in-vehicle aluminum direct liquid-cooling power modules, we have developed products improving the power density by over 20% in each generation with the 1st generation in 2012 and 2nd generation in 2015(1). To achieve even higher power density and higher power output, we have employed a reverse-conducting insulated-gate bipolar transistor (RC-IGBT) chip, which integrates an insulated-gate bipolar transistor (IGBT) and free wheeling diode (FWD), in the 3rd-generation aluminum direct liquid-cooling module and successfully realized higher heat dissipation by using cooling fins. This has allowed for a substantial footprint reduction of 30% and made it possible to have thinner devices by optimizing the cooling structure.

This paper describes the packaging technology of the 3rd-generation power module for automotive, specifically the design technologies for a high heat dissipation cooler, ultrasonic bonding and improved solder life expectancy.

2. Design Technology for High Heat Dissipation Cooler

Thermo-fluid analysis technology is used for the design of the direct liquid-cooling structure and we have carried out simulations with the flow of coolant and heat transfer taken into account. We have turned our attention to the dependency of the cooler performance on the coolant flow speed and designed a structure with the focus on how the limited amount of coolant should flow.

2.1 Design accuracy improvement

In thermal design using simulation, the accuracy of analysis is directly linked to the accuracy of the design. Accordingly, we have improved the analysis accuracy by feeding the measurement results of temperature distribution by means of an infrared camera back to the simulation and optimizing the mesh conditions. As a result of product design using an optimization model that uses this improvement effect, we have achieved an error of less than 10% in the thermal resistance between the design values and measurement results and made it possible to design a product by using a simulation.

2.2 Design issues and performance improvement

The coolers of the direct liquid-cooling structure are categorized into 2 types of structures: an open structure with the heat sink and water jacket separated from each other, or a closed structure with the water jacket integrated with heat sink(1)(2). Figure 1 shows a simulation model for evaluating the chip temperature characteristics.

The open structure uses an O-ring and gasket to tightly seal the heat sink and water jacket. For that reason, a clearance must be provided between the fin

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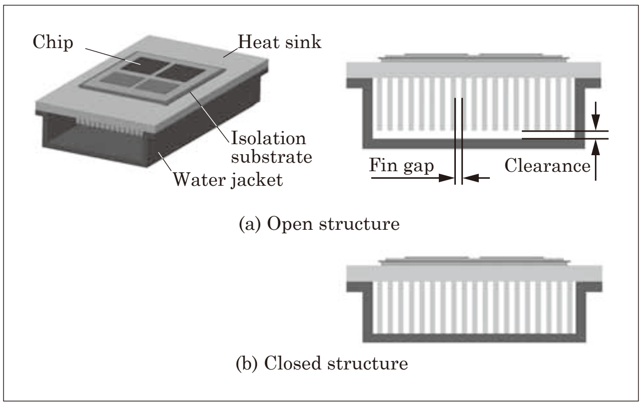
* Corporate R&D Headquarters, Fuji Electric Co., Ltd.



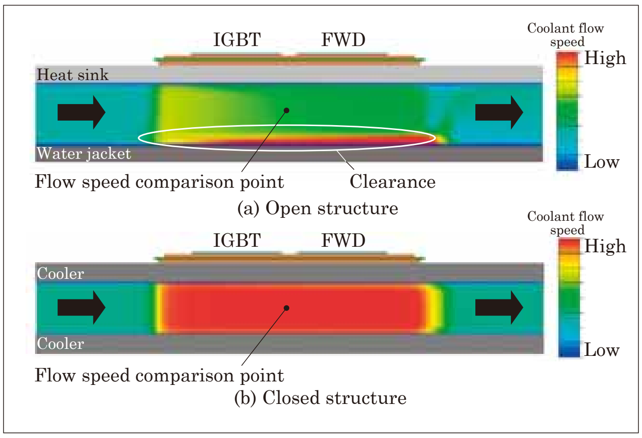
(a) Open structure

(b) Closed structure

Fig.1 Simulation models

ends and water jacket in view of the respective design tolerances and thermal deformations. This clearance increases the cross section of the flow channel through which the coolant flows. When the clearance is larger than the fin gaps, the flow resistance between the fins increases relatively and the flow speed between the fins decrease, resulting in a deteriorated cooling performance. Meanwhile, the closed structure has no clearance as in the open structure due to the water jacket joined with a heat sink.

Figure 2 shows the speed distribution of cross section obtained by thermal fluid simulation. While the open structure has the coolant flowing out to the clearance, in the closed structure, the flow speed distribution is nearly equalized and the flow speed increases by about twice because of no clearance. Figure 3 shows a comparison of the thermal resistance between the open and closed structures. The closed structure exhibits the thermal resistance reduced by 20% because of no clearance and the effect of thinning of the heat sink as compared with the open structure⁽³⁾.



(a) Open structure

(b) Closed structure

Fig.2 Cross-section flow speed distribution

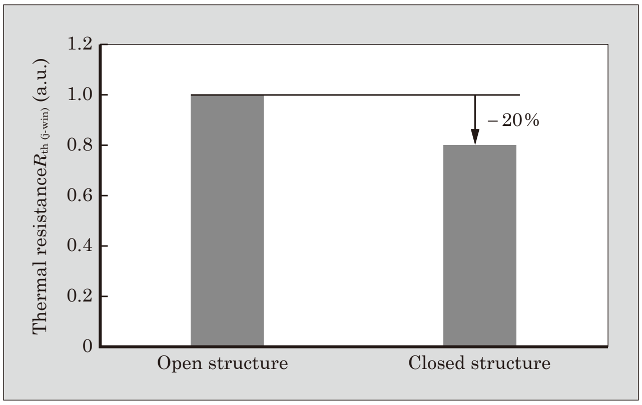


Fig.3 Thermal resistance

3. Design Technology for Ultrasonic Welding

The increase in the current density of automotive power modules requires wiring in the power module to increase the wiring capacity and reduce the space.

Figure 4 shows a comparison between the conventional aluminum wire structure, copper wire structure and copper terminal structure. The copper terminals molded in the terminal case and the copper pattern on the insulated substrate are connected together by wiring. Copper terminal wiring in which ultrasonic bonding is applied to this wiring that carries the principal current has achieved a current capacity approximately 3.5 times as large as that of the conventional aluminum wire structure, leading to a reduction in the footprint.

3.1 Ultrasonic bonding of terminals in power modules

Figure 5 shows overview of ultrasonic bonding. Ultrasonic bonding is solid-phase diffusion bonding that the surface oxide films on the bonding surfaces

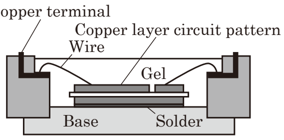
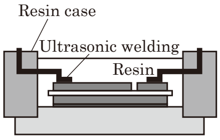
Wiring technology	Aluminum wire bonding	Copper wire bonding	Copper terminal ultrasonic welding
Cross section structure			
External appearance			
Current-carrying capacity	Medium (1.0)	High (1.7)	Very high (3.5)

Fig.4 Wiring structure

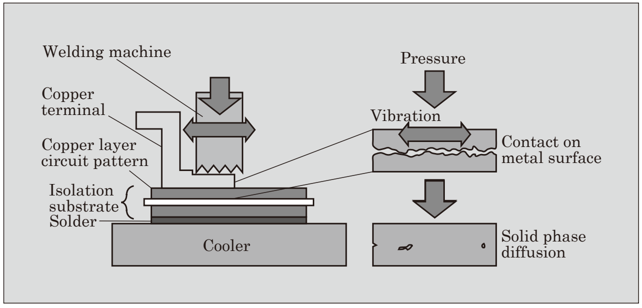


Fig.5 Overview of ultrasonic welding

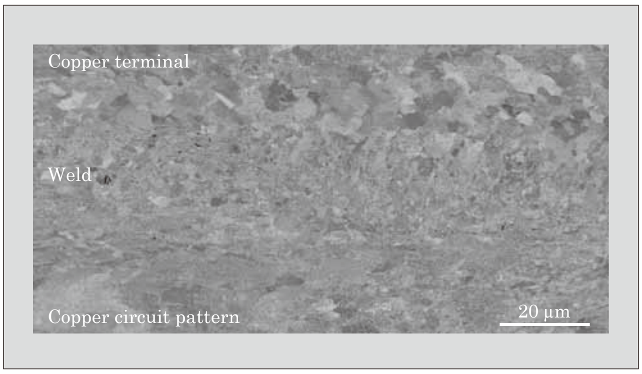


Fig.6 SEM image of cross-section of ultrasonic welding

are broken by ultrasonic vibration and pressure, and metal surfaces are contacted and diffused each other. It allows base materials to be bonded at a temperature lower than the melting point. By using this ultrasonic bonding, copper terminals are directly bonded to the copper circuit pattern on the insulated substrate circuit without any bonding material.

We observed the cross section of a copper terminal, bond and copper circuit pattern to investigate the metallographic structure of ultrasonic bonds with scanning electron microscope (SEM) (see Fig. 6). Ultrasonic bonds have a finer structure (crystal grain size) than that of the copper terminals because of work hardening. The strength depends on the crystal grain size and a smaller grain size tends to exhibit higher strength. Different crystal grain sizes may cause less accurate lifetime predictions. Accordingly, due to the fineness of the crystal grain size of ultrasonic bonds, we used test pieces in the shape of a terminal similar to the actual device to establish a lifetime prediction technology for metal solid-phase diffusion bonds of copper terminals.

3.2 Fatigue testing and study on life expectancy prediction

We built samples for lifetime prediction of ultrasonic welded joint of copper terminals (see Fig. 7) and conducted the cyclic fatigue tests. First, we determined the deformation of the applied product by using full-model thermal-stress analysis to find out the direction of load generated on copper terminals. Under the condition of forced displacement in agreement with this direction of the load, we conducted a stress simulation and fatigue testing by using an element model.

From the result of the stress simulation, we have determined that stress is generated locally on the copper terminal bond interface. In addition, from the result of fatigue testing on the copper terminal, it has been observed that cracks propagate along the bond interface due to the stress generated, causing a fracture at the bond interface. Based on the fact that the origins of the fracture coincide in both the results of simulation and fatigue test, we have used the results to study the method of lifetime prediction.

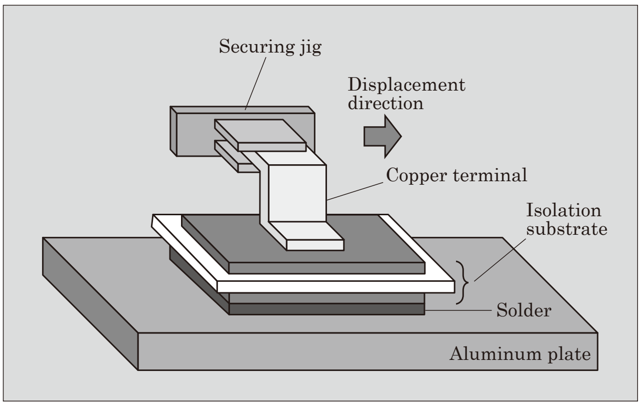


Fig.7 Model to evaluate life expectancy of copper terminals

In fatigue lifetime curves of copper terminals and copper test pieces obtained in this research, the vertical axis indicates the total strain calculated from the stress analysis, and the horizontal axis indicates the number of test repetitions at the time of terminal fracture (see Fig. 8). The copper test pieces are made from an ordinary copper material (C1100, 1/2He) machined into a dumbbell shape. The fatigue lifetime curves of these copper terminals are generally used for lifetime prediction. However, in this case, they cannot be used for the lifetime prediction of ultrasonic-welded copper terminals because the slope of fatigue lifetime curves of the ultrasonic-welded copper terminals and the copper test pieces do not coincide. The reason for the slope difference between the ultrasonic-welded copper terminals and the copper test pieces is assumed that the crystal grain sizes of the ultrasonic-welded interface are different from those of the copper test pieces⁽⁴⁾. Accordingly, we conducted fatigue testing with the actual product to verify the validity of the fatigue lifetime curve of the element model.

Consequently, the result of a lifetime evaluation of the actual product nearly matched with the fatigue lifetime curve of the ultrasonic-welded copper terminal, A fracture mode in which fracture occurs at the bond interface can be replicated by using samples for

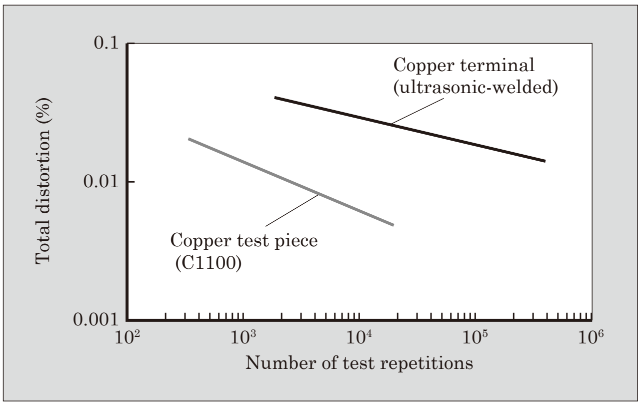


Fig.8 Fatigue life expectancy curves of copper test pieces and copper terminals

copper terminal lifetime evaluation. From these results, it was determined that this methodology can be used to estimate the lifetime evaluation of ultrasonic welded copper terminal.

4. Design Technology for Solder Lifetime

A module can achieve higher power density by increasing the guaranteed operation temperature. Meanwhile, expanding the operation temperature range of a module causes a reduction in the lifetime of the solder under the insulated substrate which is the most likely to fail in the power module. With conventional solders, changes of the physical properties due to thermal aging*1 reduce the strength, leading to a shorter life expectancy. In addition, in solders affected by this thermal aging, the lifetime designs based on the Coffin-Manson Law are difficult to achieve the required accuracy. In order to deal with these issues, we have developed a new solder that suppresses the strength reduction under high-temperature conditions.

A test piece as shown in Fig. 9 was used to conduct a comparative evaluation between the conventional and new solders. As the evaluation results, Fig. 10, Fig. 11 and Fig. 12 show the crack development speeds, SEM images of the solder structure before and after the thermal cycle test and the tensile strength after heating at 175 °C for 1,000 hours.

(1) Conventional solder

With the conventional solder (Sn-Ag solder), the crack propagation speed increases at an accelerated pace as the temperature change ΔT increases in thermal cycling (see Fig. 10). An SEM image of the solder structure shows that, before the test, intermetallic compounds precipitate at the grain boundaries of the Sn matrix and form a network (see Fig. 11). After the test, this network of intermetallic compounds has disappeared, Ag_3Sn phase has precipitated and the Sn matrix has become coarser. Because thermal cycling causes thermal deterioration of the solder structure and it leads to reduce the strength, the crack propagation speed increases as ΔT increases(4).

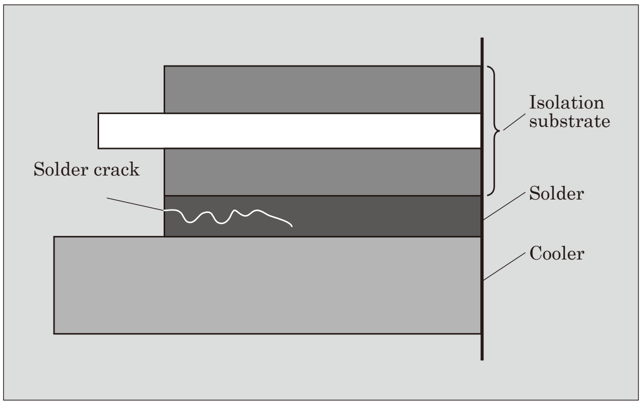


Fig.9 Test piece construction

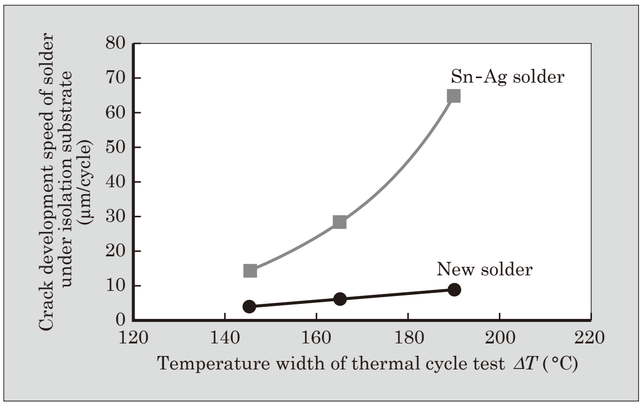
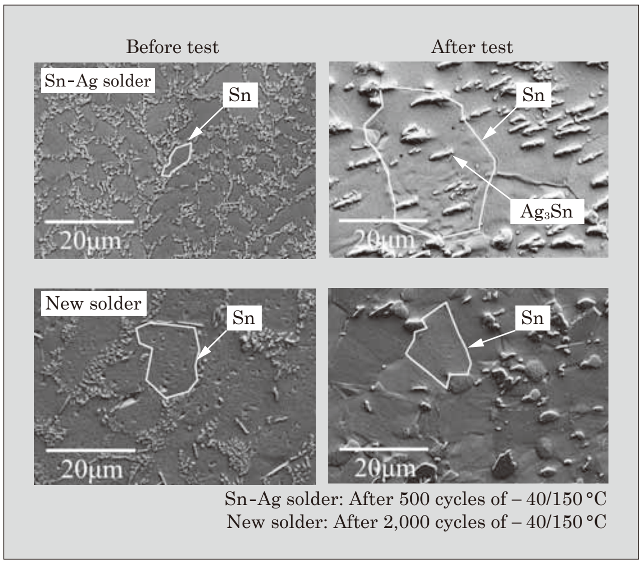


Fig.10 Solder crack development speeds



Sn-Ag solder: After 500 cycles of – 40/150 °C
New solder: After 2,000 cycles of – 40/150 °C

Fig.11 SEM images of solder structures

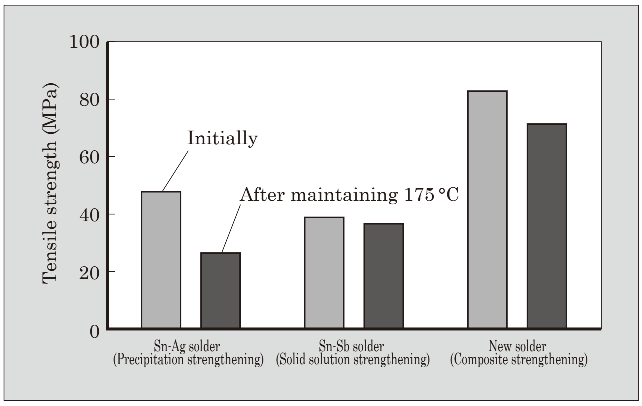


Fig.12 Tensile strengths of solders

(2) New solder

While the Sn matrix of Sn-Ag solder becomes coarser as ΔT increases, with Sn-Sb solder, coarsening of the Sn matrix is suppressed by solid solution of Sb. The new solder is strengthened by conventional precip-

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*1: Aging: Refers to a phenomenon in which metal properties (e.g. hardness) change over time.

itation strengthening in addition to this solid solution strengthening. Therefore, the strength reduction of the new solder under high temperature is less than those of Sn-Ag solder and their high strength is maintained (see Fig. 12).

The crack propagation speed of the new solder exhibits small change as ΔT increases and the increase is not at an accelerated pace but almost linear. For this reason, predict the lifetime prediction technology based on the Coffin-Manson Law can be applied and an improvement of the prediction accuracy and reliability can be achieved at the same time. With the new solder, the crack propagation speed is less than one fifth of that of Sn-Ag solder even if ΔT increases to 190 °C, which allows for a further operating temperature increase (see Fig. 10).

5. Postscript

This paper has described the packaging technology for the 3rd-generation power module for automotive applications. By improving the consistency of the results between the actual device and simulation, highly accurate design technology has been developed. We intend to work on improving elemental technologies and reducing product development periods to take advantage by using this design technology.

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