Residual Stress Distribution and Adhesive Interface Strength Analysis of Thermosetting Resin Molding

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ABSTRACT

The number of products sealed with a thermosetting resin such as semiconductor products has been increasing as the heat resistance and withstand voltage are improved and the size is miniaturized. Currently, structural design for products is being implemented using stress analysis based on CAE analysis in order to ensure reliability in products sealed with a resin. However, this type of analysis cannot predict resin cracks and interfacial peeling between the resin and component materials that cause failure. We have thus established a method for grasping curing behavior of thermosetting resin, a residual stress distribution analysis technology that can be utilized after curing has completed, and an evaluating technology for adhesive interface strength considering the adhering end distance. As a result, we can now construct structural design systems compatible with thermosetting resin sealing, thus enabling us to improve the reliability of products.

1. Introduction

The application of power electronics has been expanding in the motor control field, ranging from a conventional use in industrial equipment and electrical rolling stock to more recently adoption in hybrid vehicles and electric vehicles, as well as the power conversion field in applications for new energy sources such as photovoltaic power generation and wind power generation. As a result, the efficiency of power systems has advanced and the usage environment for these systems has diversified.

On the other hand, the increase in the world's population is expected to greatly increase power consumption from approximately 20 trillion kWh in 2013 to approximately 45 trillion kWh in 2030. In this regard, there is a great need to further reduce power usage and enhance the efficiency of energy usage. Against this background, the development and application of power modules that adopt high-efficiency SiC power semiconductors has been advancing. Power modules mounted with these SiC chips adopt thermosetting resin sealing structure to ensure reliability in various usage environments (see Fig. 1). Power module circuits are configured with various materials in complex shapes, and thermosetting resin is required to embed circuits without gaps and adhere closely to the materials.

However, since the viscosity of thermosetting resin rises as a reaction to heating, non-filling or entrainment of bubbles could occur under improper molding conditions. In addition, the occurrence of resin cracking or interfacial peeling can greatly impact reliability. Therefore, products that are going to be sealed with thermosetting resin require a careful structural design and materials design to ensure reliability.

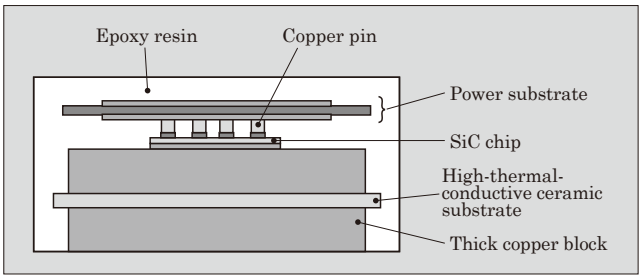

Fig.1 Cross-sectional structure of power module

In order to implement accurate structural design for products to be sealed with thermosetting resin, it is necessary to establish analysis techniques for coupling thermal stress analysis with 3D thermo-fluid analysis, which is used to reflect the curing behavior of resin. This paper describes residual stress distribution and adhesive interface strength evaluation techniques, both of which are required in establishing the coupled analysis technique.

2. Thermosetting Resin

We will describe an epoxy resin used as a sealing agent for power modules as an example of a thermosetting resin. Epoxy resin is a monomer with epoxy group properties in molecular structure. Ring opened polymerization (bridging) of the epoxy group can be done by heating with amine based or acid anhydride based curing agent. As polymerization occurs, molecular weight increases, resulting in a resin that irreversibly changes from a liquid to a gel, and then to a solid.

Many products make use of a structure that is sealed with a thermosetting resin for the following reasons.

(a) Power semiconductors: To ensure a high heat

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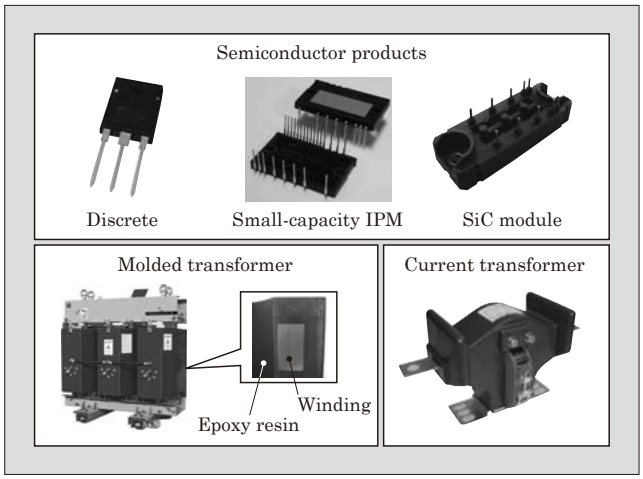


Fig.2 Products that make use of structure sealed with thermosetting resin

resistance and high withstand voltage for mounting Si chips and SiC chips

(b) Power electronics products: To facilitate miniaturization of vehicle mounted inverters and motors and to ensure vibration resistance and exothermicity

(c) Power supplies: To facilitate miniaturization and to ensure insulation compatible with the miniaturization

Figure 2 shows some standard Fuji Electric products that make use of a structure sealed with thermosetting resin.

3. Challenges Surrounding Structural Design of Products Sealed with Thermosetting Resin

Common molding methods for thermosetting resin include transfer molding, liquid injection molding utilizing a liquid resin, and cast molding. The molding process common to each of them is filling of specified mold via a flow of resin, and thereafter curing the resin through heating to create a mold of a specified shape. It is required that each of these molding processing have optimized molding conditions that correspond with the selected thermosetting resin. It is very important to grasp behavioral changes during the process of heating.

We will now give a description of an evaluation technique for the curing behavior and adhesive interface strength of thermosetting resin, both of which must be considered when carrying out the structural design of a product. As an example, we will take a look at epoxy resin, which is mainly used as a sealing agent for power semiconductors.

3.1 Curing behavior of thermosetting resin during the molding process

Figure 3 shows the time-lapse changes in the viscosity of the epoxy resin produced in a constant temperature. The epoxy resin gradually cures as heat

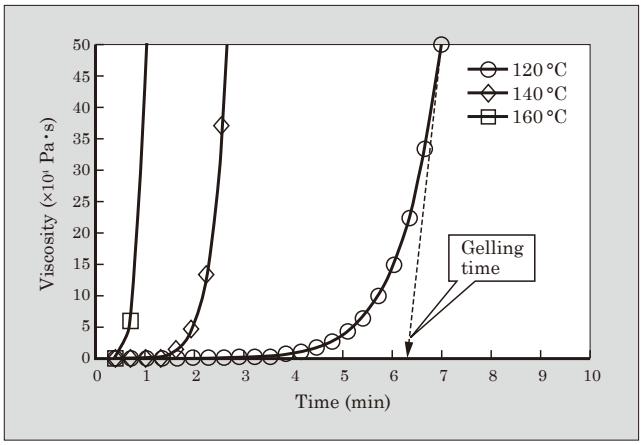


Fig.3 Time-lapse changes in viscosity of epoxy resin at constant temperature

is applied, and its viscosity rapidly increases after a certain period of time. As shown in the figure, the time extrapolated from the slope at the time of viscosity increase is referred to as gelling time, used as an indicator of curing time. Furthermore, the time up to the point when the resin reaches a viscosity limit for being able to fill the mold is the workable time at such temperature. Since temperature increase shortens the gelling time, it is necessary to optimize the resin filling process conditions in consideration of the relationship between temperature and workable time.

Moreover, volume contracts due to molecular polymerization during epoxy resin curing (see Fig. 4). During curing, a heating distribution occurs for the resin depending on the structure (shape) of the molding materials and heating method. Speed differences in the curing reaction of the epoxy resin caused by the heating distribution result in volume contraction differences in the resin. As a result, it is generally recognized that a residual stress distribution occurs for the epoxy resin.

The volume contraction that occurs when the viscosity change due to heating and during the change from a liquid to a solid is a key behavior that should be considered in the thermosetting resin molding process,

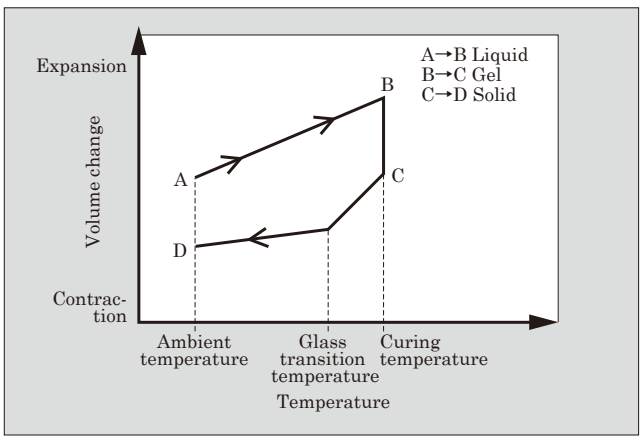


Fig.4 Behavior at time of epoxy resin curing

including that for epoxy resin.

3.2 Conventional structural design method and adhesive interface strength evaluation method

Conventional structural design for semiconductor modules use the state after resin curing as a model to perform computer aided engineering (CAE) analysis. Therefore, design has been made via a simple treatment of thermosetting resin curing behavior, such as by treating the physical properties of cured objects as elastic bodies.

Furthermore, the design of the adhesive interface strength must be done to make sure that no interfacial peeling occurs for between the structural materials and the resin of the molded product; and as such design is implemented based on the adhesive interface strength obtained from a lap-joint test piece[*1].

As a result, since it is not possible to accurately estimate adhesive interface strength without considering the behavior of the resin during molding, it is not possible to predict whether peeling will occur in the structural design process. Therefore, it is necessary to repeat testing to ensure reliability.

3.3 Structural design issues

The main defects that occur in products with regard to thermosetting resin are resin cracking and interfacial peeling between the resin and structural materials. Structural design requires selecting materials and determining the structure that prevents generation of these defects. In order to achieve this, it is necessary to be able to estimate the mechanical stress during actual operating time and assess whether it is no higher than the peeling threshold, after first accurately grasping the residual stress distribution associated with the curing behavior and curing contraction for the resin.

Therefore, some of the challenges of structural design include incorporating the analysis results of the residual stress distribution associated with resin curing, as well as establishing an evaluation technique for adhesive interface strength.

4. Residual Stress Distribution Analysis

It is difficult to directly measure or observe the residual stress distribution in the cured resin. In general, a strain gauge is mounted to measure strain, and residual stress is evaluated by converting the measurement results to stress. However, the strain gauge is only for measuring the location at which it is mounted, and it becomes necessary to secure the plane for the mounting. Therefore, in order to grasp the residual stress distribution, we implemented visualization of the residual stress distribution via CAE analysis using 3D thermo-fluid analysis software[*2] (FLOW-3D[*3]).

The 3D thermo-fluid analysis software makes use of a Macosko model by utilizing test values such as material properties of the resin including density, elastic modulus, and dependence on viscosity temperature and shear rate, to express viscosity as a function of the temperature, shear rate and curing reaction rate (see Fig. 5). Furthermore, a KAMAL model is also used to express the reaction speed by utilizing test values such as the reaction speed, reaction heat and energy associated with the curing reaction of the resin (see Fig. 6). The use of these 2 models makes it possible to express the irreversible change that occurs to the resin as it changes states from a liquid to a solid; and even for products that have a complex shape, it is possible to implement visualization by calculating the residual stress distribution from the heat distribution.

Figure 7 shows the analysis results of a stress distribution in resin by changing temperature states from the resin curing temperature to ambient temperature after sealing a thick copper plate with the resin. This is a comparison between the 3D thermo-fluid analysis and a conventional stress analysis, i.e., a 3D finite element method structural analysis that only takes into consideration the linear expansion coefficients

The most precise viscosity model for expressing viscosity as a function of temperature, shear rate and reaction rate

$$\eta = \eta' \left(\frac{\alpha_{gel}}{\alpha_{gel} - \alpha} \right)^{D+E\alpha}$$

$$\eta' = \frac{\eta_0}{\left[1 + \left(\frac{\eta_0 \gamma}{\tau^*} \right)^{1-n} \right]}$$

$$\eta_0 = F \cdot \exp\left(\frac{G}{T} \right)$$

η: Viscosity (Pa · s)
η': Temperature and shear rate dependent viscosity (Pa · s)
α_{gel}: Reaction rate at gelling time (viscosity parameter)
α: Reaction rate
τ^*, D, E, F, G: Resin inherent constants (viscosity parameters)
η_0: Viscosity at shear rate of zero (Pa · s)
γ: Shear rate (s^{-1})
n: Structural viscosity index
T: Resin temperature (K)

Viscosity parameters	α_{gel}	τ^*	D	E	F	G
Unit	–	Pa	–	–	Pa · s	K

Fig.5 Macosko model

*1: A lap-joint test piece refers to a simple laminated test piece for which an adhered laminated component is sealed with thermosetting resin.

*2: Three-dimensional thermo-fluid analysis software is a general-purpose 3D computational fluid dynamics (CFD) software for solving abnormal flow utilizing the control volume based finite difference method (FDM).

*3: FLOW-3D is a trademark or registered trademark of Flow Science, Inc. in the U.S. and other countries.

Model capable of being applied to a multi reaction patterns as a reaction speed model

$$\frac{d\alpha}{dt} = (K_1 + K_2 \cdot \alpha^M)(1-\alpha)^N$$

$$K_1 = K_a \cdot \exp\left(-\frac{E_a}{T}\right)$$

$$K_2 = K_b \cdot \exp\left(-\frac{E_b}{T}\right)$$

$$\alpha = \frac{Q}{Q_0}$$

$$\frac{dQ}{dt} = Q_0(K_1 + K_2 \cdot \alpha^M)(1-\alpha)^N$$

$\frac{d\alpha}{dt}$: Reaction speed (s^{-1})

α: Reaction rate

t: Time (s)

K_1, K_2: Coefficients of temperature functions

M, N, K_a, E_a, K_b, E_b: Material inherent coefficients (reaction speed parameters)

T: Resin temperature (K)

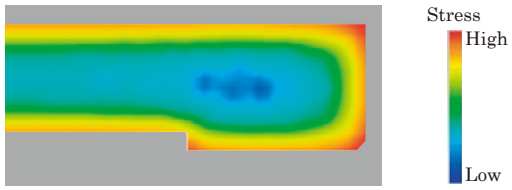
Q: Calorific value until arbitrary time (J/kg)

Q_0: Total calorific value until reaction completion (reaction speed parameter)

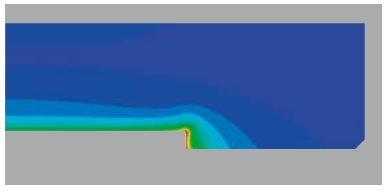
$\frac{dQ}{dt}$: Heat-generation speed (J/kg · s)

Reaction speed parameters	η	N	K_a	E_a	K_b	E_b	Q_0
Unit	–	–	s^{-1}	K	s^{-1}	K	J/kg

Fig.6 KAMAL model



(a) Stress distribution determined by 3D thermo-fluid analysis



(b) Stress distribution determined by 3D finite element method structural analysis

Fig.7 Analysis results of the stress distribution in resin during curing

and elastic modulus of the resin. Conventional stress analysis is characterized in that some of the different components of the linear expansion coefficients (interface between resin and thick copper plate) have areas of high stress. In addition, the stress distribution of other components of the resin cannot be observed. On the other hand, when using 3D thermo-fluid analysis, the heat distribution based on the thermal conductivity showed us that there are areas of higher stress in the outside periphery of the resin than within the resin. In the residual stress distribution after resin curing, the difference with 3D finite element method structural analysis is apparent. Furthermore, aside from this, we compared the analysis and test with regard to the resin contraction distribution and amount of interfacial strain between the resin and thick copper plate, and confirmed that the results of the 3D thermo-fluid analysis were appropriate.

5. Establishing an Adhesive Interface Strength Evaluation Technique

We examined adhesive interface strength by taking measurements using the lap-joint test piece and by implementing a CAE analysis.

To begin with, we carried out a test that changed the lap length from the standard length of 10 mm to a shorter length of 2 mm in order to investigate dependence for the lap length of the adhesive interface strength (breaking load / adhesive area). The results are shown in Fig. 8. Since it is assumed that adhesive interface strength does not depend on adhesive area (lap width × lap length), breaking load should be proportional to the lap length. However, in actuality, breaking load was a constant, almost entirely independent of lap length. This result leads us to surmise that adhesive interface strength might be determined by a certain component not dependent on lap length.

Next, we used a semi-symmetric model of the lap-joint test piece to implement CAE analysis, which produced the stress distribution shown in Fig. 9 when applying a load at the time of breaking. We learned that a large amount of stress is concentrated on adhesive ends with a width of 1 mm or less, and that even long lap lengths do not contribute much to the breaking load, while only the number of low-stress central areas increases. It is thought that the stress concentration contributes to a mixed strength combining both shearing force and tensile force. Therefore, we compared the von Mises stress[*4] obtained from the CAE analysis and the adhesive interface strength obtained from the test

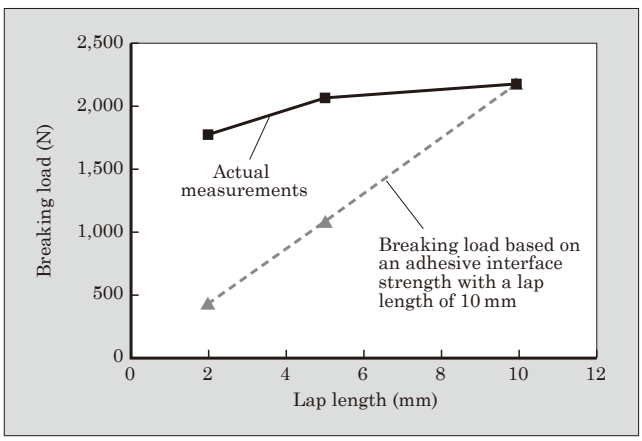


Fig.8 Dependence on breaking load lap length

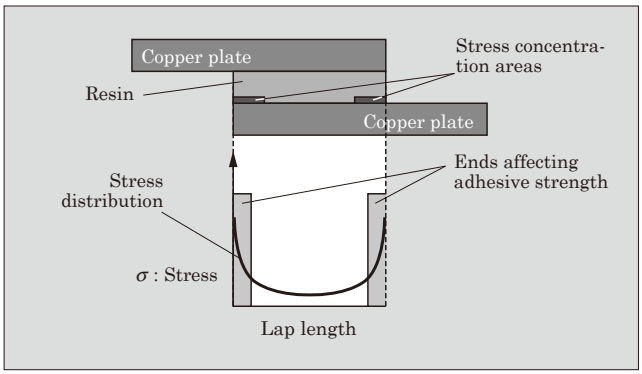


Fig.9 Stress distribution of lap-joint test piece adhesive areas

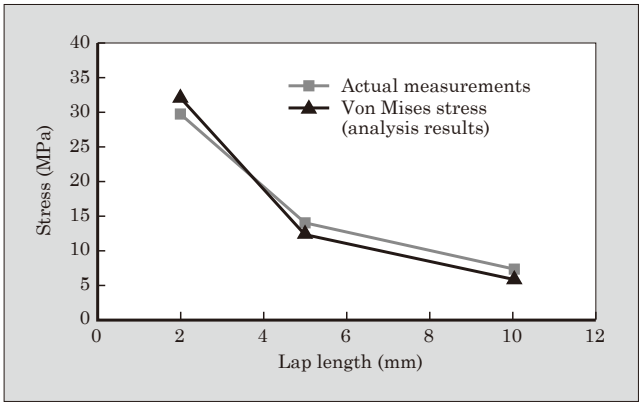


Fig.10 Evaluation results of adhesive interface strength under changed lap length

*4: Von Mises stress is the equivalent stress based on shear strain energy theory. When this stress exceeds yield stress, plastic deformation will occur. Von Mises stress was advocated by scientist Richard von Mises in the 1990s.

and learned that they matched up very well (see Fig. 10). As a result, the adhesive interface strength that causes interfacial peeling product defects can now be estimated using CAE analysis.

6. Future Tasks

Since it is important to grasp actual resin behavior when sealing with thermosetting resin, we developed a technique using 3D thermo-fluid analysis for better grasping residual stress distributions. In addition, we established an evaluation technique to investigate adhesive interface strength, which acts as a determination value for resin peeling.

In the future, we plan to continue developing thermal stress analysis tools that take into consideration residual stress, while expanding our database on the physical properties of thermosetting resin and the adhesive interface strength of thermosetting resin with various structural components.

7. Postscript

In this paper, we described the residual stress distribution and adhesive interface strength analysis of thermosetting resin molded products. As product structures become more complex with the progress of new product developments, series expansions and equipment miniaturization, an increasing number of products are requiring sealing with thermosetting resin. Through the construction of a structural design system compatible with thermosetting resin sealing, we will contribute to improving the timely supply and reliability of products such as semiconductor products.

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