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Analysis on Thermal-Force Coupling Performance of a Vehicle IGBT Packaging Module

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Abstract. Based on the basic theory of thermodynamics and finite element, the thermal characteristics and structural mechanics simulation are carried out taking an automobile IGBT packaging module as the research object. Then the distribution of temperature, thermal stress and deformation of IGBT are obtained. The thermal force coupling performance of the structure is judged according to the analysis results, so as to provide theoretical reference for the design and selection of subsequent radiators.

1.Introduction

IGBT (insulated gate bipolar transformer) is characterized by fast switching speed, high input impedance, low saturation voltage and short reverse recovery time. At present, the function of power electronic IGBT packaging module is more obvious in the national economy, which is widely used in rail transit, electric vehicles, home appliances frequency conversion and other fields. IGBT modules have made great progress in performance, process, power density and reliability with the increasing market demand for IGBT modules. But with the increase of power density, the failure of IGBT modules is increasingly obvious. Therefore, it is of great significance to study the heat transfer law inside the IGBT packaging module to improve the performance and reliability of the module. In the process of product design and development, the finite element analysis method is introduced to simulate the thermal mechanical coupling performance, which can improve the thermal performance and reliability of the product, achieve the reasonable layout of the structure, and provide theoretical reference for design engineers.

Based on the basic structure and working principle of IGBT, the structure is simplified and the threedimensional thermal analysis model is established. The distribution of temperature, thermal stress and deformation is simulated and analyzed with the basic theory of thermodynamics and finite element. Thus, the thermal-force coupling performance of the structure is judged according to the analysis results. It can provide theoretical reference for the optimization of structure and the design and selection of subsequent radiators.

2. Thermal characteristic analysis of IGBT

Thermal analysis is an important means to evaluate the quality of thermal design. The analysis of IGBT thermal characteristics is to establish a mathematical model based on the simplification of the model according to the actual situation of the project, obtain the thermal performance through analysis and calculation, and determine the thermal problems existing in the IGBT according to the analysis results, so as to take measures in time and reduce the maximum junction temperature of the structure.

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2.1 basic theory of thermal analysis

The heat transfer mode is very complex during the IGBT working. It includes the heat conduction inside the device, the convection heat transfer between the device surface and air, and the radiation heat transfer of the heat source. The heat flow is transferred from the high temperature to the low temperature ^[1-6].

2.1.1heat conduction. When there is direct contact between objects, because of the density difference caused by the temperature gradient, the heat energy is directly transferred from the high temperature to the low temperature in the form of atomic vibration, forming natural convection. The basic law of heat conduction is shown in equation (1).

$$\delta c = -\lambda \frac{\partial t}{\partial x} A \tag{1}$$

In which, $\emptyset c$ is the heat flow, and λ is the thermal conductivity, and $\frac{\partial t}{\partial x}$ is the temperature change rate in x direction, and A is the cross-section area in the direction of heat conduction. Minus sign means the direction of heat transfer is opposite to that of temperature gradient.

It can be seen from formula (1) that in order to increase the ability of heat conduction and accelerate the heat emission, the heat conduction material with high λ can be used in the structural design to increase the cross-section area in the direction of heat conduction and reduce the heat conduction path.

2.1.2 heat convection. Heat convection is the transfer of heat energy between objects by using the thermal expansion and contraction of fluids and the characteristics of fluid flow. Thermal convection is caused by the temperature difference between solid surfaces. It is shown in equation (2).

$$\phi_D = h_C A \ (t_W - t_S) \tag{2}$$

In which, h_c is the convective heat transfer coefficient, and A is the convective heat exchange area, and t_W is the hot surface temperature, and t_s is the cooling fluid temperature.

It can be seen from equation (2) that in order to enhance the intensity of heat convection, the coefficient of convective heat transfer and the area of convective heat transfer can be increased appropriately. Heat conduction and convection exist in the whole process of convective heat transfer.

2.1.3 thermal radiation. The radiation caused by temperature is called thermal radiation, which is also an electromagnetic wave of electromagnetic radiation. Unlike heat conduction and heat convection, the heat transfer form of radiation is not completely dependent on the contact between objects.

2.2 IGBT temperature field analysis

2.2.1 structural simplification. The structure analyzed in this paper is a motor controller for pure electric vehicles, with a peripheral dimension of 139mm * 72mm * 30mm. There are three pairs of IGBT in the structure, as shown in Figure 1. The outside of the module is surrounded by resin shell and embedded with terminals, electrodes and resin inserts. IGBT chip and continuous current diode are embedded in the module and welded on the DCB lining board. The chips are interconnected by silver wire.



Figure 1. IGBT structure diagram

In the structure, the chip is welded on the DCB liner. The DCB liner is welded on the bottom copper plate. And the heat is released from the chip, passes through a series of conductive layers, dielectric

layers and solder layers, and finally passes to the copper plate. The solid model of IGBT packaging module is a six-layer structure, from top to bottom are chip, chip welding layer, liner copper layer, liner plate, liner welding layer and substrate.

In the process of building the simulation geometry model, the following assumptions are made. First, the liner and the copper layer of the liner are simplified into regular figures. Second, the heat transfer of the chip connecting line is smaller than that of the whole module, so the module ignores the connecting line. Third, in the work of IGBT module, the heat transfer mode mainly includes the heat conduction of the chip heating. Therefore, the thermal resistance model is established according to the distribution of IGBT and diode chip. The simplified model is shown in Figure 2.



Figure 2. simplified 3D simulation model of IGBT module

2.2.2 structural discretization. Because the convective heat transfer between the structures and the air needs to be considered in the analysis, the solid element modeling can more truly reflect the state of the IGBT module and get more accurate results.

In view of the structural characteristics and the analysis requirements of the three-dimensional heat transfer process, the mapping grid division is adopted in the structural discretization process. The hexahedron element with high simulation accuracy is obtained, which can effectively avoid the problem of too sparse and too dense grid division. The mesh division of the solid model is shown in Figure 3.



Figure 3. finite element analysis grid model of IGBT module

2.2.3 material properties. Material property is an important input parameter in the analysis of structural thermal characteristics. In the thermal-force coupling analysis, six parameters are mainly used, which are elastic modulus, Poisson's ratio, density, thermal expansion coefficient, thermal conductivity and specific heat capacity. In this paper, the material characteristic parameters of IGBT are obtained by referring to material performance manual and experiment in combination with practical engineering application, as shown in Table 1.

Table 1. material characteristic parameters of IGBT module									
material	density (tmm ⁻³)	elastic modulus (Nmm ⁻²)	Poisson	specific heat conductivity (Wm ⁻¹ K ⁻¹)	specific heat (Jkg ⁻¹ K ⁻¹)	thermal expansion coefficient (K ⁻¹)			
SiC	7.8e-009	210000	0.3	129	500	1.1e-005			
Chip bonding layer	7.4e-009	24000	0.36	64	220	2.67e-005			
Liner copper layer	8.94e-009	103000	0.33	398	385	1.75e-005			
Lining board	3.8e-009	390000	0.35	25	880	7.7e-006			

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Liner welding layer	7.4e-009	24000	0.36	64	220	2.67e-005
Copper substrate	8.94e-009	103000	0.33	398	385	1.75e-005

2.2.4 temperature field simulation. The following assumptions are made during applying boundary conditions. First, there are no defects including impurities and cavities in the welding layer. And the solder is evenly distributed. Second, the heat generated by the chip depends on the control mode and circuit parameters of the circuit. A specific heat value is applied as a uniform volume heat source. Third, equal heat convection coefficient applied to IGBT module substrate is equivalent to the heat dissipation effect.

Therefore, according to the steady-state characteristics of IGBT module, the average chip power consumption is selected as the load to be applied in the IGBT finite element model.

The total loss of IGBT module includes the loss of IGBT and the loss of diode, which also includes the on-state loss and the switching loss.

The loss values of IGBT module are calculated as follows.

$$P_{\text{cond}} = \int_0^{1/2} V_{\text{CE}} (t) \times i(t) \times \tau(t) d_t$$
(3)

$$P_{SW} = f_{SW} \times \frac{1}{T} \int_0^{1/2} (E_{on} + E_{off}) (t, I)d_t$$
(4)
$$P = P_{cond} + P_{SW}$$
(5)

In which, P_{cond} is the on-state loss, P_{SW} is the switching loss, P is the total loss, i (t) is the sinusoidal output current, V_{CE} (t) is the Voltage drop of IGBT under conduction, τ (t) is the Duty Ratio of inverter bridge output.

According to the severe service conditions of the whole vehicle, the ambient temperature is set to 60°C without radiation heat exchange. According to the relevant parameters given by the manufacturer, the loss of each IGBT under rated working condition is obtained. The total loss of IBGT module is calculated to be 662.4w, which is applied in the analysis model as a heat source. The substrate is in contact with the atmosphere, which is set as the state of natural convection. The temperature field simulation results of the finite element analysis are shown in Figure 4.



Figure 4. temperature distribution cloud chart of IGBT module

It can be seen that the internal temperature distribution of IGBT module is not uniform when working in steady state, and the temperature difference is quite large. The surface temperature of the chip on both sides is relatively low, and the surface temperature of the chip in the middle is relatively high. There is a coupling phenomenon of the heat source, which makes the distribution of the temperature field more complex than that of the heat source. The maximum junction temperature of IBGT module is 93.4°C, and the minimum temperature is 63.3° C. The temperature difference Δ T is 30.1° C.

The highest temperature position of other materials such as liner and substrate is directly below the highest temperature position of the chip. It indicates that the heat generated by IGBT chip is transferred to the substrate through the welding layer and liner one by one.

3. Thermal stress and deformation analysis of IGBT

Due to the different materials of each layer of IGBT module, its thermodynamic behavior is also different. The degree of expansion or contraction of each other is different during heated or cooled. At

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the same time, from the above temperature field analysis, the temperature of each part of the structure is different. Each part is affected by the adjacent parts of different temperature. So, it can't expand freely, resulting in the generation of thermal stress. In order to improve the service life and reliability of the structure, it is necessary to carry out thermal stress analysis^[7-9].

IGBT thermal stress analysis adopts indirect coupling method. It means that the temperature results of thermal analysis are indirectly coupled to the mechanical structure, and the results of temperature field are used as the load of mechanical analysis.

In the analysis of IGBT thermal stress and deformation, the element type of the structure is transformed first. At the same time, in order to match the simulation results with the actual situation, the displacement constraint is applied at the four mounting holes of the bottom copper plate. The resulting stress and displacement distributions are shown in Figure 5 and Figure 6.



(a) the front structure (b) the back structure Figure 5. cloud chart of thermal stress distribution of IGBT module



Figure 6. cloud chart of thermal deformation distribution of IGBT module

From the results of thermal stress analysis, the maximum stress of the chip is about 70MPa. There is a relative stress concentration at the welding point of DCB plate and copper base plate. The maximum stress is about 200MPa which is near the welding and fixed position area of copper base plate and DCB concentrated. The maximum stress at the welding point with DCB is about 450MPa, which is exceeded the yield strength limit of the material.

From the distribution cloud chart of thermal deformation distribution, it can be seen that the structure has obvious out of plane displacement, showing a warped state. The thermal deformation in the middle position is the largest, which maximum displacement is 0.22mm.

The regions with stress concentration and large thermal deformation are most prone to creep and fracture, which leads to IGBT module failure and structural reliability reduction. Therefore, when considering the heat dissipation effect, mechanical strength and stress distribution, the requirements of heat dissipation and thermal stress distribution should be considered to select the best base and radiator.

4.Conclusion

In this paper, the IGBT module of a certain automobile is taken as the research object. Firstly, according to the conductive mechanism and basic structure of IGBT, a three-dimensional thermal model is established. The structure is simplified and discretized. The temperature field distribution of IGBT module under the influence of heating elements is simulated and analyzed. On this basis, the heat produced by uneven temperature distribution and different thermal properties of structural materials is analyzed. Based on this, the thermal-force coupling performance is obtained. The results show that

without the external heat dissipation device, the temperature rise effect of the device is obvious, and there is a local stress concentration phenomenon, and the maximum stress has exceeded the yield strength limit of the material. Therefore, it is necessary to improve the internal structure of the device, and to select appropriate external heat dissipation equipment to reduce the working temperature of IGBT and the resulting thermal stress, in order to improve the thermal performance of the structure.

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References

- [1] Wu Tianhua, Wang Xiaomo, Xu Guoliang. (2011) Engineering Heat Transfer [M]. Huazhong University of science and Technology Press, Wuhan.
- [2] Gong Guoyou. Thermal design principle of electronic products and calculation of heat dissipation area. Journal of Chengdu Electronic Machinery College,2009 (2): 9-12.
- [3] Yang Xiangmu. Modeling and Simulation of Low-power IGBT Under the Condition of Natural Air Cooling. Journal of Zhaoqing University,2013(3):33-36.
- [4] Sun Haifeng, Wang Yanan. IGBT Thermal Model Simulation Based on Finite Element Method. Electric Power Science and Engineering,2019(6):15-22.
- [5] Zhang Jian, Lu Changzhi, Zhang Xiaoling, Xie Xuesong, Huang Yueqiang. Thermal Simulation and Analysis of IGBT Based on ANSYS. Microelectronics, 2011(2):139-142.
- [6] Suhir, E. Thermal Stress Failures in Electronics and Photonics: Physics, Modeling, Prevention. Journal of Thermal Stresses, 2013(6): 536-563.
- [7] Jiang Bingsong, Tang Longgu. Research on the Effect of Stress on IGBT Electrical Characteristics and the Source of Stress. High Power Converter Technology, 2015(2): 67-70.
- [8] BAHMAN A S, MA K, BLAABJE R G F. Thermal impedance model of high power IGBT modules considering heat coupling effects. 2014 International Power Electronics and Application Conference and Exposition. IEEE, 2014.
- [9] Zhai Chao, Guo Qing, Sheng Kuang. Research of Thermal Stress in IGBT Module. Journal of Mechanical & Electrical Engineering, 2013(9): 1153-1158.