Deformation analysis of press-pack IGBT using thermal mechanical coupling method

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ABSTRACT Press-pack Insulated Gate Bipolar Transistors (PP IGBT) are becoming increasingly used in HVDC and FACT applications. Due to its unique packaging, its reliability issues have also attracted increasing attention in the engineering field. More comprehensive investigation into the thermal, electrical and mechanical factors should be conducted to reveal the operation condition and status of the devices. The objective of this work is to study the relationship among the deformation of the collector groove and the thermal stress of the chip as well as the contact pressure by simulating the PP IGBT under normal and abnormal conditions. A sophisticated 3D finite element (FE) model of a PP IGBT has been developed which includes the coupling with thermal-mechanical effect. Also, the influence of different pressure and thermal stress on deformation is discussed thoroughly that can provide insight of how to monitor the status of a PP IGBT from the perspective of deformation.

Keywords: Press-pack IGBT, thermal-mechanical, deformation, 3D FE model, reliability.

1. Introduction

IGBTs have been a popular high-power solution in recent years, and they are also well suited to high-reliability applications, like for example in high-voltage direct current (HVDC) applications [1,2]. Compared with traditional packaged IGBTs, press-pack (PP) IGBTs are outstanding in terms of capacity and reliability, which has also become the ideal choice for high power traction drive and wind generation [3,4]. However, the structure of a PP IGBT is much more complicated compared to the classical solder-based packaged module and produces therefore other potential issues for the system reliable operation. The two potential failure modes are: the gate-oxide damage and the micro eroding between the die and molybdenum plate [5]. In particular, the uneven pressure and internal thermal stress distribution can cause a catastrophic failure that results in system shutdown [6].

At present, two bondless structures of press pack technologies are commercially available on the market. One is the spring-type crimping technology from ABB which can balance the pressure unevenness to a certain extent [7], but the short-circuit failure mode (SCFM) can only be maintained for a short time. More research focused on the other type of press pack technology. The other type of structure is the hard-crimping technology which is mostly applied in HVDC and wind power applications. Manufacturers are Toshiba and Westcode [8] to name a few. The majority of the published research on PP IGBT devices is mainly focused on analyzing the changes of physical parameters of the devices using simulation analysis. For example [9] investigates the operation under a thermal cycle using finite element modelling (FEM) but did not consider the impact of the clamping fixtures. To study the performance of PP IGBT with clamping fixture, a 3D FEM simulation is conducted to investigate the clamping conditions of the static thermal scatter of the chips [10]. Also an investigation has been carried out to reveal the relationship between the clamping force and the electrical contact resistance and thermal contact resistance [11]. The results show that the pressure distribution is significantly affected by the clamping force. In [12] a CFD simulation of PP IGBT is conducted using a unique coolant channel design to reduce temperature spread [12]. Another research work proposed the influence of the pressure between the molybdenum plate and silicon chip stating that low and high pressure can cause severe damage [13] concluding that the clamping force is an important parameter which affects the PP IGBT reliability. In [14] a comparison of different sensors have been investigated to measure defomation of the PP IGBT . The plasma-extraction transit-time (PETT) method has been proposed in [15] to detect the temperature of the chip inside the PP IGBT.

In this paper, the finite element (FE) method is applied to determine the thermal stress and deformation strain in press-pack IGBT. A real size-based model is established with the physical condition including the thermal and mechanical parameters. The simulation results are analyzed and discussed in detail according to different operating conditions. The findings reveal a relationship between the deformation of the collector lid groove, the chip's thermal distribution, and the clamping force. The heat difference on the chip is caused by the uneven pressure distribution, which ultimately affects the pressure dispersed on the lid. The lid gradually deforms as a result of this. The goal of this research is to show how different clamping forces and different types of thermal distribution affect the deformation of the groove, which can further demonstrate how to determine the device's condition by sensing deformation.

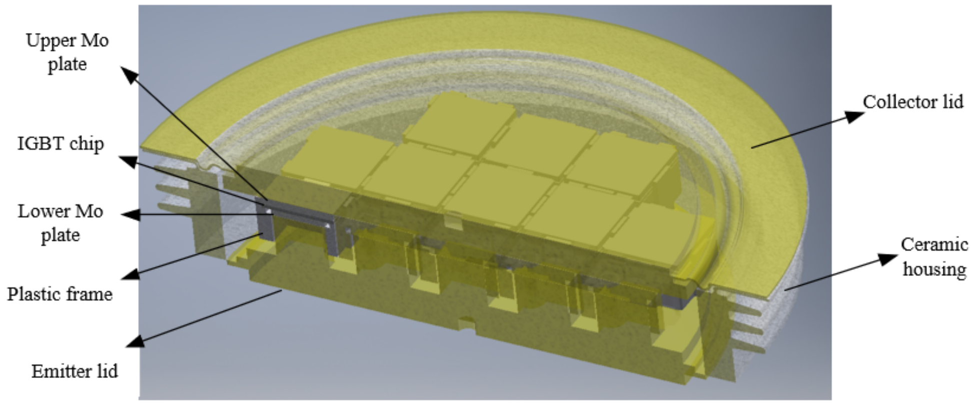


Fig. 1. Cross-section schematic of press-pack IGBT

2. Modeling

2.1 Press pack IGBT characteristics

In this research, a 4500V-800A multi-chip press pack IGBT is used as a case study. The cross-section view of the module schematic is shown in Fig. 1, where the structure can be determined as 6 layers, the collector and emitter pole which are made of copper, upper and lower molybdenum plates with the silicon chip in the middle and a thin silver layer underneath the lower molybdenum plates. The function of soft silver foil is to ensure the uniformity of pressure distribution and electrical contact to the maximum extent. The collector and emitter copper lid have a positioning hole in the center to connect with the heatsink to prevent the relative position of the heatsink and the module from being misaligned. The gate distribution board is connected to the IGBT chip via a spring-loaded pin and the entire structure is laid in a sealed capsule. Clamping force is applied to achieve the thermal and electrical contact within the PP IGBTs, the flatness of all the components is crucial since the high requirement of the even contact pressure distribution.

2.2 FE model development

In order to reduce the computational burden as much as possible while ensuring the accuracy of the simulation, the model considers the relationship between the deformation of the collector groove and the internal chip thermal stress as well as the mechanical stress of the fixture. The internal sub-module plastic frame and gate distribution board and the gate pin of the PPI are removed, because for the analysis of deformation, it is an acceptable approximation to model only the chip, the Mo plate, and the copper electrode in contact with the longitudinal rigid surface, thereby further reducing the calculation workload significantly. Fig. 2 shows the 3D model that remove the components mentioned above with the multi-zone meshing which balance the results and computation speed at the same time. In the simulation, all elements of PPI are stacked layers of materials with uniform, isotropic and elastoplastic mechanical response, and have isotropic flow rules.

In the simulation process, the physical properties of the material are the key parameters for establishing the model. A summary of the material properties of all components of the model is presented in Table 1. The FE model is simulated with the static thermal and structure platform. The calculation of the two processes all assumes the friction model which affected most by the surface roughness and the different material combination, and the friction coefficient 0.5 is used for all calculations.

To analyze the relationship between deformation and the static strain of thermal and mechanical, the thermal generated by the power consumption of the internal chip and the pressure exerted by the external fixture are used as two key variables to produce deformation. In this work, the constraints of the simulation are listed as follows. The device is assumed to operate in a normally on state, and the average current injected into the chip is used as the source of thermal strain. At the same time, a convective heat transfer coefficient is set between the outside of the device and the heat sink and the outer edge of the heat sink is maintained at room temperature. In addition, the pressure applied by the external clamping fixture is set on the top of the collector heatsink and kept uniform while setting a fixed support on the bottom of the emitter heatsink.

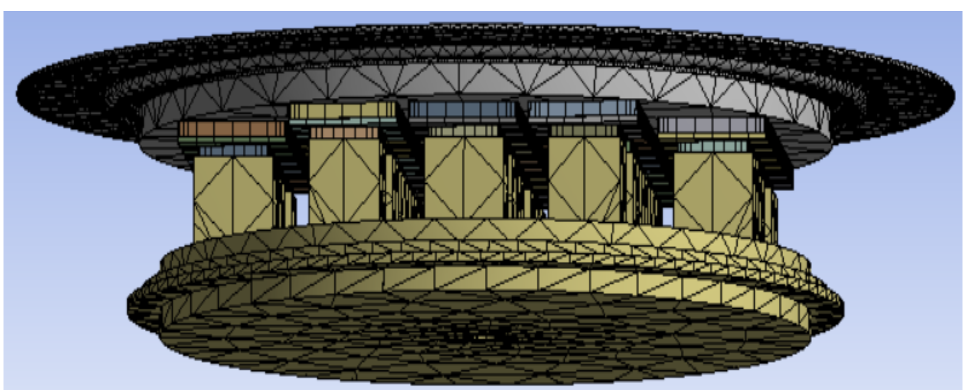


Fig. 2. 3D FE model of PPI with multi-zone mesh

Table 1. Mechanical properties used in the FE model

Material	Young's module (GPa)	Possion's ratio	Material density (kg/m^3)	Coefficient of thermal conductivity [W/(m*K)]	Coefficient of thermal expansion α (1/°C)
Silicon	162	0.23	2330	148	4.8E-6
Molybdenum	320	0.28	10220	130	4.9E-06
Copper	129	0.34	8933	385	1.71E-05

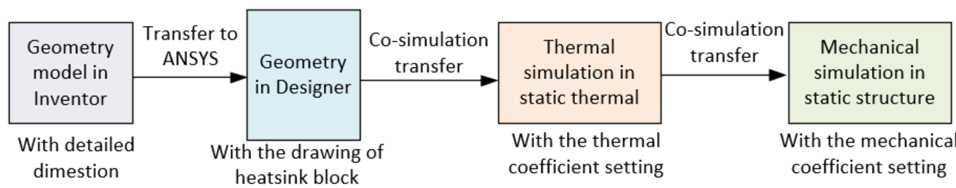
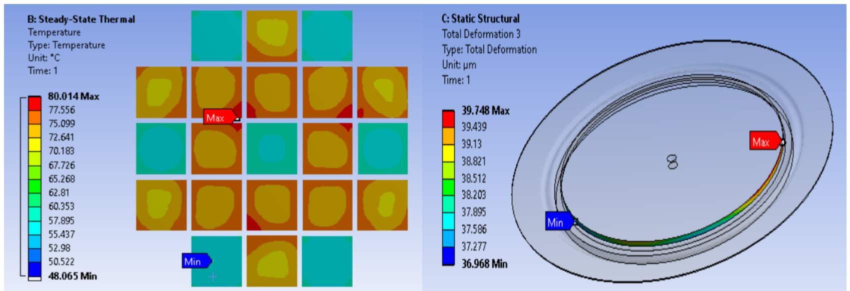


Fig. 3. Simulation flowchart: modeling, thermal analysis and mechanical analysis

3. Result and discussion

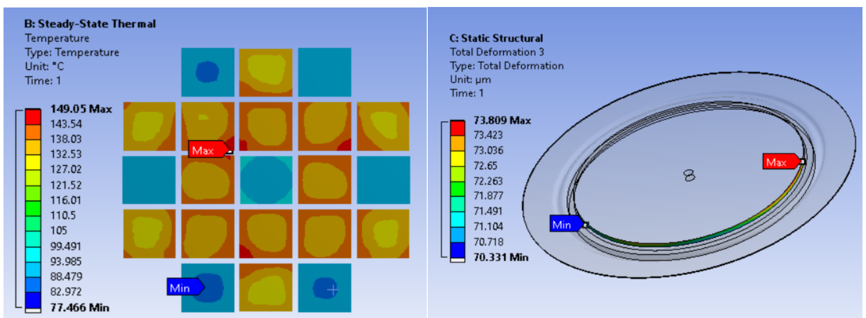
3.1 Press-pack simulation varying power density

In the simulation, the relationship between the deformation of the collector groove and the internal thermal stress and external pressure is mainly selected and analyzed. Fig 3 shows the basic simulation procedure in modeling and thermal, mechanical analysis. The 3D geometry model is developed in Inventor with the detailed dimension, then the model is transferred to Ansys platform. The heatsink block is built in the Designer of the Ansys, after that, the static thermal software is used for the thermal analysis, all the thermal material property are set in this step. The final step is the deformation analysis by using the static structure, the mechanical property and multizone mesh are used for finding the deformation results. Setting different boundary conditions on the influence of heat stress and pressure on deformation is investigated under the assumption that the module structure and material properties are consistent. First, according to the characteristics of the steady-state operation of the module, when the module is working at the rated current, the on-state loss is distributed to the 14 IGBT chips and 7 diodes, in this work the uniform load applied to the IGBT chip is 600pw/ um3 and to the diode chip 200 pw/ um3 (1/3 of rated current). With a rated force of 30KN applied on the top heatsink, Fig. 4 and Fig. 5 present the deformation distribution and the thermal distribution of the chip layout based on different power dissipation. From the simulation result of Fig. 4, it can be seen that the



(a) (b)

Fig. 4. (a)Temperature distribution across chip surface and (b) deformation against lid groove at 80°C



(a) (b)

Fig. 5. (a)Temperature distribution across chip surface and (b) deformation against lid groove at 149°C

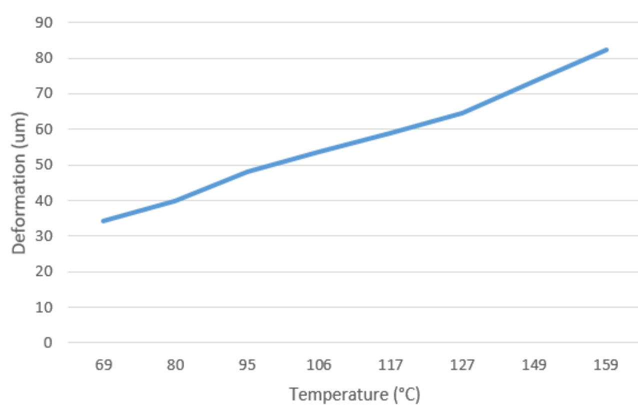


Fig. 6. Relationship between the temperature and deformation

highest chip temperature is 80°C when the module reaches to the thermal steady state, and the temperature of the outer ring for the IGBT chips is higher than the internal ring for the IGBT chips. The deformation on the groove is more consistent along the direction perpendicular to the tangent plane because the internal pressure and thermal stress are more uniform. This represents the reflection of the deformation of the device under the rated current and pressure in a healthy state.

In order to study the relationship between deformation and thermal stress in a healthy and evenly distributed state, the simulation has been conducted by keeping the external clamping force constant and changing the power consumption of the chip. Fig. 6 shows the relationship between the temperature and deformation caused by the variation of the power consumption. It is evident that as the power consumption increases, the chip temperature rises accordingly, as a result, the deformation of the groove is increased linearly with a constant gradient overall. Since the deformation is mainly caused by the accumulation of heat and the external clamping force. (1) reflects the process of calculating the temperature from the accumulation of power consumption, where ρ stands the density, k, Cp and Q are the thermal conductivity, the specific heat capacity, and the heat flux, respectively. T is the temperature function containing the position x and time t. (2) shows the process of deformation caused by thermal stress where ε is strain, which is the function of the temperature T. Equation (3) express the basic total deformation composition.

$$C_p \rho \frac{\partial}{\partial t} T(x,t) - k\Delta T(x,t) = Q \tag{1}$$

$$\varepsilon = \alpha \Delta T \tag{2}$$

$$UU_{total} = \sqrt{{U_x}^2 + {U_y}^2 + {U_z}^2} \tag{3}$$

3.2 Press-pack simulation varying clamping force

To further investigate the relationship between the deformation and the clamping force, a varying clamping force has been applied to the developed PP IGBT model. Fig. 7 shows how the deformation changes as the clamping force are increased. This is accomplished by maintaining a consistent power dissipation. When the clamping force is increased from 5 to 40 KN, it is obvious that the overall deformation of the groove, which is represented by the blue curve, reduces, but this is not substantial. The red line which shows the deformation of the lid along the X axis, is practically stable with a small rise.

When compared to the results of altering the power density in the chip, it is evident that when all other parameters are normal, power dissipation has a bigger impact on deformation than pressure. However, this is based on the assumption that everything is in perfect contact, so that heat can be transferred effectively even if the pressure is insufficient. In reality if the pressure is too low or too high, the uneven pressure on each chip will result in an uneven current and the chip will fail. The chip's contact thermal resistance and electrical resistance change over time, causing some chips to overheat and short-circuit.

Therefore, it is necessary to analyze the relationship between deformation and internal thermal stress and external pressure in this extreme case by establishing a model of overheating of a certain chip.

3.3 Press-pack simulation with one chip failed

In this section, a 3D model containing a failed chip is established to undertake the analysis. From Figs. 4 and 5, it was shown that the chip with the highest temperature is concentrated in the upper left part in a healthy state of normal operation, so this chip is selected as an overheated chip for modeling. The findings of the deformation distribution and the thermal distribution of the chip arrangement are shown in Fig. 8.

This result is based on applying the higher power dissipation on this specific chip while keeping the power dissipation on the rest IGBT chips uniform as well as applying the diodes with uniform load. The figure clearly shows the position of the overheated chip. Besides, it can be seen that the deformation of the groove at the position of the overheated chip exceeds other parts, which indicates that the position and size of the deformation can be used to determine the status of the module when there is a fault on the chip. To further explore the influence of the overheated chip on the deformation, the result of Fig. 9 is obtained by adjusting the power loss. When the power loss continues to rise, not only the deformation of the groove closest to the overheated chip, but also the deformation of adjacent components, increases significantly. The temperature of the remaining chips rises due to the thermal coupling of the internal chip, which causes the temperature of the collector lid to rise as well.

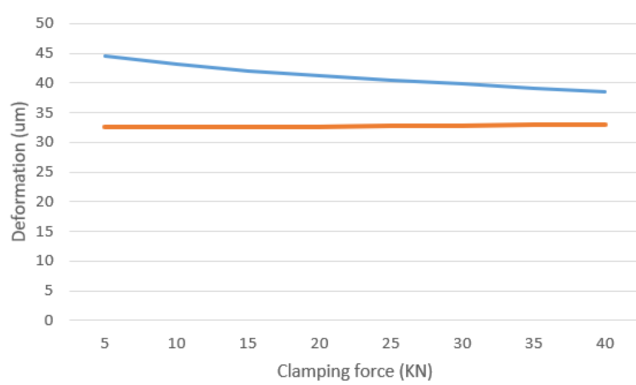
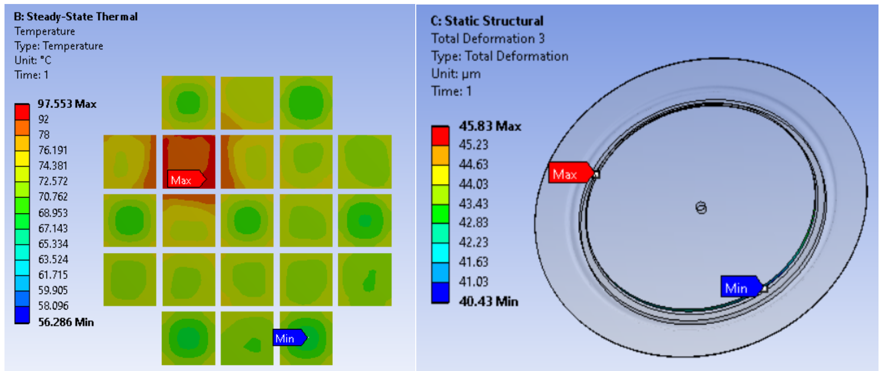


Fig. 7. Relationship between the clamping force and deformation



(a) (b)

Fig. 8. (a)Temperature distribution across chip surface with one overheated chip and (b) deformation against lid groove at 97°C

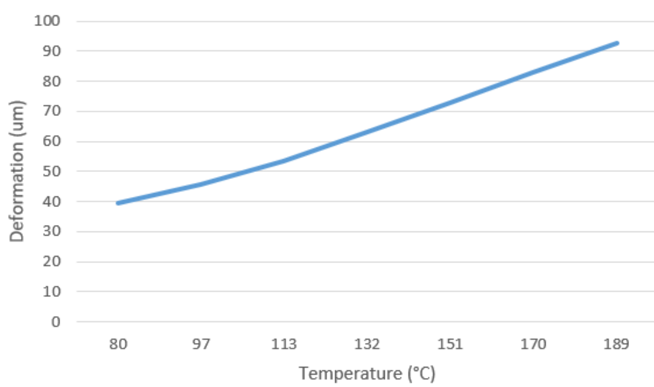
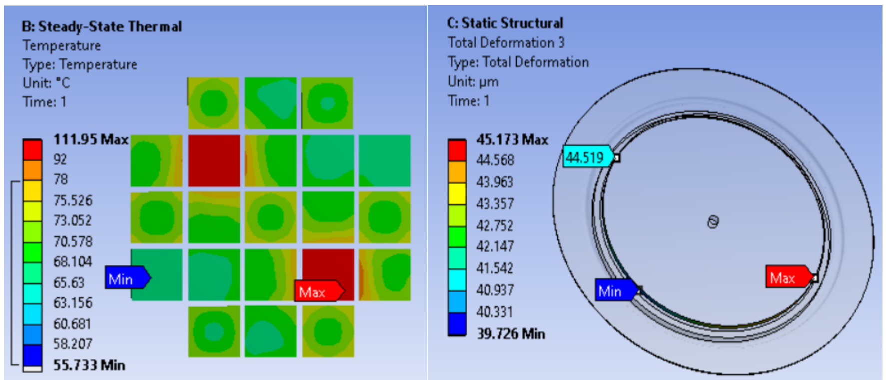


Fig. 9. Relationship between the temperature and deformation

Comparing the previous results where an even power dissipation on the chips with varying power density and clamping force was applied. It can be seen that the previous simulation with the increase of power loss and the increase of the applied clamping force, the deformation of the groove part also increases, but because the two variables are uniformly distributed, and the layout of the internal IGBT and diodes are centrally symmetrical and asymmetrical, so the resulting deformation is more evenly distributed on the entire groove. However, when a chip is overheated or even short-circuited, the deformation will increase with the increase of power loss. Also, it can be clearly seen that the deformation of the groove near the hot spot is significantly larger than the other parts of the groove. From this point, it can be determined that the chip in this area is not working properly and may cause the final failure of the module.



(a) (b)

Fig. 10. (a)Temperature distribution across chip surface with two overheated chips and (b) deformation against lid groove at 112°C

3.4 Press-pack simulation with two chips failed

Although the simulation result of an overheated chip shows the difference in the deformation at the groove, it is necessary to study the situation when there are multiple chips overheated. In order to simulate the extreme situation where there are two failed chips another simulation was conducted.

Fig. 10 shows the results of deformation distribution and thermal distribution. It can be seen that the deformation near the grooves of the two overheated chips is significantly larger than the other parts, similar to the previous conclusion. Compared with the previous result where only one chip was overheated, under the condition of the same total power dissipation, the dominant level of deformation is reduced but the difference between the minimum deformation point and the maximum deformation point is still obvious. Thus, the groove deformation can be used as indicator for overheating chips.

4. Conclusion

This paper studies the relationship between the deformation of the collector lid groove and the internal chip thermal stress and external clamping force through 3D physical modeling of a press pack IGBT. It is concluded that the thermal stress has a much greater influence on the deformation than the clamping force. In addition, a model with an overheated chip has been established, and the relationship between deformation and internal thermal stress in this case was studied to prove the difference of deformation under the distinct condition. Also, a model with two overheated chips located diagonally is studied and derived similar findings. It can be concluded that deformation of the lid groove can be used to determine the status of the device.

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