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Parametric Study and Reliability Assessment of IGBT Module

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ABSTRACT

In the investigation presented, to keep maximum temperature within permissible limit steady state analysis of 6-pack, 1200V IGBT power modules is carried out. Using base plate having base pins, DBC copper with a solder layer having substrate and IGBT chips a 3D model is constructed. Geometric and material variables of substrate, pin sizes and pin density with and without varying heat transfer coefficient, characterizes the thermo-mechanical performance of the module. Reliability prediction is based on the assumption that the solder interconnections are the weakest part of the module, as the inelastic deformation energy is accumulated within it, which causes failure. A 2D model will be used for crack initiation and propagation under thermo-mechanical loading. A virtual crack closure technique (VCCT) method is used to predict life of the module. Commercial Finite Element Analysis software is used for the study of an IGBT module.

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I. INTRODUCTION

The sales volume of the hybrid cars is on a growth trend due to the increasing prices of the petroleum products and global warming. By the combination of two power sources, gasoline engine or electric motors and according to driving condition optimizing the load sharing hybrid systems achieve improved fuel economy. In a gasoline hybrid system, an electric power conversion system that includes an inverter and a converter is used to convert the power generated, charge and discharge the battery, and to drive the motor. The main switching device used in electric power conversation system is IGBT. IGBT has wide range of application in the industry, consumer market and transportation. Automobile and railway train applications use IGBT modules. [1]

HEV use power IGBT modules which dissipate a considerable amount of heat and exhibit electrical characteristics, which strongly depend on their junction temperature. These electric vehicles use IGBT modules whose quality and reliability depends on the efficient dissipation of heat generated in the module. To cool the electronic components and maintain the electric performance of the system thermal management is required moreover it provides long term reliability by minimizing the thermally induced stresses.These IGBT modules must be light in weight, smaller in size, more efficient in energy use, less costly and able to meet specified automobile standards. Reduced number of IGBT power chips in design concepts such as integrating inverter, DC-DC converter and electronic control unit can lower the size and weight of power module. To eliminate the thermal grease interfaces between the module and the heat sink, Integrated pin fin, direct liquid cooled base plates is used which also provides excellent thermo-mechanical stability with effective thermal management of IGBT chips.

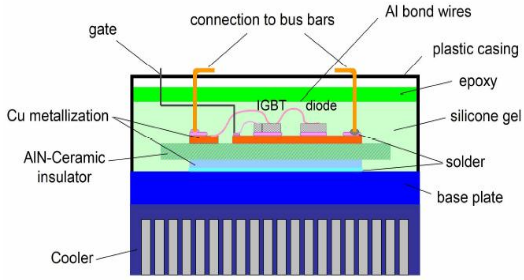


Fig.1 Schematic representation of IGBT power module [1]

I. BACKGROUND

Many theories and hypotheses have been suggested for predicting structural failure. The two most popular criteria for crack growth are namely, 1) The maximum Von-Misses stress or principle stress criterion [2-3] based on stress analysis and; 2) The strain energy release rate criterion [4-5] based on fracture mechanics. Nowadays, the Strain Energy Release Rate G is calculated by means of techniques in conjunction with the finite element method, such as Virtual Crack Closure Technique. The first VCCT approach to compute SERR was proposed by Rybicki and Kanninen (1977) [6].The Strain Energy Release Rate is calculated from forces at crack tip and relative displacement of the crack faces behind it for four noded element. Later it was extended to higher order element by Raju (1987) [7] and to 3D cracked body by Shiv Kumar et al (1988) [8].

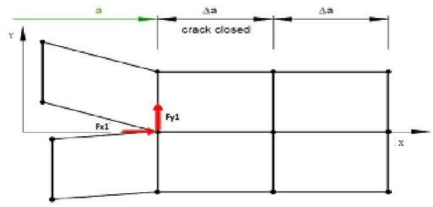
Thermal management becomes critical for the better performance of the IGBT based power module used in HEV application. The increase of surface heat flux of the IGBT module demands the detailed design of heat transfer paths from power chip to the heat sink. The increase of surface heat flux of the IGBT moduledemands the detailed design of heat transfer paths from power chip to the heat sink. Accurate analysis of heat dissipation from the IGBT module is needed. Jun He et al has worked on the thermal design and measurement of IGBT power modules for transient and steady state condition. To improve the arrangement of wire bonds and layout of bonding pads effective reduction in temperature gradient and the maximum temperature on the IGBT surface was suggested. [9]

ZoubirKhatir described thermal simulations of high power IGBT modules based on boundary element method and also validation of numerical tool is shown in steady-state and dynamic operations during a power cycle, comparing it with experimental measurements [10]. The work has been done on the method of development of thermal grease and to study the effect of thermal grease thickness on the IGBT chip temperature [11]. Thermal management and heat spreading issues have been handled previously but less attention has been directed on the heat transfer analysis of structure module [12,13,14]. In this paper effective cooling of the IGBT modules used in hybrid vehicles is considered to study its effect on maximum temperature.

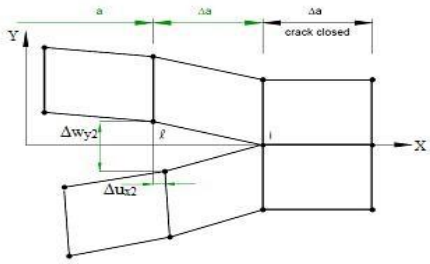
Virtual Crack Closure Technique (VCCT)

To characterize the onset and growth of delamination the use of fracture mechanics has become common practice over the past two decades [17]. The VCCT is a well-established method for computing the energy release rate (ERR) when analyzing fracture problems via the finite element method [18-19]. For mixed-mode fracture problems, the VCCT is also commonly used to partition the fracture modes, i.e. to determine the SERR contributions related to fracture modes I (due to interlaminar tension), mode II (due to interlaminar sliding shear), and mode III (due to interlaminar scissoring shear). The technique is based on the numerical implementation of Irwin's crack closure integral [20]. According to VCCT, the evaluation of the SERR can be obtained starting from assumption that for infinitesimal crack opening, the strain energy released is equal to the amount of work required to close the crack [21]. The energy required to close the crack is given (refer fig. 5) by equation,

$$\Delta E = \frac{1}{2}(F_{x1}\Delta u_{x2} + F_{y1}\Delta w_{y2}) \quad \text{........(1)}$$



Crack is closed



Crack is open

Fig.4 Two Step VCCT

For 2D four noded element the mode I and mode II components of the strain energy release rate, G_I and G_{II} , are calculated as shown in Fig.6

$$G_I = -\frac{1}{2\Delta a}F_Y(w_l - w_{l*}) \quad \text{.................(2)}$$

$$G_{II} = -\frac{1}{2\Delta a}F_X(u_l - u_{l*}) \quad \text{.................(3)}$$

The total energy release rate G_T is calculated from the individual mode components as,

$$G_T = G_I + G_{II} + G_{III} \quad \text{.................(4)}$$

Where, GIII=0 for the two-dimensional case discussed.

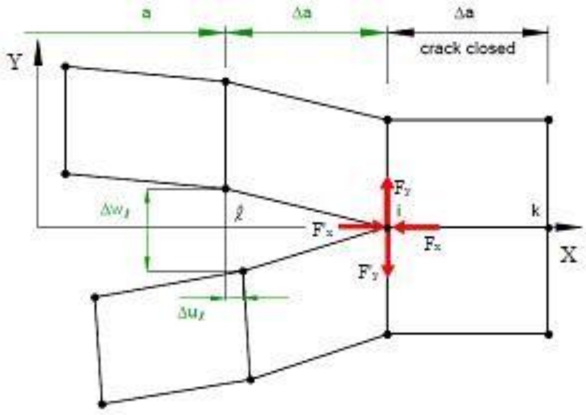


Fig.5 VCCT for four noded element

Delamination Criteria

Calculated energy release rate G components are compared to interfacial fracture toughness i.e. critical SERR to predict the delamination onset and growth. When the total energy release rate exceeds this interfacialfracture toughness value, failure occurs i.e. the crack will grow [21] when,

$$G_T \geq G_C \qquad ....(5)$$

Interfacial Fracture Toughness

Adhesive strength can be calculated by using interfacial fracture mechanics which determines adhesive strength in terms of a critical interfacial strain energy release rate Gc. This critical SERR is interfacial fracture toughness. Interfacial Fracture toughness is a property which describes the ability of a material containing a crack to resist fracture. The interfacial fracture toughness, which is critical value of G required for crack propagation, can only be obtained experimentally. Gc obtained is a function of several parameters like temperature, moisture and mode mixity. Sandeep Gupta et al determined interfacial fracture toughness of different epoxies by using a mixed mode bending fixture [22]. For interface between SAC alloy (SnAgCu) and Copper, the interfacial facture toughness varies from 23.49 J/m2 to 76.11 J/m2. [23]

II. DETAILS OF MODEL

In this study, Copper and AlSiC base plate is used. Use of direct cooled AlSiC base plates in IGBT modules not only eliminates the thermal grease interfaces between the module and the heat sink but also provides excellent thermo-mechanical stability with effective thermal management of IGBT chips. The heat dissipation performance of power modules with AlSiC base plate will remain consistent even after thousands of thermal cycles, while the thermal performance of power modules with copper base plate will gradually decrease after each thermal cycle; this is due to coefficient of thermal expansion miss-matches the system. Another design advantage of AlSiC base plate is the higher stiffness as compared to copper and aluminium[15].

A three dimensional model of IGBT module that consists of AlSiC base plate with pins of 0.93 mm radius and 3.5 mm length, DBC attached with solder layer using AlN substrate and IGBT chips is used for analysis. Total power of 6 kW; 500 W on each IGBT chip is applied to study its impact on the maximum temperature and the temperature distribution across the IGBT module. Convective heat transfer coefficient of 5 W/m²°C is applied on the chip side of the IGBT module considering the free convection with air and very high h of 10000 W/m²°C is applied on the pin side considering forced convection with liquid [16]. The physical dimensions of each layer within the module construction and material properties are given in Table 1.

TABLE.1 MATERIAL PROPERTIES AND DIMENSIONS

Part	Dimensions(mm)	Materials	Thermal conductivity (W/m°C)
Substrate	41.7 × 27.5	AlN	180
Base Plate	174.1 × 92	AlSiC	190
Die	12.7 × 12.7	Silicon	120
Copper	41.7 × 27.5	Copper	401
Solder Layer	41.7 × 27.5	SnAg3.5	78

III. MODELING METHODOLOGY

Commercial Finite Element Analysis software is used to study the characterization of the IGBT based power modules used in HEV. Maximum temperature (T max) of the base plate is simulated for various parameters and design modifications as mentioned above. Geometry of IGBT module is created using design modeler. A front view and top view of the model is as shown in Fig.2 and Fig.3 respectively.

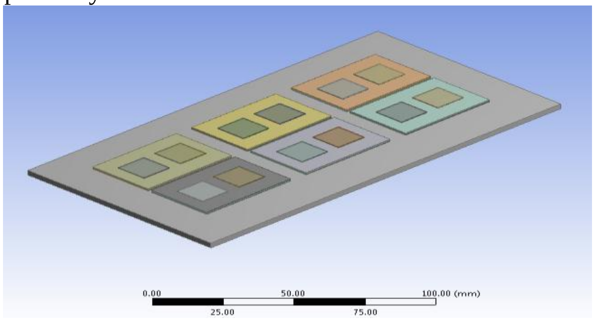


Fig.2 Isometric view of IGBT Module

Fig.4 shows the three dimensional finite element model of the IGBT module, where total number of nodes are around 1494K and elements are around311K. Elements Solid87 and Solid90 are used for components while Conta 174 and Targe 170 are used for contact elements. Mesh sensitivity analysis is carried out where temperature varies in the range of +/- 5%; fine meshing is used for the analysis. There are two paths for heat dissipation to the ambient. One is from the substrates to IGBT chips then to the ambient. The second is from the substrate to base plate then to the ambient. Maximum of the heat dissipation is through the latter path. There are power module designs utilizing air cooled power modules but most of the HEV systems use direct liquid cooled IGBT power modules as in many cases air cooling is not sufficient.

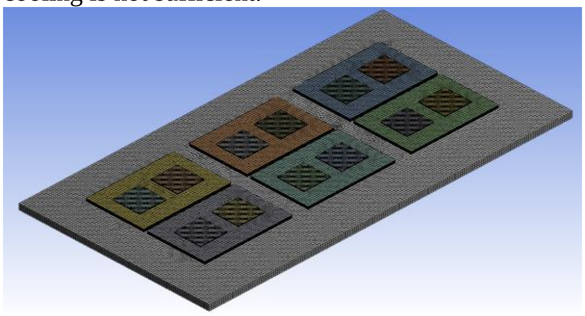


Fig.3 FEM of IGBT Module

Baseline study considers the dimensions and material data as per given in Table1 and total power of 6kW; 500W on each chip. The maximum temperature is simulated for baseline case. Parametric study is carried out for thermal characterization of the module. Geometric parameters such as base plate thickness, substrate thickness and Pin sizes are considered with different materials for this study. Following cases are considered for characterization of the module for effective cooling of the IGBT.

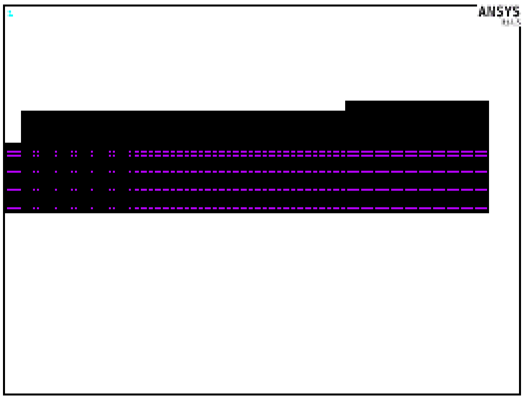


Fig.4 2D FEM of IGBT module

For reliability prediction 2D model is created. Symmetry model is considered for the analysis. Element solid182 is considered for the analysis. Mesh sensitivity analysis is carried out where temperature varies in the range of +/- 5%; fine meshing is used for the analysis.

Case 1: Effect of base plate

Base plate with Copper and AlSiC material is varied in thickness, to study its effect on maximum temperature of the module.

Case 2: Effect of substrate

Substrate thickness is varied with different material to study its effect on maximum temperature of the module. Different materials used for substrate are Aluminum Nitride (AlN), Aluminum oxide (Al2O3), Silicon Nitride(Si3N4), Silicon carbide(SiC) and its properties are shown in Table 2.

TABLE.2 SUBSTRATE MATERIAL PROPERTIES

Material	Thermal conductivity (W/m ^{0}C)	Flexural Strength (MPa)	Elastic Modulus (GPa)	Hardness (kg/mm2)
Al2O3	18	330	300	1175
Si3N4	30	830	310	1580
SiC	120	550	410	2800
AlN	180	320	330	1100

Case 3: Effect of pin sizes and pin density

The Different value of pin radius with different pin density are used to study its effect on maximum temperature of the module. Different pin radius used are 0.93, 0.825, 0.75mm respectively.

Case 4: Effect of pin density on maximum temperature for varying h on pin side of the module

In addition to different pin density at constant h, pin densities for varying h are also considered for this analysis to study the effect on maximum temperature. Base plate with 1300, 882, 576 and 231 pins for varied h from 10000, 9000, 8000, 7000, 6000 W/m2^{0}C is considered for studying the effect of pin density on maximum temperature.

Case 5: Initial study for reliability prediction

For the reliability prediction 2D model is considered. IGBT module is subjected to thermal cycles ranging from-55˚C to 160˚C and -40˚C to 125˚C with 15 min ramps and 15 min dwells. [5]. Plain strain condition is considered for the analysis. All nodes at bottom surface of base-plate are fixed. Material properties used for the analysis re shown in table 3

TABLE.3 MATERIAL PROPERTIES

Part	Young's Modulus (GPa)	Poisson's Ratio	Coefficient of Thermal Expansion (ppm/˚C)
Substrate	330	0.24	4.5
Base Plate	188	0.29	8.75
Die	131	0.3	2.8
Copper	121	0.3	17.3
Solder Layer	56.223	0.4	20.72

IV. RESULT AND DISCUSSION

Baseline Case :

Fig.7 shows the results for maximum temperature distribution of IGBT module for the baseline case. Maximum temperature for baseline case comes to 136.46°C which is much lower than 150°C (acceptable value)[3].

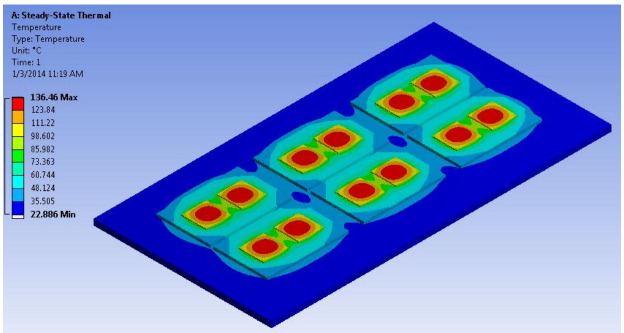


Fig.5 Maximum temperature distribution for baseline case

Case 1: Effect of base plate

Effect of Copper and AlSiC as a base plate material on maximum temperature of the module is shown in Fig.6. As base plate thickness increases, maximum temperature of IGBT module increases. A base plate that is too thick or too thin will have minimum or maximum conduction losses, but heat spreading in the lateral direction will decrease or increase, resulting in a lower system thermal efficiency and excessive weight. So thinner AlSiC base plate that is thermo-mechanically stable is considered better for removing the heat generated in the module over copper base plate due to disadvantage of copper material.

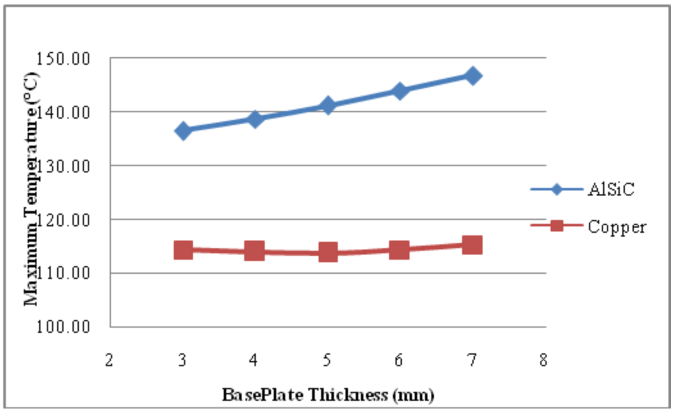


Fig.6 Effect of base plate on maximum temperature

Case 2: Effect of substrate

Effect of various substrate materials on the maximum temperature of the module is shown in Fig.7. As the thermal conductivity of the material increases there is drop in maximum temperature of the IGBT module. Heat dissipation through the base plate is reduced due to the presence of Al2O3 as a thermal barrier between the IGBT chip and AlSiC base plate. Substrate thickness can be reduced with Si3N4 as a substrate material, as it is much stronger material than AlN and Al2O3, but not able to dissipate more heat through base plate. As the thermal conductivity of AlN as substrate is higher and less coefficient of thermal expansion mismatch between AlN and AlSiC, contribute to a high reliability design. So the AlN as substrate material is ultimate choice for removing the heat generated in the module.

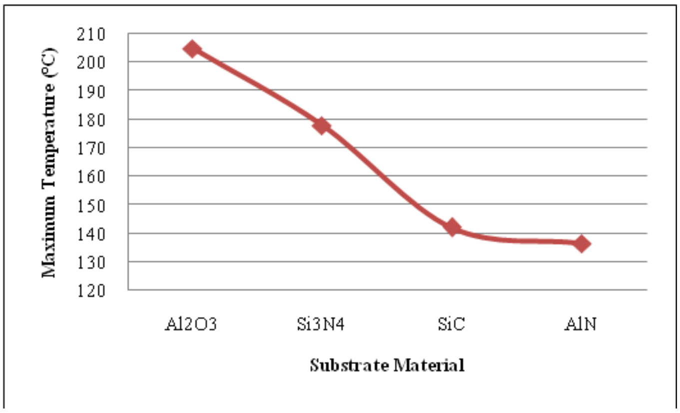


Fig.7 Effect of substrate material on maximum temperature

Effect of substrate on maximum temperature of the module is shown in Fig.8. Too thick substrate will result in lower thermal efficiency and excessive weight and too thin substrate will harm the mechanical reliability of the module. So the substrate with optimal thickness is better for removing the heat generated in the module.

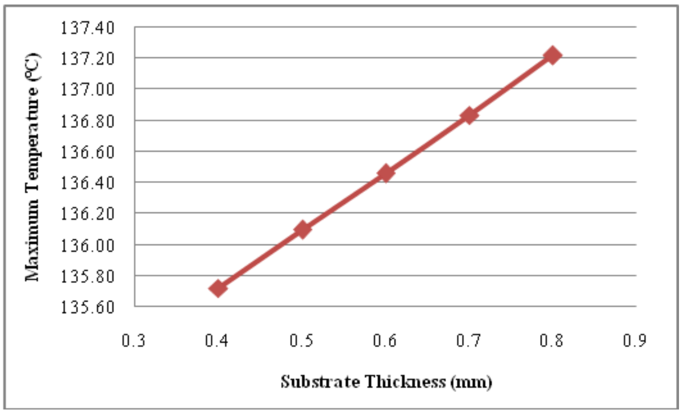


Fig.8 Effect of substrate thickness on maximum temperature

Case 3: Effect of pin size and pin density

As we decrease the pin size, the maximum temperature of the module goes on increasing and increasing the pin density, the maximum temperature of the module goes on decreasing as shown in Fig.9. Increasing the height of the pin beyond certain limit, provides no useful purpose, as the module temperature reaches ambient temperature. Pins spacing determine the airflow across the pin surface. Then as air molecules pass by the pin surface, heat energy is transferred to the air. As pin spacing decreases, less air can pass across the pin surface and no heat energy is transferred. Pins with minimum spacing, maximum radius and maximum density are the better choice to reduce the maximum temperature. But, due to increase in pin density the cost of the IGBT module increases and manufacturing becomes complicated. So the pin density that best suits the given application shall be used.

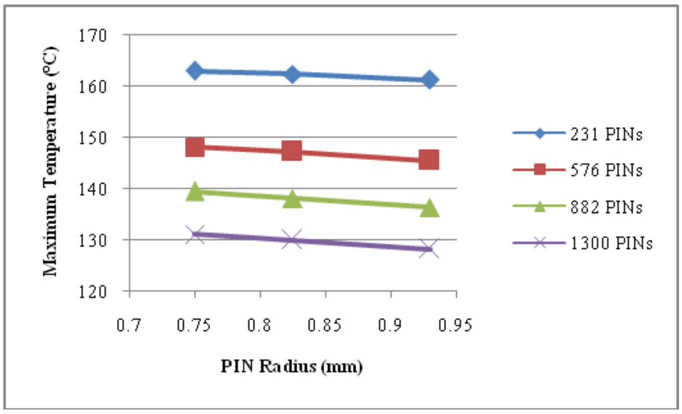


Fig.9 Effect of pin radius and pin density on maximum temperature

Case 4: Effect of pin density on maximum temperature for varying convective heat transfer coefficient on pin side of the module (h)

Effect of Number of pins with varying convection on maximum temperature of the module is shown in Fig.10. Higher pin density with lower convective heat transfer coefficient gives lower temperature as compared to lower pin density with higher convective heat transfer coefficient. This implies a need for higher number of pins as compared to any high end /advanced cooling system.This can definitely reduce the overall costin achieving the desire maximum temperature.

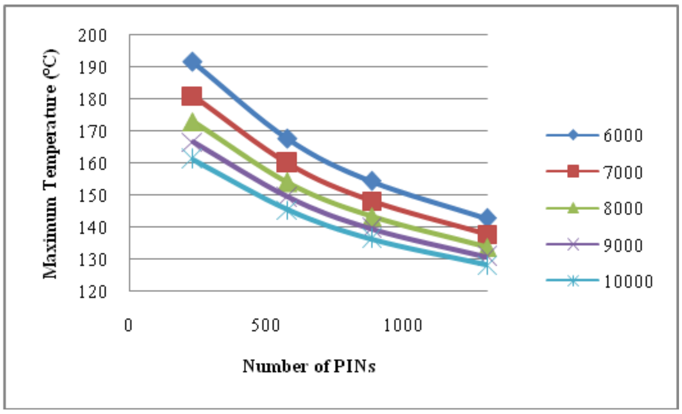


Fig.10 Effect of number of pins with varying convection on maximum temperature

Case 5: Initial study for reliability prediction

From the initial analysis it is predicted that the solder layer is subjected to maximum stress. Solder layer situated below the die is subjected to maximum stress due coefficient of thermal mismatch between the two layer.

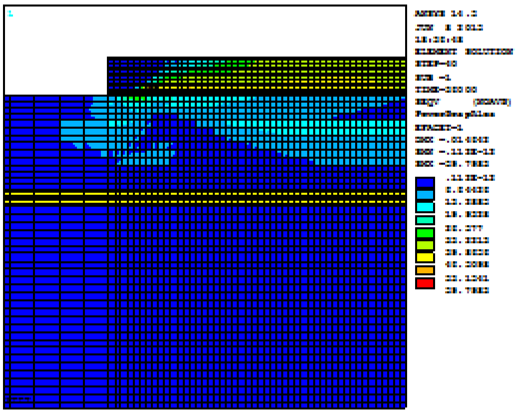


Fig.11 Stresses on 2D IGBT module

V. CONCLUSION

The thermo-mechanical analysis is carried out to study the base plate characteristics to keep the maximum temperature below reliable working temperature. In HEV applications, there are limitations on the inlet temperature of the liquid and hence limitations on liquid used (heat transfer coefficient). A parametric study of the IGBT module for geometric and material variables of substrate, pin sizes and pin density with varying heat transfer coefficient shows statically significant changes in maximum temperature of the module. Results indicated that maximum temperature is dropped for constant high convective heat transfer coefficient with AlSiC as a base plate and AlN substrate thickness is optimum (minimum). For effective cooling of the module, pins with high density and high size (radius) are better. Design modification such as increasing numbers of pins on base plate will reduces the maximum temperature, that is statically significant as compared to other geometric parameters or material variables. Considering all the cases, base plate with maximum number of pins is best option for thermal management. Drop in the maximum temperature of the module is 9% to that of the permissible value, which ultimately cools the IGBT module. This study will be very helpful in providing the effective cooling of IGBT modules which ultimately improve the reliability. Future work will be the reliability prediction of the module by VCCT method considering 2D geometry.

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