Abstract
Power modules equipped in electrified vehicles often operate at harsh conditions. Thermal stress in power modules are known to be one of the major factors resulting performance degradations or damages in solder joints in power modules. In this paper, the temperature distribution analysis and the lifetime analysis were conducted with consideration of real operation conditions, especially ambient temperatures and coolant temperatures. Simulation results reveal that the effects of ambient temperature increment depends on the state of power semiconductors and also influenced by coolant temperature. The increased temperature also increases thermal stress, resulting reduced lifetime of IGBT solder joint (7% reduction) at an ambient temperature of 100°C, which is often observed in vehicle engines. In addition, the IGBT solder joint exhibits shorter (~25% reduction) lifetime compared to diode solder joint because of higher power loss. Therefore, power module design should simultaneously consider heat generated from devices and given by operating conditions.

Keywords: power modules, thermal reliability, lifetime, operation conditions

1 Introduction
Recently, various electrified vehicles are emerging, including EV (Electric Vehicle), HEV (Hybrid Electric Vehicle), PHEV (Plug-in Hybrid Vehicle), and FCEV (Fuel Cell Electric Vehicle). These electrified vehicles will be more popular along with the expansion of infrastructure [1-2]. Power (inverter/converter) modules are one of the core components for such vehicles, and convert the battery or fuel-cell power to drive motors. The converting power continues to increases and thus, the recent power modules are demanded to be operational at high power conditions. Such high power modules suffer severe thermal reliability problems, including performance degradation [3-5], long-term fatigue [6-8], or permanent damages in power modules [9-10]. One of the main causes of these problems is because operating power semiconductors in power modules heat up, due to power loss, leading to thermal stress because significant mismatches in thermal expansion exist at each adjacent layer consisting a power module [3-7]. In order to solve the thermal stress problems, there were many studies aiming to reduce temperature [11] or thermal stress [9], or to analyse lifetime of solder joint [6-8]. These studies generally used thermal cycling and power cycling evaluations to predict the life time of power modules in accelerated manner. These approaches are generally accepted and widely employed. However, it should be noted that real operation conditions of vehicle, such as under hood temperatures, are another important factor. As an
example, the under hood temperature of gasoline vehicles have been known to reach 100°C [12-13]. Thus, the real operating conditions are anticipated to have critical impact on power module performance and life time. Therefore, the reliability analysis of power modules should consider not only heat (generated from power loss in power semiconductors) but also high temperatures (observed in real operation conditions). This paper presents an analysis co-considering both heat from semiconductors and from operation conditions. FEM simulations were conducted using parameters determined from commercial modules, to represent real situations. The FEM simulation results reveal temperature distributions and stress in various conditions, and provide an estimated lifetime of the lead free solder joint.

Table 1: Examples of temperature extremes observed in automotive applications [12]

<table>
<thead>
<tr>
<th>Location</th>
<th>Maximum temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>On engine on transmission</td>
<td>140°C</td>
</tr>
<tr>
<td>At engine (Intake manifold)</td>
<td>125°C</td>
</tr>
<tr>
<td>Under hood near Engine</td>
<td>120°C</td>
</tr>
<tr>
<td>Under hood remote location</td>
<td>105°C</td>
</tr>
<tr>
<td>Exterior</td>
<td>70°C</td>
</tr>
<tr>
<td>Passenger compartment</td>
<td>70-80°C</td>
</tr>
</tbody>
</table>

2 Module description

2.1 Component of module

A power module analysed herein is a simplified model representing the intelligent power module (IPM) of Prius 2010. [14]. Figure 1 shows a schematic image of the power module. The used module is composed of a direct bond aluminium (DBA) plate, two pairs of IGBT and diode, solder, aluminium (for cooling infrastructure), and wire-bonding ribbon. The DBA is made of a patterned aluminium plate bonded on an aluminium nitride (AlN) layer. The AlN functions as heat conductor and electrical insulator, because of its good thermal conductivity and electrical insulation. Two IGBTs and two diode shown in the figure are solder bonded to the aluminium plate. The cross-section of the solder’s edge is assumed to be trapezoid as real meniscus shape [15-16]. Top side of the solder layer has a size the same with that of IGBTs and diodes. Table 2 lists sizes of each component.

Table 2: Component sizes used in simulations [14-16]

<table>
<thead>
<tr>
<th>Component</th>
<th>Component Size [mm] Width × Length × Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon IGBT</td>
<td>15 × 15 × 0.3</td>
</tr>
<tr>
<td>Silicon diode</td>
<td>15 × 7.5 × 0.3</td>
</tr>
<tr>
<td>Aluminium on DBA</td>
<td>20 × 40 × 0.6</td>
</tr>
<tr>
<td>Aluminium nitride on DBA</td>
<td>22 × 44 × 0.6</td>
</tr>
<tr>
<td>SnAgCu Solder for device bonding</td>
<td>Top side: Length and width are the same with those of IGBT and diode</td>
</tr>
<tr>
<td></td>
<td>Bottom side: 16 × 16 × 0.1</td>
</tr>
</tbody>
</table>

Figure 1: A schematic of the used power module

2.2 Problem definition

When the electrified vehicle is driving, the power module generates power loss. The power loss induces heat of module itself. The heated module generates thermal stress induced by coefficient of thermal expansion (CTE) mismatches at each layer of the power module. The thermal stress induces reliability problem of solder joint layer. The heat generated by module itself is major factor about thermal reliability, but this paper focused on the real operating condition in HEV. Because the HEV engine equipped is operated in harsh environment with vibration and high ambient temperature. Although especially ambient temperature looks not effective for power module reliability, the major problem is that the power module is exposed of continuous high temperature. Whether the Silicon IGBT operates maximum performance with maximum junction temperature or not, the high
ambient temperature continuously affects to power module. For this reason, high ambient temperature in HEV will be another major component to reduce power electronic module lifetime.

3 FEM Simulation

3.1 Material

In this model, the aluminium nitride and aluminium for cooling infrastructure model were assumed linear-elastic model. Aluminium for DBA was assumed plasticity model. Because the stress of aluminium model exceeds the yield strength easily. And aluminium's plasticity properties was models as no hardening plasticity, i.e. perfect plasticity. And the solder was applied creep and plasticity model and temperature dependency. The Garofalo hyperbolic sine law was applied to this model.

The creep input components of A, B, n, Q are 44100[1/sec], 0.005[1/MPa], 4.2, 44995[J/mol], respectively. Creep properties is used from Hong, Lau's data [20-21].

The lifetime of the solder joint was calculated by the following energy based the Morrow's life prediction model. And energy type was the obtained creep energy dissipation density.

$$\Delta W_c = W_f (2N_f)^m$$ (2)

$\Delta W_c$: dissipated energy density per cycles

$W_f$: Fatigue energy coefficient

$N_f$: Failure cycles

m: Fatigue energy exponent [23]

These model parameter applied to COMSOL by using Kim's experiment result [19].

$$\Delta W_c = 60.17 (2N_f)^{-0.87892}$$ (3)

3.2 Simulation process

The simulation was conducted by COMSOL Multiphysics FEM simulation software. The layer thickness varied from 150 micro meter (solder) to 2.5millimeter (aluminium for cooling). Each layer was applied different mesh size because each layer has different thickness. Thin layers were extremely fine meshed, including the solder layer and the contact area between IGBTs, diodes and ribbons. The main focused area was solder layer and the contact area between IGBT, Diode and ribbon. Thin layer and major layer was defined extremely fine mesh, the other layer was normal and coarse mesh type. Every mesh component was composed of triangular and tetrahedral mesh and the number of elements were 44744. Thermal boundary condition was defined power dissipation model. The IGBT and Diode was applied 120W, 20W with cycles. Each devices are used as heat source. Figure 2 is IGBT power loss cycle and Diode power cycle was applied 1/6times to IGBT cycles. The ambient condition was applied from 25°C to 125°C with convection heat flux model considering real operation condition in engine equipped vehicle. The heat transfer coefficient was 30[ W/m²K ]. The cooling condition was applied to the bottom of aluminium. The heat transfer coefficient of cooling considered that real power module has maximum junction temperature 150°C in case of silicon IGBT in the real operating condition. When the proposed power module was designed with corresponding

<table>
<thead>
<tr>
<th>Materials</th>
<th>Al</th>
<th>AlN</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus [GPa]</td>
<td>70</td>
<td>330</td>
<td>30</td>
</tr>
<tr>
<td>Poisson Ratio</td>
<td>0.35</td>
<td>0.23</td>
<td>0.28</td>
</tr>
<tr>
<td>Yield Strength [MPa]</td>
<td>20</td>
<td>Elastic</td>
<td></td>
</tr>
<tr>
<td>CTE [ppm/K]</td>
<td>23.1</td>
<td>4.5</td>
<td>4.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solder name</th>
<th>SnAgCu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>298</td>
</tr>
<tr>
<td>Modulus [GPa]</td>
<td>53</td>
</tr>
<tr>
<td>CTE [ppm/K]</td>
<td>21.3</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.4</td>
</tr>
</tbody>
</table>
| Yield strength [MPa] | 30 / 45 / 18 /
| Strain (0/0.01/0.1) | 180   | 83   | 38     |

$$\frac{d e^{\sigma}}{dt} = A \sinh(B\sigma)^n e^{\frac{Q}{RT}}$$ (1)

A: creep rate coefficient

B: $\frac{1}{\sigma_{eff}}$ [1/Pa], $\sigma_{eff}$ effective stress

n: Garofalo n parameter

Q: activation energy
real module, cooling boundary condition was assumed $800 \text{ W/m}^2\text{K}$ and temperature $75 \degree \text{C}$. The equivalent cooling model was considering with maximum junction temperature and power dissipation [3-4, 22].

The mechanical boundary conditions were set that the component of the aluminium for cooling was applied zero displacement in all directions and the other component was applied free displacement in all directions. Power loss is applied to each dissipation was applied maximum performance cycle with each ambient temperature from room temperature to maximum temperature $125 \degree \text{C}$. The simulation have following 3 steps. First step was the steady state heat transfer model by using power dissipation. The temperature distribution was compared along with ambient and coolant temperature. Second step was creep analysis by using Garofalo model and the temperature result from step1. The creep analysis was considered nonlinear time dependent analysis. Last, in order to calculate the fatigue life, the energy based the Morrow’s fatigue model was applied by using calculated creep energy dissipation data from step2.

## Results

Figure 2: IGBT power loss cycle

![Figure 2: IGBT power loss cycle](image)

The mechanical boundary conditions were set that the component of the aluminium for cooling was applied zero displacement in all directions and the other component was applied free displacement in all directions. Power loss is applied to each dissipation was applied maximum performance cycle with each ambient temperature from room temperature to maximum temperature $125 \degree \text{C}$. The simulation have following 3 steps. First step was the steady state heat transfer model by using power dissipation. The temperature distribution was compared along with ambient and coolant temperature. Second step was creep analysis by using Garofalo model and the temperature result from step1. The creep analysis was considered nonlinear time dependent analysis. Last, in order to calculate the fatigue life, the energy based the Morrow’s fatigue model was applied by using calculated creep energy dissipation data from step2.

Figure 3: Temperature distribution (operation temperature: $25 \degree \text{C}$, power loss: 120W)

![Figure 3: Temperature distribution (operation temperature: $25 \degree \text{C}$, power loss: 120W)](image)

Figure 4: Temperature distribution (operation temperature: $125 \degree \text{C}$, power loss: 120W)

![Figure 4: Temperature distribution (operation temperature: $125 \degree \text{C}$, power loss: 120W)](image)
Figures 3 and 4 are temperature distribution at ambient temperature 25°C, 125°C respectively. The temperature range was from 129 to 153 and from 138 to 162°C in the condition of the maximum module power loss situation and heated up extra 9°C. Figure 5 and 6 are temperature distribution in the condition of minimum module power loss situation. From these thermal distribution data, the ambient temperature in real operation condition under hood can be make extra 6% higher temperature.

Figures 7 and 8 are the z direction stress distribution IGBT solder side boundary. Each figures have two stress distribution bars in the condition of maximum and minimum power loss. From these z direction stress distribution data, the ambient temperature in real operation condition under hood can be make extra 9%/120W power loss) and 4%(30W power loss) higher z direction stress in the solder side boundary.

Figure 9 is the temperature distribution at coolant temperature 95°C. The coolant temperature was applied more 20°C. The temperature range was from 156 to 180 in the condition of the maximum module power loss situation and heated up extra 18°C. The maximum temperature change level was 0.9°C by coolant 1°C increment.
Figure 10 is the shear stress distribution in the boundary between IGBT and solder. The left figure is same condition with Figure 4 and right figure is same condition with Figure 9. The maximum shear stress is higher 20% at the corner in the condition of coolant temperature higher 18°C. From these shear stress data, the heated coolant can be make extra 1% higher shear stress per 1°C at the corner.

Figure 11 is creep energy dissipation density curve. When the creep dissipation energy density is higher and higher, fatigue lifetime would decrease. The graph of figure 9 shows the creep dissipation density curve with changing ambient temperature and location. The location is the boundary points which are IGBT to solder layer and Diode to solder layer. The creep dissipation energy density is higher in IGBT to solder layer and at high ambient temperature. From these graph, 125°C condition could be expected as short lifetime to failure.

5 Conclusion

The maximum temperature in power module was changed by high ambient temperature and coolant temperature in real operation condition. For these reason, the solder joint layer was induced to higher thermal stress and faster failure. The solder was simulated by Garofalo sine hyperbolic law for creep and Morrow’s energy based model for fatigue. From the simulated results, the lifetime of IGBT solder joint was shorter 25% than diode layer. And the increase of ambient temperature 100°C reduced 7% lifetime of solder joint. The heat generated from ambient temperature or coolant on real operation condition could make serious thermal reliability
problem in the power module solder joint. Not only the module power loss, but also real operation condition in the engine equipped vehicle could lead to serious reliability problem. These are verified and analysed with FEM simulation.

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References


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