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Sensitivity of Solder Joint Fatigue to Sources of Variation in Advanced Vehicular Power Electronics Cooling

Conference Paper
NREL/CP-540-46417
June 2010

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Presented at the 2009 ASME International Mechanical Engineering Conference and Exposition
Lake Buena Vista, Florida
November 13–19, 2009

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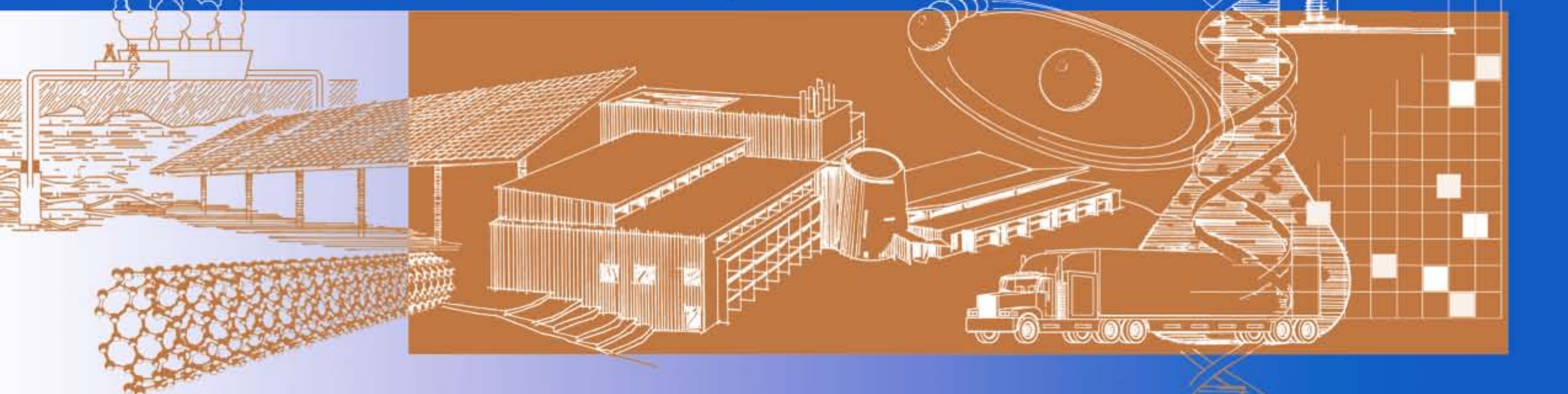

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Sensitivity of Solder Joint Fatigue to Sources of Variation in Advanced Vehicular Power Electronics Cooling*

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ABSTRACT

This paper demonstrates a methodology for taking variation into account in thermal and fatigue analyses of the die attach for an inverter of an electric traction drive vehicle. This method can be used to understand how variation and mission profile affect parameters of interest in a design. Three parameters are varied to represent manufacturing, material, and loading variation: solder joint voiding, aluminum nitride substrate thermal conductivity, and heat generation at the integrated gate bipolar transistor, or IGBT. The influence of these parameters on temperature and solder fatigue life is presented. The heat generation loading variation shows the largest influence on the results for the assumptions used in this problem setup.

INTRODUCTION

Power inverters are key components of the electric traction drives of hybrid electric, plug-in hybrid electric, fuel cell electric, and pure electric vehicles [1, 2]. Research and development of power inverters is currently focused on reducing the cost, weight, and volume of the technology while maintaining and/or increasing reliability [1, 2]. If the research goals related to cost, weight, volume, and reliability can be met, more advanced vehicles can enter the marketplace and reduce the amount of petroleum required for transportation.

Current-generation inverter designs used in today's hybrid vehicles are built on proven technology that has demonstrated high reliability. In contrast, the next generation of inverter concepts combines new materials, new heat transfer methods, and new packaging concepts under increased loads and in smaller spaces. Furthermore, there is interest in expanding the range of temperatures and stresses under which these technologies can operate [3, 4]. For these new technologies and conditions, reliability is, as yet, unproven.

In a production environment, reliability data can be obtained from statistical measures of empirical data or from product testing. However, design changes during production to fix reliability problems are quite expensive. In contrast, during the early phases of research, design changes are cheap to make. However, prototypes may not even be available. Therefore, at the very earliest stages of design, other methods must be used to estimate reliability (see page 3 of [5] for further discussion). One such method is physical simulation, which we employ here.

Die attach failure has been reported as a critical failure mechanism in power electronics packages and will be the focus of this paper [5, 6]. Die solder joint fatigue is one form of die debonding failure. De-adhesion of the die is another major die debonding failure mechanism [5]. De-adhesion is mainly due to manufacturing defects such as excessive solder voiding or poor wetting of the solder [5]. In this study, we assume that the manufacturing quality is sufficient to avoid failure via de-adhesion. Die attach fatigue results in cracking, which eventually causes the thermal resistance of the joint to increase. Thus, failure of the die attach solder typically results in failure of the power semiconductor due to exceeding the device's thermal limits [6].

In this paper, we explore the sensitivity of die attach solder joint fatigue to sources of variation for a baseline liquid-cooled power inverter (with pin-fin heat exchanger) placed in a high-temperature automotive environment. Sources of variation can come from the manufacturing process (variation in package geometry and/or some initial voiding during solder joint creation), the material properties, and the loading (coolant temperatures, flow rates, and heat inputs) [2]. Variations and uncertainty associated with these physical parameters exhibit probabilistic distributions (probability density functions). Therefore, the fatigue life (an output) will also exhibit a probability density function.

The modeling technique demonstrated here provides a framework for evaluating the effect of variation on solder joint fatigue prediction. Solder joint fatigue failure was chosen to study because it is an important failure mode for modern day automotive power inverters [5, 6].

*This paper was originally presented at the 2009 ASME International Mechanical Engineering Conference & Exposition, November 13-19, 2009, Lake Buena Vista, Florida (paper no. IMECE2009-11443).

There are numerous studies on solder joint reliability in the context of electronics packaging (see, for example, [7-11]). Analytical models have been proposed to estimate the thermally induced (elastic) stresses due to differences in coefficients of thermal expansion between adjacent layers in multilayered bonded materials (see, for example, [12-13]). In these studies, both experimental and analytical evidence indicates that stresses in “soft” lead-based soldered joints (similar to what is used in our analysis) are highest at the edges.

Reference [6] applies the finite element method to explore the failure of solder joints in power electronics packages. The authors use Anand’s viscoplastic model, which incorporates both plasticity and creep phenomena to describe the behavior of the solder joint. The authors are able to show that thermal cycling has a significant effect on solder joint reliability and recommend connecting the finite element model with a damage mechanics constitutive model to predict the number of cycles to failure.

In reference [2], the authors apply a suite of computer-aided engineering tools, including finite element analysis, to study two reliability issues in power electronics modules: wire bond liftoff and substrate fracturing. The combined effects of process and material uncertainty on reliability are highlighted as concerns. The authors state that if a physics-of-failure model were available, an assessment of cycles to failure could be made.

MODEL DESCRIPTION

The physical model that we created for this study is presented in this section. We used a commercially available finite element code for simulation. We varied three parameters in this study: the heat generated from the IGBT (a variation in loading), the thermal conductivity of the IGBT solder joint (assumed to be due to the initial presence of voids), and the thermal conductivity of the substrate (a variation in material properties). These three properties were chosen to demonstrate the process of applying robust design techniques to the domain of power module thermal stress and reliability simulation. In truth, any parameter that can be modeled could have been chosen.

Model Overview

For this analysis, we considered a standard inverter design with a basic geometry similar to that of commercially available designs. The emphasis of this study is on demonstrating the analytical approach, although we will also point out some general insights that can be gained from the analytical results.

As an example to give the context of our model, Figure 1 shows the power inverter from a popular hybrid electric vehicle. The left-hand side of the inverter (circled by a dashed line) is used to power the main traction motor of the vehicle and will be the focus of our subsequent discussion. The traction motor inverter consists of 12 IGBTs and 12 diodes, and each pair of two IGBTs and two diodes (i.e., four devices) forms an electrical switch (each pair is electrically in parallel to reduce the amount of current any one device is exposed to). Electrical current is routed across the inverter through the metallization on the surface of the inverter and through wire bonds. Wire bonds are also used to deliver current from the gate driver (not shown) to the individual IGBTs to turn them on and off. A more extensive discussion of this inverter topology can be found in [14].

Our physical model is shown in Figures 2 and 3. The model represents a subset of the full vehicle inverter. We assume that the boundary conditions on the model correspond to the last device cooled along the cooling channel; this device typically experiences the hottest temperatures. Our model consists of one IGBT and diode pair and the layers of the inverter package between the devices and the cooling system. The model is simplified to show only the relevant geometry. For example, wire bonds are not explicitly modeled.

It will be important in our model to get a correct prediction of heat transfer and temperatures because the stresses that cause fatigue in the solder joint are thermally induced due to differences in the coefficient of thermal expansion. For this reason, we will briefly discuss the thermal boundary conditions and relevant material properties before focusing on the interaction of model variation and fatigue results.

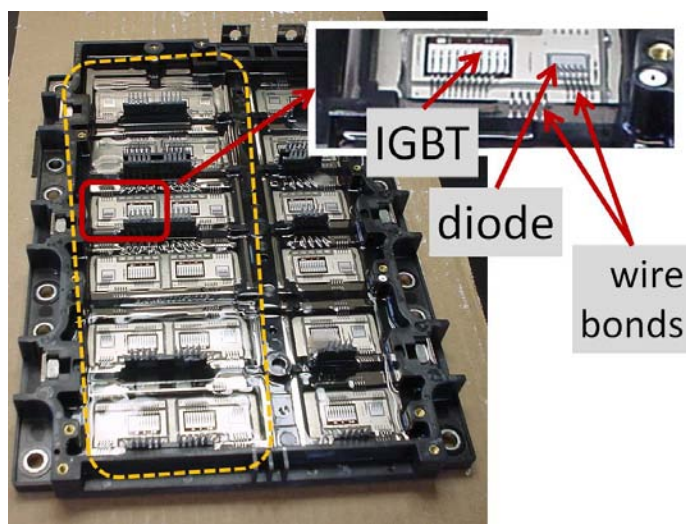

Figure 1. Example of Hybrid Electric Vehicle Inverter

Model Geometry

The geometry used for the devices is similar in size, shape, and layout to that of commercial hybrid inverters. In our design, we employ an elliptical pin-fin heat exchanger (see Figure 2). The large rectangular region on the top of the model is the IGBT. The smaller square device is a diode. Below the IGBT and diode is a direct bond copper (DBC) substrate consisting of a top copper metallization layer, a substrate layer of aluminum nitride (AlN), and a lower copper layer. The IGBT and diode are soldered to the DBC. In turn, the DBC is soldered to the next layer down, which is a base plate. The base plate is fixed to the heat sink via bolts (not shown) and contains a thermal interface material (TIM) to create good thermal contact. Note that newer designs integrate the base plate and heat sink into one solid item. The advantage of having a separate heat sink and base plate is that inverter manufacturers can create inverters separate from end-use heat exchanger designs. The disadvantage lies in the need for thermal interface materials that can cause a bottleneck for heat transfer.

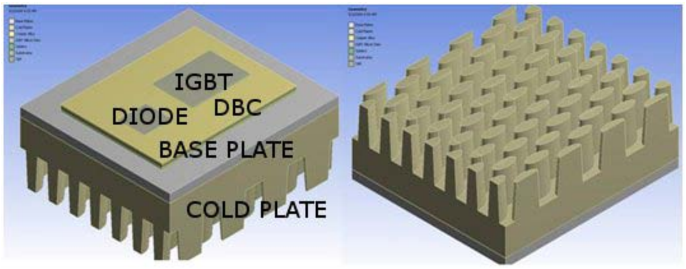

Figure 2. Physical Model of Subsection of Inverter

The geometry of the inverter and thicknesses of the layers are shown in Figure 3 and Figure 4. Additional details, including general trends for the heat transfer performance of this inverter design, can be found in [15]. Note that the dimensions used are based on actual measurements from a commercial inverter.

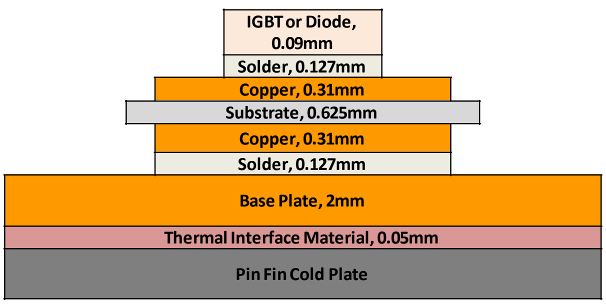

Figure 3. Layer Thicknesses and Materials

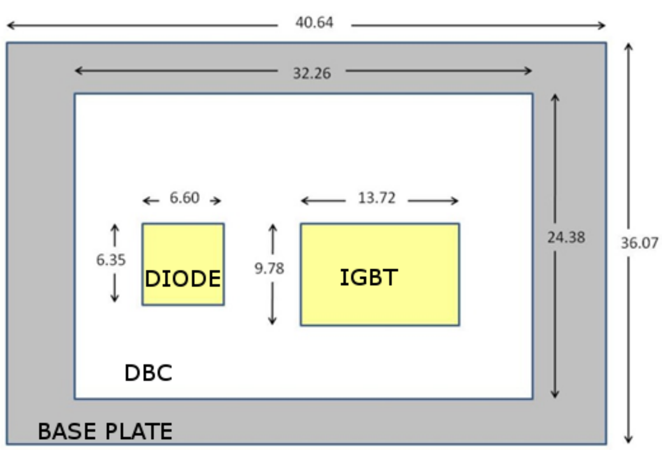

Figure 4. Inverter Subset Dimensions (mm)

Material Properties and Fatigue Model

The material properties used for the model were obtained from [16]. An important set of properties used in this study are solder fatigue properties which are given in Table 1 and estimated from the material properties and [17].

Table 1. Fatigue Properties of 63sn-37pb Solder

Fatigue Property	Value
Fatigue Strength Coefficient (MPa)	93.3
Fatigue Strength Exponent	-0.085
Fatigue Ductility Coefficient (MPa)	1.0×10^{-6}
Fatigue Ductility Exponent	-0.6
Cyclic Strength Coefficient (MPa)	93.3
Cyclic Strain Hardening Exponent	0.15

The solder joints can experience both elastic and plastic deformation during high-temperature excursions. The stresses that occur in the solder joint arise due to thermally induced stresses caused by differences in coefficients of thermal expansions between layers of the inverter module. The model we use to account for the elastic and plastic strain conditions is the Coffin-Manson strain-life relationship:

$$\frac{\Delta\epsilon}{2} = \frac{\sigma_f'}{E} \cdot \left(2 \cdot N_f\right)^b + \epsilon_f' \cdot \left(2 \cdot N_f\right)^c \qquad (1)$$

In (1), $\Delta\epsilon$ is the change in strain due to the application of our loading condition. The factor of 2 occurs because (1) is derived under the assumption of completely reversed loading—i.e., a load is fully applied in one direction and then applied at the same magnitude in the opposite direction. Thus, the total change in strain for the application of a load in one direction is half the total. N_f is the number of cycles to failure (the parameter of interest). E is the modulus of elasticity.

The remaining four terms are fatigue strength coefficient, σ_f', fatigue strength exponent, b, fatigue ductility coefficient, ϵ_f', and fatigue ductility exponent, c. The first term on the right-hand side of (1) accounts for cycles to failure under elastic deformation, while the second term accounts for cycles to failure under plastic deformations. An in-depth derivation and discussion of this relationship and the parameters that are used can be found in Chapter 7-2 of [18] and Chapter 2 of [17]. A discussion of the engineering behind the fatigue module that implements the strain-life model in our finite element tool can be found in [19]. We are not currently set up to incorporate a viscoplastic effect with this model but are exploring its use in future models.

Thermal Boundary Conditions

The model is assumed to have adiabatic boundary conditions everywhere other than the heat sink. Thermal boundary conditions at the heat sink correspond to an average heat transfer coefficient of approximately 10,500 W/m^2.K at the pin-fins and 1,200 W/m^2.K on the underside of the heat sink. The heat transfer coefficients are estimated from a combination of computational fluid dynamics models and empirical correlations such as from [20].

The coolant being assumed is a 50/50 by mass mixture of water and ethylene glycol at 10 liters per minute flow rate total (equal to 5 liters per minute through the pin-fin array explicitly shown in the model). The coolant temperature under the device is assumed to be 105°C, which is a condition of interest to the FreedomCAR and Fuel Electrical and Electronics Technical

Team. A discussion of the rationale and motivation for the FreedomCAR and Fuel Partnership, as well as the coolant temperature setting, can be found in [1].

Loading Cycle

Heat generation in the IGBT and diodes of an inverter during normal operation is due to a combination of on-state and switching losses. This heat is simulated in the model as a constant heat input at the IGBT and diodes, respectively. Heat is assumed to be transferred only through the heat sink. All other boundary conditions are assumed to be adiabatic. The inverter is typically packaged under the hood in a casing as part of a larger power module. A silicone gel is typically layered on the top of the inverter surface to protect it from direct exposure to the environment. Although heat may be conducted through the wire bonds themselves, we have taken the conservative assumption that no heat is transferred through the top of the inverter.

Although an automotive inverter is subjected to other loading conditions—most notably, vibrations and corrosive environments—we have chosen only one loading condition for consideration during this study.

The loading cycle used in this study is similar to power cycling. The simulation test is equivalent to heating the inverter under its own power to steady-state conditions and then allowing the inverter to cool back to the initial ambient condition. Note that we do not take transient phenomena such as creep into account during this process.

Variational Parameters

Three parameters of the inverter design were chosen to be stochastic in nature to study how these input parameters affect solder joint fatigue life. The first input parameter is heat generation at the IGBT, which represents a variation in loading. Note that the diode heat generation is a constant 15.5 W.

The next parameter is the thermal conductivity of the solder joint, where we are assuming that some initial voiding of the solder is affecting the overall thermal conductivity of the joint. This represents a variation in manufacturing. The impact of voids on thermal impedance depends on the type and location of the void and is nonlinear due to spreading resistance [21, 22]. Thus, we do not have a direct correlation between solder void fraction and thermal impedance. We assume that there is no significant voiding near the corners, where we expect the solder to initially fatigue.

The third parameter we explore is the thermal conductivity of the AlN substrate, which represents variation in material properties.

The probability density functions for these three parameters have been estimated from the following sources. For the heat generation, estimates were taken from a study of heat generation in a Toyota Prius test car, but scaled up to levels corresponding to the FreedomCAR and Fuel partnership targets for a 55 kW traction motor system (see [23] for details). The variation in thermal conductivity of the solder joint is assumed to arise from variations in solder material properties and variation in void fraction of the solder. Reference [21] gives a good correlation between void percentage and increase in thermal impedance. Finally, the variation in the AlN thermal conductivity is an estimate based on the range of material properties seen for available products [24-27].

A graphical representation of the sampled probability density functions for these variational parameters is given in Figure 5. The ordinate or vertical axis for each parameter shows the number of simulation runs carried out at the given value along the abscissa or horizontal axis. The actual distributions of the variational parameters are not known, so normal distributions were assumed.

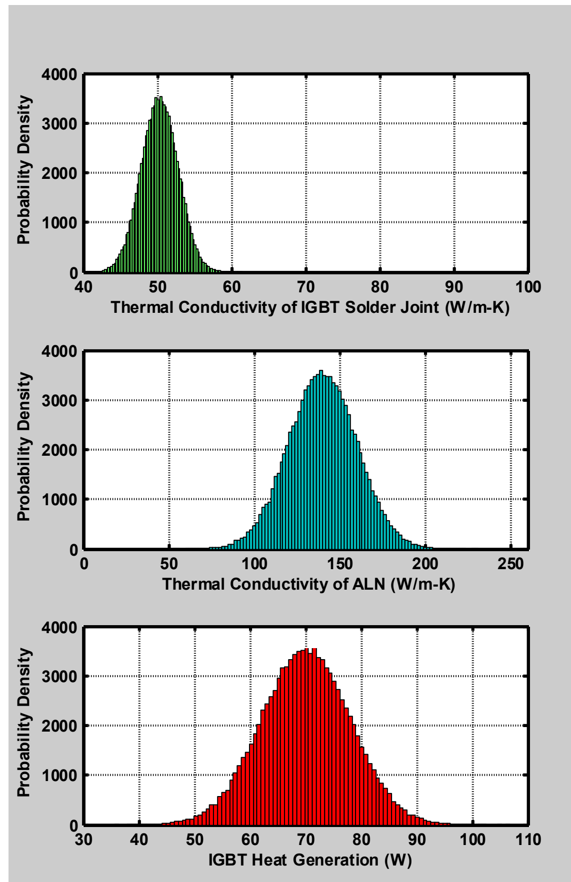

Figure 5. Variational Parameter Probability Density Functions

WORKFLOW

Simulation proceeds by inputting values from the categories of geometry and boundary conditions, material properties, and loading profiles into the physical models. A suite of analytical tools then runs a thermal simulation and a structural simulation; the Coffin-Manson relation is then used to estimate fatigue of the solder joint. Finally, the outputs from the various physical models are obtained. This process is depicted graphically in Figure 6. Variational parameters are handled by sampling various combinations of the input values and rerunning the simulation tool suite. Note that multiple runs can be performed very quickly under conditions in which the input loading changes by some constant factor in comparison to a reference case. Under these circumstances, only the reference case needs to be fully run, and the results can be scaled to determine all other cases.

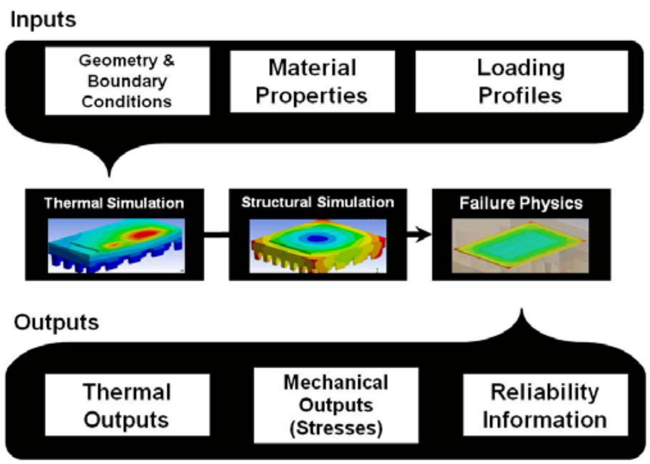

Figure 6. Simulation Workflow

The sampling of two variational parameters (AlN thermal conductivity and solder joint thermal conductivity) is depicted in Figure 8.

RESULTS

The thermal and fatigue results are presented in the sections that follow. In addition, we show how concepts from robust design could be applied to interpret the results.

Thermal Results

Because the magnitude of the heat generated by the IGBT is higher than that of the diode, we see the highest temperatures consistently occurring on the IGBT device itself. Maximum temperature varies stochastically with the input variable distributions, and the IGBT heat rejection is the most significant. A snapshot of the temperature distribution across the model is given in Figure 7. The output distribution of maximum IGBT temperature is given in Figure 10. A maximum specification limit of 150^{o}C is assumed for the IGBT.

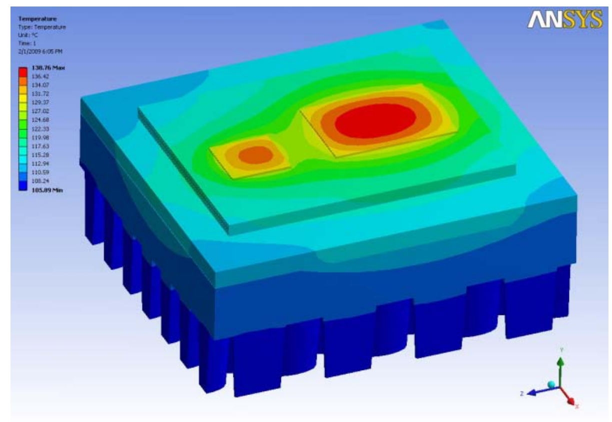

Figure 7. Temperature Distribution (T_{max} = 138.8)

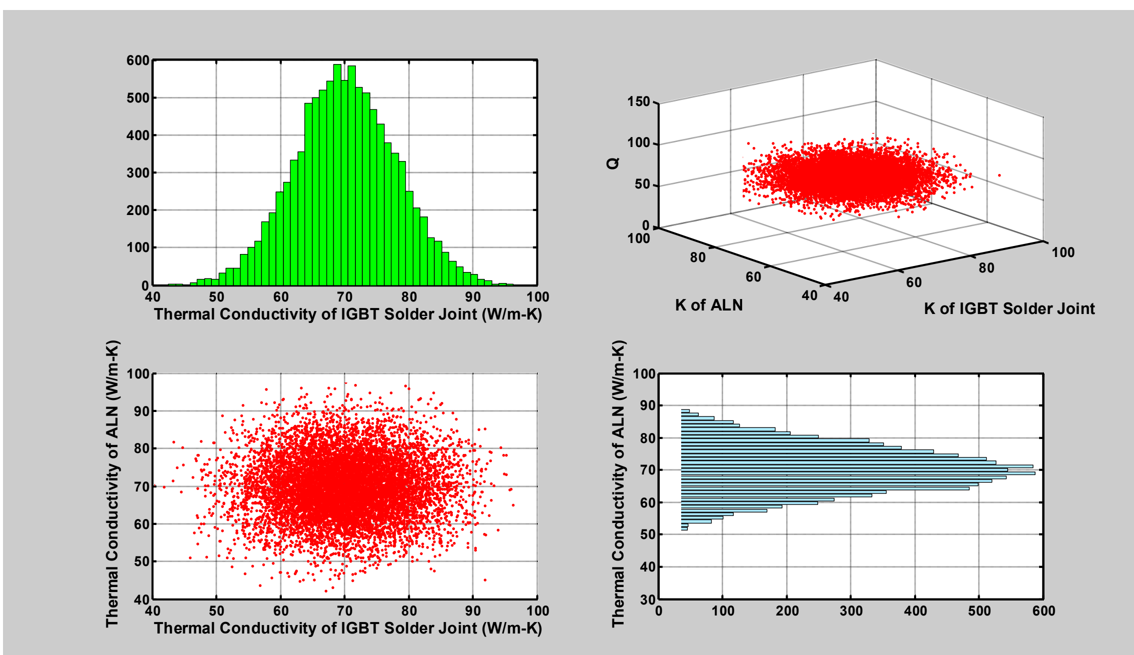

Figure 8. Sampling Variational Parameters

Fatigue Results

In this section, we look at the cycles to failure of the IGBT solder joint. For a discussion of failure prediction for other solder joints in the package, see [28]. We define failure to represent the number of cycles until the onset of cracking in the solder joint. Upon onset of cracking, the device may survive additional cycles as the crack propagates and eventually causes the effective thermal conductivity to get so low that the device junction temperature goes above specification limits and/or the die becomes completely unattached.

The highest areas of stress occur at the edges and corners, resulting in cracks propagating from these locations. This can be seen in the plot of cycles to failure in Figure 9. This same phenomenon can be seen in the literature [29, 10] and can be explained through simple analytical models of stresses in epitaxial layered devices (see, for example, [12]).

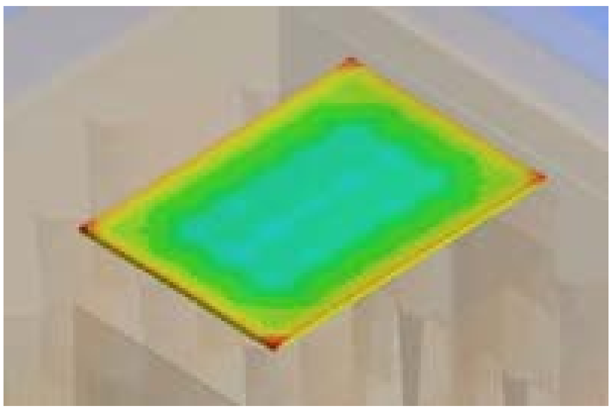

Figure 9. Fatigue Life of IGBT Solder

Robust Design Investigation

In this section, we show the output distributions that arise from the stochastic inputs used (see Figure 5). In Figure 10, the distribution of maximum IGBT temperature is shown. As can be seen, the output distribution of maximum junction temperature is within an acceptable range for the problem setup chosen. The results are normally distributed, and the number of standard deviations away from the mean is plotted on the graphs.

A cycle life of 22,000 cycles was selected for a desired life of this product based on 4 cycles per day, 365 days per year, and a target 15-year life. Figure 11 shows the distribution of cycles to failure and indicates that the IGBT die attach, under the given conditions, would survive the 15-year life with >99% confidence.

The influence of the input parameters on the final results is presented in Figure 12 and Figure 13. The influence is calculated by normalizing the difference between the output result when the input parameter is high and when the input parameter is low. As can be seen, the thermal loading has the highest influence on both the solder joint reliability and the maximum package temperature, which indicates the importance of knowing the usage environment for reliability work.

CONCLUSIONS

This paper presented a methodology for taking variable input parameters into account during a solder die attach fatigue analysis for an automotive inverter of an electric traction drive vehicle. Since the inverter, its boundary conditions, and loading conditions were invented for the purpose of this analysis, we must be careful in drawing specific conclusions about overall inverter performance. Specifically, several failure mechanisms associated with an automotive inverter are not taken into account in the current study (for example, wire bond fatigue failure and substrate cracking). Furthermore, our failure physics model did not take viscoplastic effects such as creep into account.

For the conditions evaluated in this study, the thermal loading condition was shown to have the strongest effect on the output parameters of temperature and fatigue life. Although we did not look at an extensive list of variational parameters, the large impact that heat generation has on fatigue life highlights the importance of understanding the mission profile to which the inverter will be subjected.

Using the design process presented, we have shown that one may be able to estimate the fatigue life of a power inverter for automotive applications using commercially available software. This method allows the designer to understand how variation in input parameters and mission profile can affect metrics of interest, such as fatigue life.

Further work on transient heat generation should be conducted using vehicle systems tools to better estimate a loading profile in place of the simple loading cycle used in this study. Additional loads, such as vibrations, should also be taken into account along with a more comprehensive analysis of additional failure modes and mechanisms (such as wire bond flexural fatigue and substrate cracking). Validation testing will be critical to confirm model predictions. Once these additions are made to the scope of the problem, a meaningful robust design optimization can be attempted.

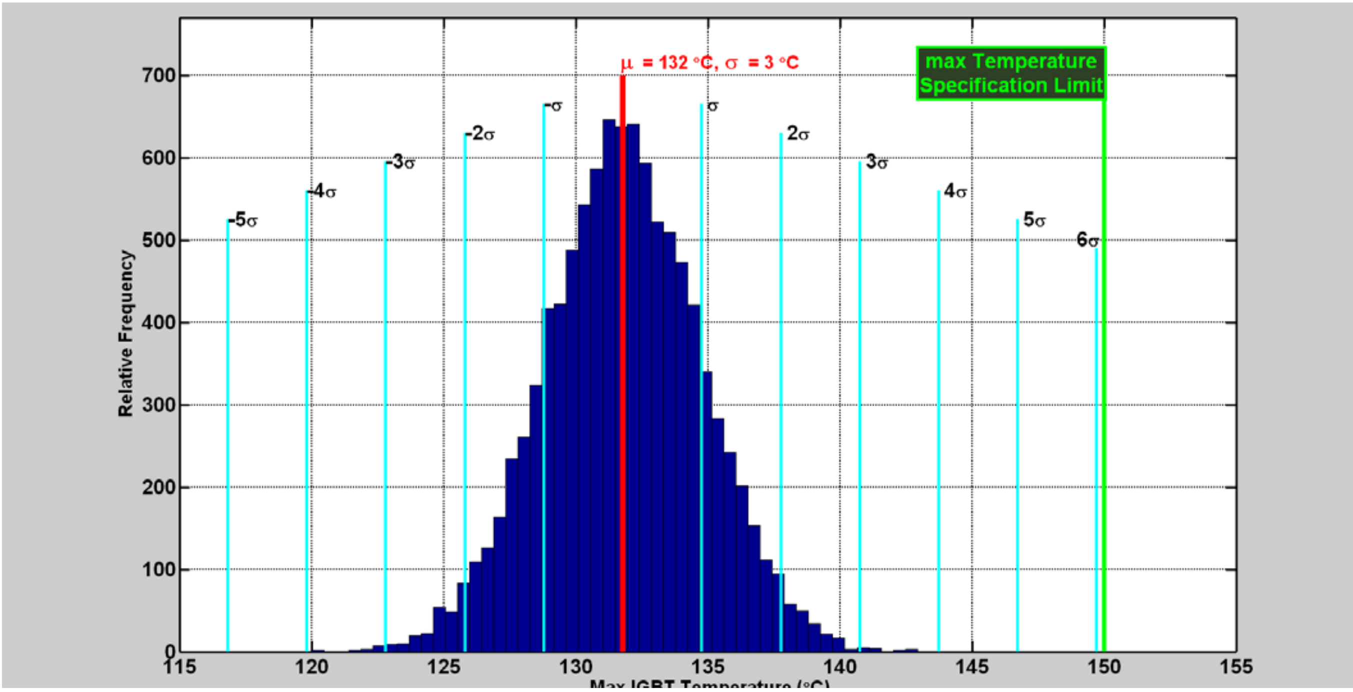

Figure 10. Maximum IGBT Temperature Distribution

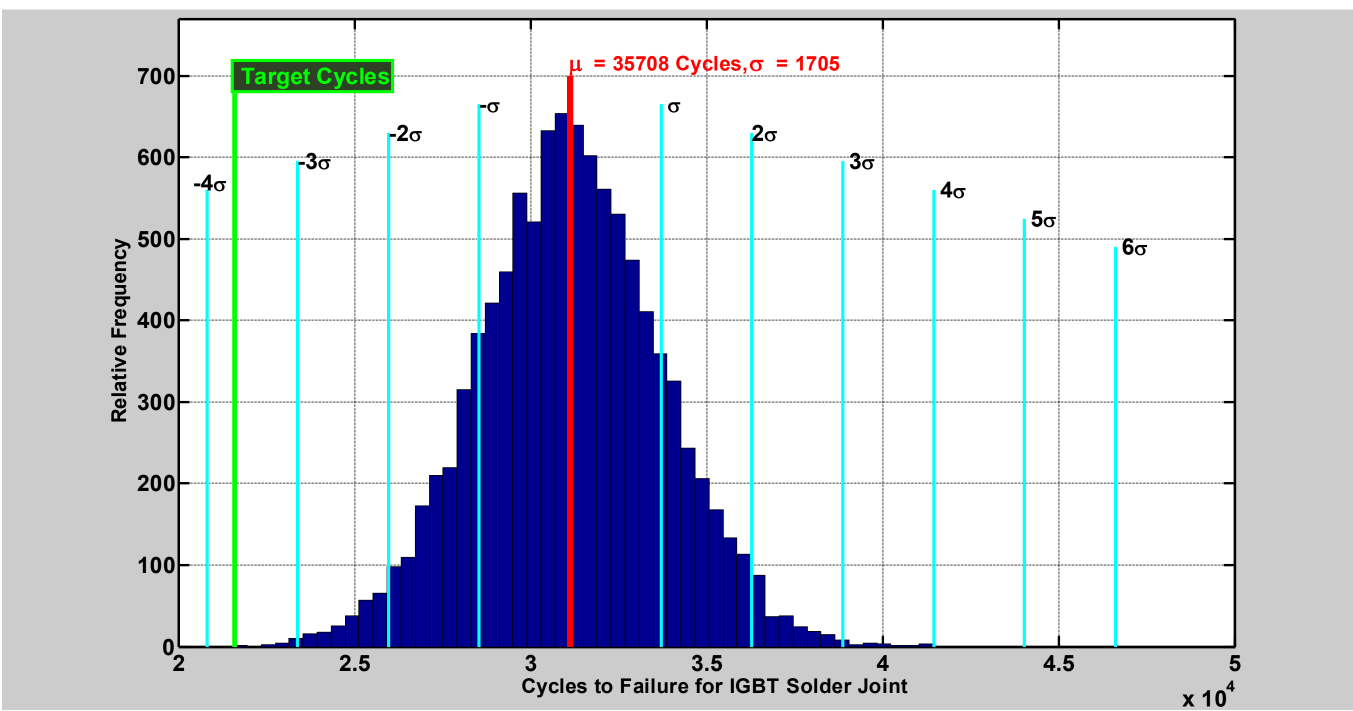

Figure 11. Distribution of Cycles to Failure of IGBT Solder Joint

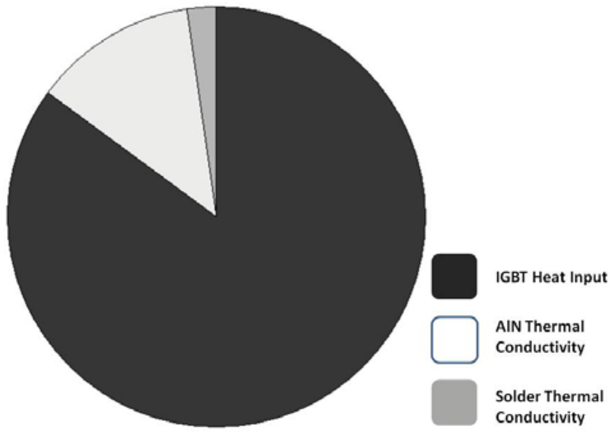

Figure 12. Influence of Inputs on Maximum Temperature

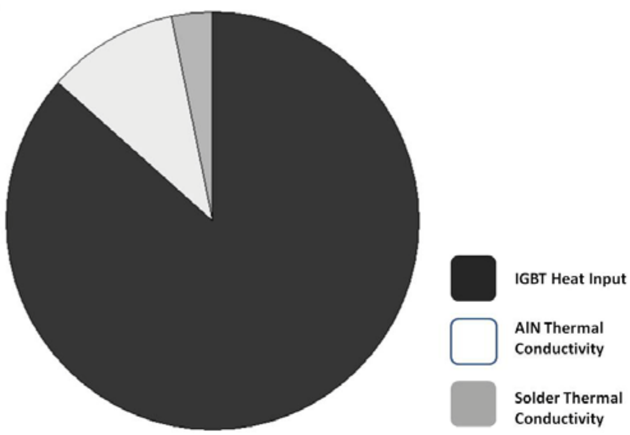

Figure 13. Influence of Inputs on IGBT Solder Fatigue

NOMENCLATURE

IGBT	integrated gate bipolar transistor
$\Delta\epsilon$	change in strain due to loading
N_f	number of cycles to failure
E	modulus of elasticity (Young's Modulus)
σ_f'	fatigue strength coefficient
b	fatigue strength exponent
ϵ_f'	fatigue ductility coefficient
c	fatigue ductility exponent
PDF	probability density function

ACKNOWLEDGMENTS

We would like to acknowledge Susan Rogers of the U.S. Department of Energy's Vehicle Technologies Program for funding this effort.

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
June 2010

2. REPORT TYPE
Conference Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Sensitivity of Solder Joint Fatigue to Sources of Variation in Advanced Vehicular Power Electronics Cooling

5a. CONTRACT NUMBER
DE-AC36-08-GO28308

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
A. Vlahinos, Advanced Engineering Solutions
Michael O'Keefe, NREL

5d. PROJECT NUMBER
NREL/CP-540-46417

5e. TASK NUMBER
FC08.7000

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-540-46417

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
This paper demonstrates a methodology for taking variation into account in thermal and fatigue analyses of the die attach for an inverter of an electric traction drive vehicle. This method can be used to understand how variation and mission profile affect parameters of interest in a design. Three parameters are varied to represent manufacturing, material, and loading variation: solder joint voiding, aluminum nitride substrate thermal conductivity, and heat generation at the integrated gate bipolar transistor. The influence of these parameters on temperature and solder fatigue life is presented. The heat generation loading variation shows the largest influence on the results for the assumptions used in this problem setup.

15. SUBJECT TERMS
power electronics; power electronics cooling; solder joint fatigue analysis

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
Unclassified	Unclassified	Unclassified	UL		19b. TELEPHONE NUMBER (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18