Thermomechanical Modeling of Sintered Silver – A Fracture Mechanics-based Approach: Extended Abstract

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Thermomechanical Modeling of Sintered Silver – A Fracture Mechanics-Based Approach

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Abstract
Sintered silver has proven to be a promising candidate for use as a die-attach and substrate-attach material in automotive power electronics components. It holds promise of greater reliability than lead-based and lead-free solders, especially at higher temperatures (>200°C). Accurate predictive lifetime models of sintered silver need to be developed and its failure mechanisms thoroughly characterized before it can be deployed as a die-attach or substrate-attach material in wide-bandgap device-based packages. We present a finite element method (FEM) modeling methodology that can offer greater accuracy in predicting the failure of sintered silver under accelerated thermal cycling. A fracture mechanics-based approach is adopted in the FEM model, and J-integral/thermal cycle values are computed. In this paper, we outline the procedures for obtaining the J-integral/thermal cycle values in a computational model and report on the possible advantage of using these values as modeling parameters in a predictive lifetime model.

Key words
J-integral, predictive lifetime model, sintered silver, thermomechanical modeling, power electronics.

I. Introduction
A power electronics package in an automotive inverter, as shown in Fig. 1, will need to be redesigned with novel materials if it is to withstand the thermal and mechanical challenges brought about by the usage of wide-bandgap devices and elevated temperatures. Materials that can reliably operate at higher temperatures (>200°C) for long periods of time need to be used. Sintered silver is one such material that has proven to be a promising candidate for use as a bonded material at the interfaces. As opposed to certain solders, it can reliably operate at higher temperatures without significant creep issues while still efficiently conducting heat away from the devices. Although the choice of sintered silver in electronics packages is not fully without any drawbacks due to the requirement of higher application pressures (~40 MPa) for bonding, research over time has led to several manufacturers to develop sintered silver materials that require lower (3–5 MPa) or no bonding pressures. Pressure-bonded sintered silver has even been commercially deployed as a die-attach material in inverters/converters, but large-area applications of pressure-less sintered-silver material and its reliability evaluation are still in the research and development phase.

A major output of the reliability evaluation of an interface material is its predictive lifetime model. Failure of these materials due to thermomechanical fatigue when subjected to thermal or mechanical loads in its operational environment is a major concern in the automotive industry. Inaccurate lifetime estimations of interface materials lead to a large safety factor in the design of electronics packages, which in turn results in conservative designs and increased costs. Hence, accurate predictive lifetime models are crucial to the industry in cost- and time-effective optimal designs.

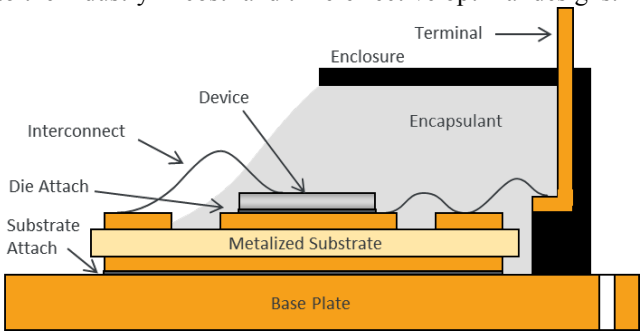

Fig. 1. A traditional power electronics package.

Predictive lifetime models based on different parameters such as stress and strain have been formulated in the past. A detailed review of the predictive models developed for solder joint fatigue is available in [1]. Among these different models, researchers have identified energy-based models to be a good indicator of solder joint fatigue. In

energy-based models, strain energy, which combines the effect of both stresses and strains in a single term, is correlated with experimentally obtained cycles to failure through a data-fitting equation. This approach can be reasonably applied to sintered-silver, provided they undergo the failure mechanisms under similar loading conditions.

Another class of lifetime models that can offer better predictive capabilities of interface material failure is fracture-mechanics-based fatigue models. Instead of strain energy density, stress intensity factor or J-integral values are computed through simulations, and then correlated with experimental results to formulate the predictive lifetime model. The rationale behind adopting a fracture mechanics-based approach is that the failure mechanisms observed for solder and sintered silver under thermal cycling is crack initiation and propagation. Hence, it can be reasonably argued that a parameter that can adequately describe the deformation and stress field around a crack front in the material can offer improved accuracy in predicting its lifetime.

In this paper, we first describe the sample and the loading conditions. Then, we explain the modeling procedure to calculate strain energy density/thermal cycle of a large-area, substrate attach in an experimental sample and also outline the modeling methodology adopted to compute J-integral/ cycle values in an FEM model.

II. Sample Description & Loading Conditions

The sample consisted of a substrate-attach bonded between a 5-mm-thick Cu baseplate and a 0.72-mm-thick direct-bonded-copper substrate with the ceramic thickness being 0.32 mm. The ceramic material was Si_3N_4. Both the baseplate and the substrate ceramic had a 50.8-mm x 50.8-mm footprint area while the edges of the substrate attach and the substrate metallization were offset by 1 mm from the outer edge of the sample. We adopted this sample configuration from a previous study that was conducted at NREL.

We created a meshed, quarter-symmetric model of the sample in ANSYS for analysis, as shown in Fig. 2. A modified thermal cycling profile based on Joint Electron Devices Engineering Council (JEDEC) standard number 22-A104D [2] was applied to the entire FEM model as the boundary loading condition. The load profile started at 25°C, the reference temperature, followed by a ramp up to 150°C, and then the cyclic loading initiated. First, the temperature was held constant at 150°C for 10 minutes, and then ramped down to -40°C. The temperature was again held constant at -40°C for another 10 minutes, and finally ramped up to 150°C to complete one cycle. The ramp rate was set at 5°C/min for both ramping phases. Also, a fixed point load was applied to the center node in addition to symmetry boundary conditions to prevent rigid body motion of the model.

In this study, we used the Anand constitutive model [3] to simulate the deformation behavior of sintered-silver, but the appropriate constitutive model to use is an aspect that requires further study. Different types of sintered-silver materials have been described in the literature, and constitutive models developed for one material type may not accurately depict the deformation process in another. Additionally, the type of constitutive model that can best represent sintered silver is still an active area of research.

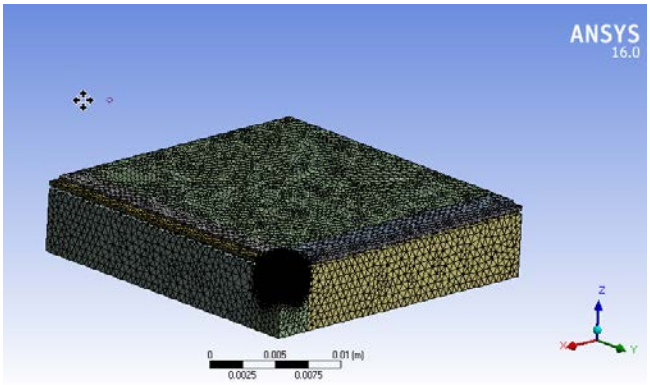

Fig.2. Quarter-symmetric model of the sample. Tetrahedral mesh is used.

III. Modeling Methodology

A. Strain Energy Density

Strain energy density at a particular node in the FEM model is the time integral of the product of stresses and incremental strains in all six directions at that node. As mentioned in the Introduction, it is a well-defined parameter that has proven to correlate well with experimental cycles-to-failure results. In the post-processing phase of the FEM model of the sample, strain energy density values were found to be higher at the corner fillet regions due to higher stress concentrations. We separated out the fillet volume at the corner region from the rest of the sample, and using ANSYS commands, computed a volume-averaged value of the strain energy density/ thermal cycle results in this region. We adopted this volume-averaging technique from [4].

B. J-integral

J-integral is an elastic-plastic fracture mechanics parameter that was developed to describe the stress and displacement fields around a crack tip or crack front. It is a contour integral computed along a counterclockwise path around a crack front and is a convenient parameter for crack tip studies mainly because of its path-independent nature. However, it has to be noted that the path independence of J-integral for elastic-plastic materials holds only under certain circumstances, such as when the material behavior can be

described based on a deformation theory of plasticity [5] or when the material is subjected to purely monotonic loading. Under such circumstances, elastic-plastic materials can be idealized as non-linear elastic materials, and J-integral effectively characterizes the crack tip stress and displacement field.

Most of the constitutive models that were developed to describe material deformation are based on an incremental theory of plasticity. In these models, material plasticity is defined in the form of a strain rate tensor as a function of other parameters such as time, temperature, and stress. A few researchers have reported that the incremental theory of plasticity mimics the deformation theory of plasticity in cases when the applied loading is proportional in all directions, and J-integral remains path-independent [6]. Nevertheless, even if the loading is non-proportional under the incremental theory of plasticity, the path-independent nature of J-integral does not completely break down [7]. It exhibits a converging trend with successive contours around a crack front. This converged value can be considered as a valid parameter to input in the predictive lifetime models. It also has to be noted that the relevance of parameters computed numerically can be justified only after developing a model incorporating experimental results and determining the accuracy of that model in predicting the lifetime of sintered-silver samples tested under different loading conditions.

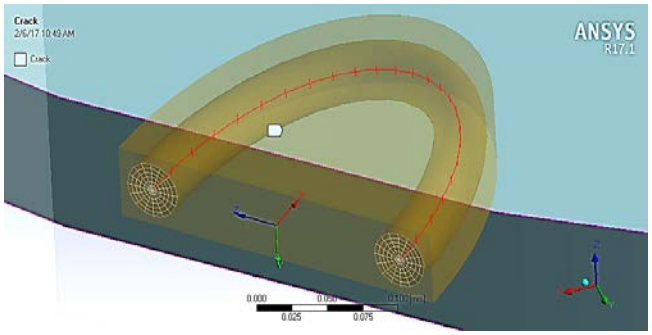

Fig. 3. Crack feature inserted in the model.

Previous simulations of sintered silver in ANSYS showed that higher values of strain energy density occur in the corner fillet regions where the cracks are likely to initiate. In order to calculate J-integral in ANSYS, we manually inserted a crack feature in the model, as shown in Fig. 3. The semi-elliptical red curve denotes the manually inserted crack front. Six contours, shown as circles that run through the entire crack front, can be seen at both ends of the crack. We discretized these features sufficiently enough to obtain convergence in the computed J-integral values. For a contour surrounding the crack front, J-integral is given by the equation:

$$J = \int_{\Gamma}(W.dy - T_i.\left(\frac{\partial u_i}{\partial x}\right).ds \quad (1)$$

Γ – contour surrounding the crack front
W – strain energy density
T_i – traction vector
u_i – displacement vector

In ANSYS, J-integral is actually computed using an energy domain integral method. More details of this method can be found in [8].

We conducted three simulations with incrementally decreasing bond pad areas to get J-integral values that correspond to different stages of crack propagation. More simulations were run computing strain energy density values as it was computationally less intense.

IV. Results & Discussions

Fig. 4 shows a plot of strain energy density per cycle value for different bond pad regions obtained through multiple simulations.

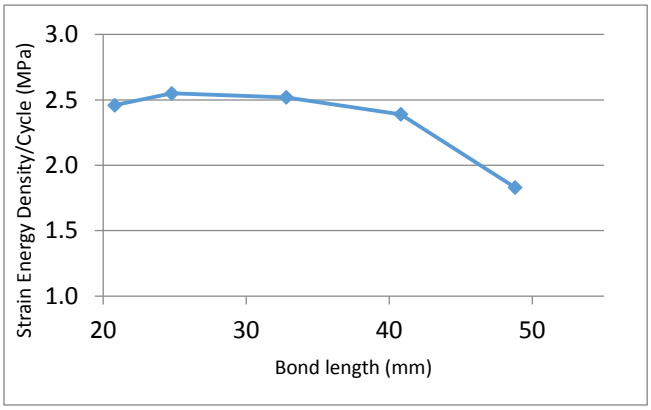

Fig. 4. Strain energy density results.

For simulations with the crack feature, a contour plot of J-integral along the crack front was obtained in the post processing phase. Analysis of J-integral values at the crack front nodes from each contour shows that path dependence becomes less pronounced with each successive contour and is within 5% to 6% after six contours. In order to avoid any singularity issues, J-integral values from the sixth contour were then averaged along the crack front nodes. Also, as J-integral is a cumulative value, it keeps increasing with each thermal cycle. Hence, J-integral over a thermal cycle range was obtained and taken as the final output. Fig. 5 shows a contour plot of J-integral along the crack front.

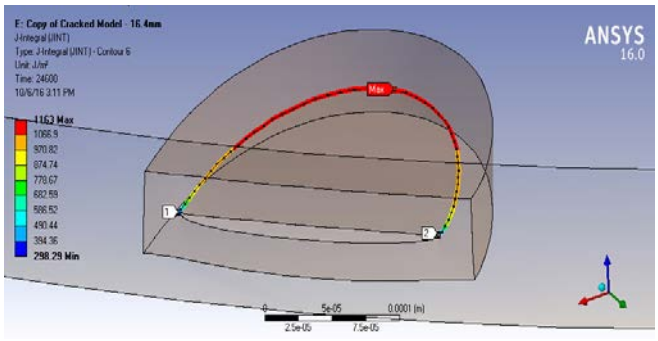

Fig. 5. J-integral plot.

A plot of J-integral/cycle values versus bond length is shown in Fig. 6. Similar to the strain energy density values in Fig. 4, J-integral values exhibit a rising trend with decreasing bond lengths.

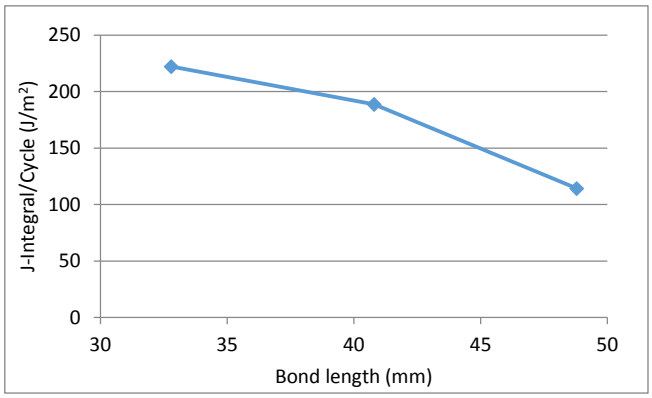

Fig. 6. J-integral versus bond length.

III. Conclusion

In this paper, we have outlined a modeling methodology to compute strain energy density and J-integral values of sintered-silver material in a representative power electronics package. J-integral, despite its perceived limitations in applicability to materials defined using an incremental plasticity theory, can be used as a modeling parameter input in predictive lifetime models. With successive contours around a crack front, it exhibits a converging trend and becomes more or less path-independent. Finally, the relevance of these parameters for use in predictive lifetime models can be determined only based on the accuracy of the model when applied to similar sintered-silver material bonded configurations subjected to different loading conditions.

The next steps in this project include efforts to develop an appropriate constitutive model for pressureless sintered silver and obtaining experimental cycles-to-failure results. With experimental results in place, predictive lifetime models will be formulated based on both strain energy density and J-integral values separately, and their accuracy will be tested under different loading conditions.

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