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Simulation And Experiment of Thermal Fatigue In The CPV Die Attach

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Abstract. FEM simulation and accelerated thermal cycling have been performed for the CPV die attach. Trends in fatigue damage accumulation and equivalent test time are explored and found to be most sensitive to temperature ramp rate. Die attach crack growth is measured through cycling and found to be in excellent agreement with simulations of the inelastic strain energy accumulated. Simulations of an entire year of weather data provides for the relative ranking of fatigue damage between four cites as well as their equivalent accelerated test time.

Keywords: Thermal Fatigue, Accelerated Lifetime Testing, FEM, CPV, Die Attach, Solder, Strain Energy
PACS: 88.40.jp, 62.20.me, 92.60.Wc

INTRODUCTION

When in service under concentrated direct sunlight, the cell assembly in a concentrating photovoltaic (CPV) module will experience a complex time history of temperature. This history will contain many temperature reversals, or thermal cycles, that will impart stress to the die attach due to a mismatch in coefficient of thermal expansion between the cell and its substrate. With every cycle, inelastic strain energy will be gained by the die attach. The accumulation of this energy will lead to die attach cracking and ultimately to cell failure. A finite element model (FEM) has been created to quantify the thermal fatigue damage of the CPV die attach. The model is employed to simulate how the parameters of accelerated thermal cycling influence the rate of fatigue damage accumulation. Accelerated thermal fatigue experiments that measure the rate of die attach crack growth are conducted to begin validation of these simulations.

Quantifying thermal fatigue, which provides for comparison among accelerated thermal cycles, similarly allows for comparison between chamber thermal cycling and temperature changes encountered through actual service conditions. To this end, the weather in several geographic locations is used as input into the model. The damage accumulated through service and accelerated testing then provides for a direct calculation of the equivalent service time of the test sequence.

METHODS

FEM Simulation

We simulate the solid mechanics of the CPV cell assembly using the finite element method [1]. We use the Anand model to compute the viscoplastic material response in the solder layer using properties for 60Sn40Pb solder [2]. For a given history of temperature conditions, this model computes the inelastic work accumulated in the solder layer. For accelerated test cycles, the temperature throughout the cell assembly is assumed to be uniform and is prescribed according to the test cycle promulgated by IEC 62108. For outdoor exposure, we use an empirical fit to compute cell and heat sink temperature histories from measurements of direct normal irradiance (DNI), ambient temperature and wind speed with time resolution of one minute. The model uses the value of inelastic work accumulated to reflect lumped progress toward failure. We propose that a typical cell assembly will fail after it has sustained a characteristic quantity of damage. By comparing the damage done by exposure to various thermal conditions, a given assembly's relative lifetime in those conditions can be estimated.

We simulated accelerated test cycles based upon the IEC 62108 type TCA2 cycle (–40 to 110 °C, 60 minute ramps, 10 minute dwells), with changes to the hot and cold dwell times and ramp rates. To explore the effect of cold dwell time, the hot dwell time is held constant at 10 minutes and the cold dwell set at 0, 10 and 100 minutes. Similarly, to explore the effect of hot dwell time, the cold dwell time is held constant at 10 minutes and the hot dwell set at 0, 10 and 100 minutes. Finally, while holding the hot and cold dwell constant at 10 min, the ramp rate between dwells is set to 3.75, 7.5, 15 and 30 °C/min. All corresponding damage results are normalized with respect to that of the standard TCA2 cycle.

One year of derived cell temperature data for Golden, Colorado, Phoenix, Arizona, Oakridge, Tennessee and Las Vegas, Nevada were used as input to the FEM model. The method of deriving transient cell temperature from frequent measurements of ambient temperature, direct normal irradiance (DNI) and wind speed has been previously presented [1, 3]. Cell temperature is assumed to be off-set from the module temperature by a contribution proportional to DNI and fitted from experiment. The model is based on the same generic cell assembly employed in the thermal cycling simulations and therefore provides for a direct comparison of accumulated thermal fatigue damage.

Thermal Cycling Experiments

CPV cell assemblies were thermally cycled in two chambers, one with five-minute dwells and 15°C/min ramp rates between −40 and 110 °C (15 samples) and one with 10 minute dwells and 7.5°C/min ramp rates between −40 and 110 °C. (11 samples). The assemblies were periodically removed from cycling for evaluation via C-Mode Scanning Acoustic Microscopy (CSAM) to image the extent of crack growth. The amount of inelastic work accumulated through each set of cycling conditions was simulated with the FEM for the cell assembly design tested. Validation of the FEM is begun through comparison of the simulation and experimental results.

RESULTS AND ANALYSIS

Simulation

The modified temperature cycles and resulting accumulation of damage are shown in Figures 1–3. Changing the cold dwell time has the larger effect on damage rate, where decreasing the dwell to 0 min decreases the accumulated damage by 9%. Similarly decreasing the hot dwell time only decreases the accumulated damage by ~2%.

Stress in the solder layer relaxes during the hot dwell period, enabling high stresses to develop during the cooling ramp, during which the majority of the damage in the standard cycle is done. But the high temperature of accelerated test cycles enables substantial stress relaxation to occur even when the hot dwell time is zero. Thus the damage per cycle is relatively insensitive to changes in the hot dwell time. The kinetics of plastic flow in the solder are slowed at low temperatures, so stress relaxation occurs more slowly during the cold dwell period. Increasing the cold dwell time allows more relaxation to occur, enabling the heating ramp to accumulate more damage.

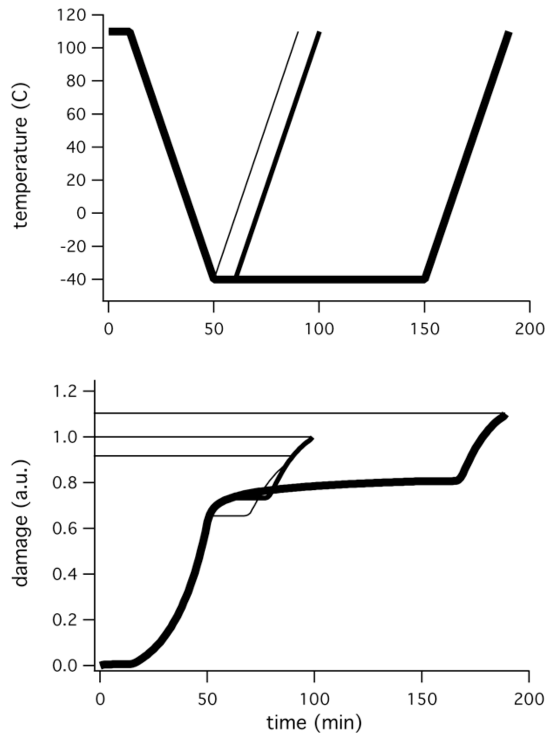

FIGURE 1. Temperature profiles and simulated accumulated damage for varying cold dwell times.

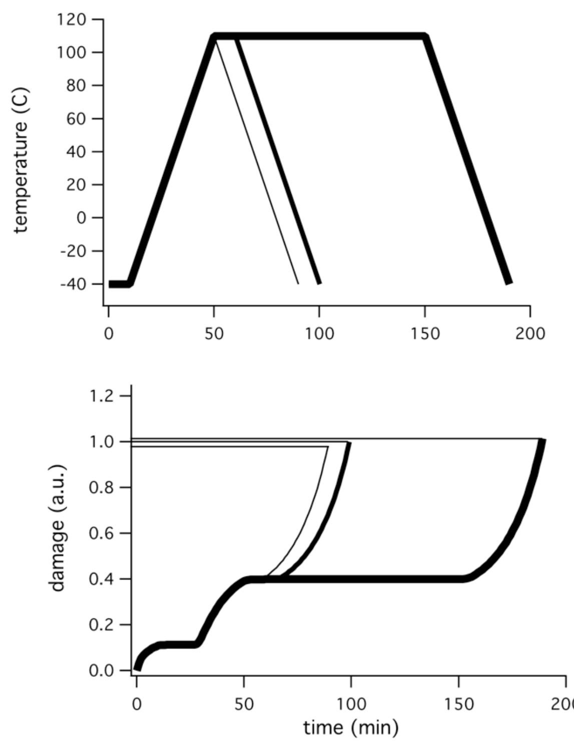

FIGURE 2. Temperature profiles and simulated accumulated damage for varying hot dwell times.

Increasing the ramp rate increases the damage done per cycle primarily by increasing the damage done during both ramps, Fig. 3. Faster changes in temperature cause higher stresses to develop in the solder layer before plastic flow can cause them to relax, resulting in more damage during the ramp period. More damage is also done during the dwell times because the solder layer is subjected to higher stress at the beginning of each period.

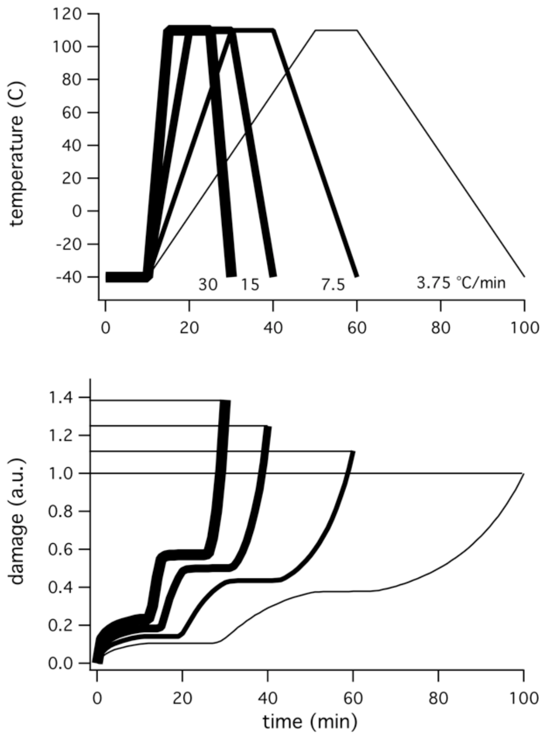

FIGURE 3. Temperature profiles and simulated accumulated damage for varying ramp rates.

The normalized test time for the cycles with modified dwell time and ramp rate are shown in Figs. 4 and 5. These plots illustrate the influence each parameter has on overall test time, and are normalized with respect to the standard cycle (10 minute dwell, 3.75 °C/min). Therefore the normalized test time describes test times that will accumulate similar amounts of fatigue damage. With a practically inverse relationship, doubling the temperature ramp rate has the potential of halving the overall test time. While decreasing both dwell times from the standard 10 minutes will also reduce the overall test time, the magnitude of this effect is much smaller and appears to increase back to unity as the hot dwell time approaches zero.

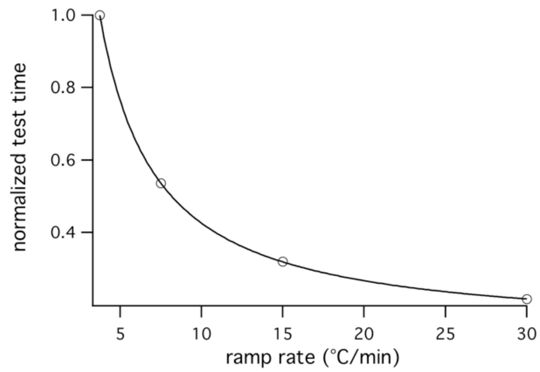

FIGURE 4. Normalized test time for increasing temperature ramp rates.

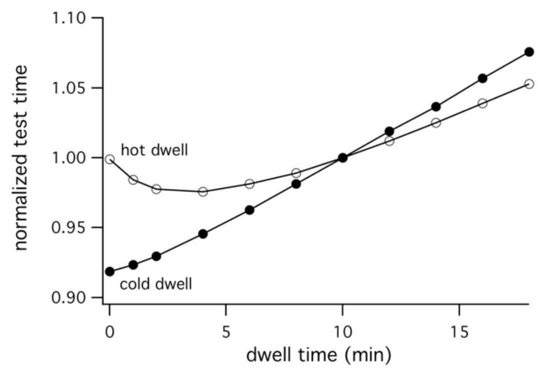

FIGURE 5. Normalized test time for increasing hot and cold dwell times.

The FEM simulation of the two experimental thermal cycles is presented in Fig. 6. According to these simulations, the cycle with the slower ramp rate accumulates 66 % of the damage of the faster cycle. If the total cycle time is also considered, the faster cycle accumulates damage 2.5 times faster than the slower cycle.

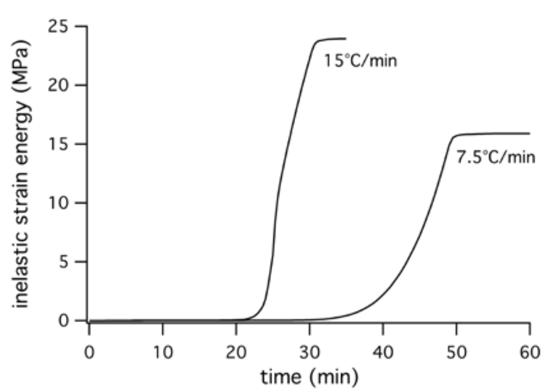

FIGURE 6. FEM simulated accumulation of inelastic strain energy (damage) for the two experimental thermal cycles.

Thermal Cycling

The results of the thermal cycling experiments are summarized in Fig. 7. Crack area percent was measured relative to the complete cell area from CSAM images. Crack area emanating from multiple corners was not differentiated in the measurements and therefore is included in the total area calculation. The same measurements are presented in terms of test time in Fig. 8.

A Weibull plot of expected cell failure is presented in Fig. 9. The failure criterion is defined as a 3.5 area% crack. This value was chosen as it was previously shown sufficient to precipitate thermal runaway and failure of the CPV cell [4]. The Weibull fits are detailed in Table 1 and demonstrate that the faster ramp rate test results in a mean number of cycles to failure that is 68 % of the number required for the slower test. This experimental result is in excellent agreement with the FEM simulations of these thermal cycles which calculated a 66 % difference in the damage accumulated per cycle. In terms of test time, the higher rate and shorter dwell time cycle reaches the failure criterion ~2.5 times faster than the slower ramp rate cycle, also as predicted by the FEM simulation, Fig. 8.

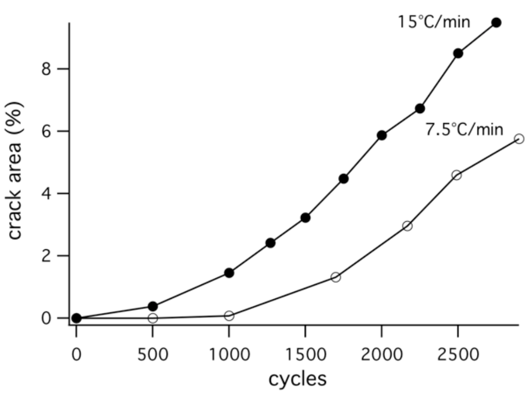

FIGURE 7. Crack growth vs. number of cycles.

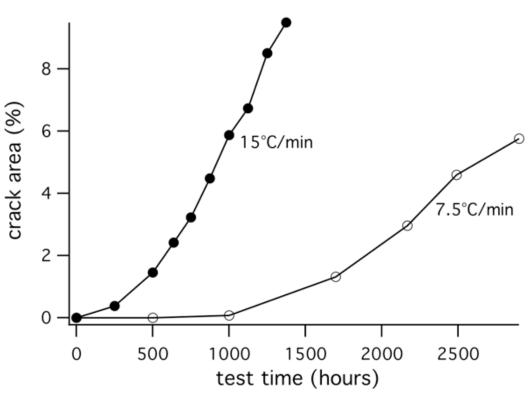

FIGURE 8. Crack growth vs. test time.

ramp rate °C/min	shape m	mean N
7.5	9	2500
15	6	1700

TABLE 1. Weibull fit of die attach failure.

For each distribution, the failure rate is increasing with time, suggesting this mode is an aging process and the cell assemblies are more likely to fail as cycling continues.

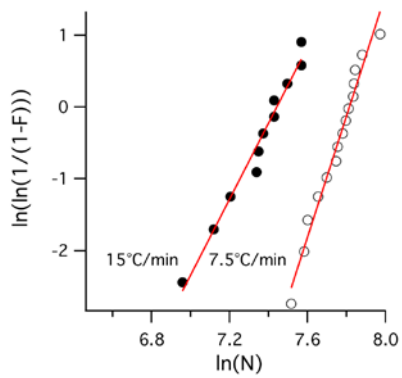

FIGURE 9. Weibull plot of die attach failure.

Service

The simulated damage accumulated through a year of exposure in the four cities is presented in Fig. 9. These values are normalized with respect to the standard TCA2 cycle previously simulated. The gap in data for Las Vegas is a result of corrupt weather data that we were not able to model, therefore the results are interpolated through this period. The result suggests that one year of exposure in Golden, Colorado is equivalent to ~80 standard TCA2 thermal cycles and that the full IEC 62108 thermal cycling sequence is equivalent to 6-8 years exposure in the cities simulated.

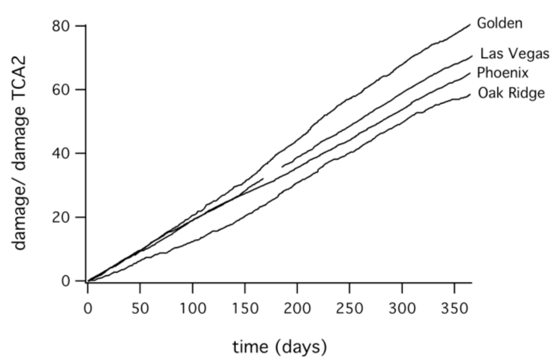

FIGURE 10. Normalized damage for one year in the four cities modeled.

These absolute results are only pertinent to the generic package modeled, including its derived module temperature and cell temperature off-set. The relative results between cities, however, are expected to be fairly independent of these specific factors.

CONCLUSIONS

We have shown how different kinds of temperature changes cause different amounts of damage in the CPV die attach layer. Thermal cycles with long dwell times and fast ramp rates cause more damage per cycle than those with short dwell times and slow ramp rates. When damage per cycle is divided by total cycle time, the equivalent total test time is only weakly dependent on dwell time but still strongly correlated with ramp rate. Therefore increasing ramp rate appears to be the most practical approach to develop a more highly accelerated thermal cycling test. Achieving test cycle ramp rates as high as 30°C/min may be technically difficult, particularly with test equipment that is designed for the standard cycles. Unconventional test equipment, such as equipment that tests only the cell assembly instead of the entire module or equipment that heats the cells with forward bias for example, may be the route to achieve these higher ramp rates.

The results of initial experiments correspond well with FEM simulations. These observations have begun to validate our approach of using the value of inelastic work accumulated to reflect lumped progress toward failure. This methods provides for the calculation of an equivalent test time: the number of accelerated thermal cycles equivalent to a period of outdoor exposure. Employing this method, we found one year of service in Golden is equivalent to ~80 TCA2 thermal cycles for the generic cell assembly modeled. This translates to the entire TCA2 test sequence being equivalent to a ~6 year exposure in Golden. Varying the cell assembly design and operating temperature will affect this calculation, however the relative comparison between cities should remain similar regardless of these factors.

ACKNOWLEDGEMENT

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