**SOLDER FATIGUE REDUCTION IN POINT FOCUS
PHOTOVOLTAIC CONCENTRATOR MODULES***

SAND--91-0462C

DE92 002006

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ABSTRACT

Solder fatigue tests have been conducted on point focus photovoltaic concentrator cell assemblies to identify a baseline fatigue life and to quantify the fatigue life improvements that result using a copper-molybdenum-copper low-expansion insert between the solar cell and copper heat spreader. Solder microstructural changes and fatigue crack growth were identified using cross sections and ultrasonic scans of the fatigued solder joints. The Coffin-Manson and Total Strain fatigue models for low-cycle fatigue were evaluated for use in fatigue life predictions. Since both of these models require strain calculations, two strain calculation methods were compared: hand-calculated shear strain and a finite element method shear strain. At present, the available theoretical models for low-cycle solder fatigue are limited in their ability to predict failure; consequently, extensive thermal cycling is continuing to define the fatigue life for point focus photovoltaic cell assemblies.

INTRODUCTION

Solder fatigue under solar cells used in point focus photovoltaic concentrator modules occurs as a result of the extreme thermal expansion mismatch between the silicon cell and the copper heat spreader (Fig. 1). Over the module's 20- to 30-year life, many diurnal cycles (>10,000) generate cyclic plastic and creep strain in the solder under the cell and in the solder on the top electrical interconnects. If the cyclic strain is high enough, then the resultant damage or defects in the solder structure will cause fatigue cracking before the module's functional life is over. As cycling continues, the fatigue cracks may grow at varying rates depending on the cycle and/or distance from the center of the solar cell.

The type of fatigue of interest in this paper is called high-temperature, low-cycle fatigue (LCF), which is defined by an area of study where fatigue occurs after relatively few cycles (less than

10,000), cyclic inelastic strain is high (over 0.2 to 1%), and cycle temperatures are high relative to the melting point of the metal (over 0.66 melt temperature °K). Some of the more important factors that affect LCF are cyclic plastic and creep strain, maximum cyclic temperature, cycle frequency, and cycle hold time.

Cyclic inelastic strain is the most used parameter to determine fatigue life. The problems associated with using this parameter alone are that the validity of the data is limited to the parametric range over which the fatigue data were taken, and determining the magnitude of the inelastic strain can be difficult in actual solder joint geometries. If maximum cycle temperature, cycle frequency, and cycle hold time are altered, then fatigue life can change significantly. At high cycle temperatures the microstructure and mechanical properties of the solder change dramatically. Heterogeneous coarsening of the solder microstructure occurs more rapidly at high temperature, which results in a weaker, more fatigued crack-prone joint (1,2). At lower cycle frequency and longer hold times, strain from solder creep increases and can introduce more damage to the solder than plastic strain alone. When plastic strain is low (less than 1%), creep strain can be the dominant damage source (3,4,5).

Fig. 1. Photovoltaic Cell Assembly

FATIGUE LIFE TESTING

The temperature cycle profile of -40 to 110°C was chosen because it is the temperature cycle range required by the qualification test for photovoltaic concentrator modules (6). Previous work by E. H. Richards, et al. (7) has shown that solder fatigue life in photovoltaic cell assemblies is quite sensitive to cycle frequency, hold time, and temperature. Their test results indicated that at high cycle frequencies, fatigue life increases

*Prepared by Sandia National Laboratories, Albuquerque, NM 87185 and Livermore, CA 94550; operated for the U.S. Department of Energy under Contract DE-AC04-76DP00789.

significantly (4,5). Based on this information, a temperature cycle was chosen to achieve a relatively high cycle frequency without neglecting the effects of strain rate and hold time. The objective is to simulate the actual use environment of one cycle per day as much as possible and provide test results within a reasonable time frame. The ramp rate and hold time chosen was 6°C/min. with a 12-min. hold at temperature. This yields a cycle time of 1.23 hrs. or 19.46 cycles/day. Actual temperature profiles indicate that cell assembly temperature during the hold times is not constant. The temperature of the cell assembly will be about 2 to 5°C below set point at the start of soak, and peak 2 to 5°C above set point at the end of soak.

Fatigue life data was generated using this temperature cycle for point-contact cells and bifacial cells with 25- μ m thick 62.5Sn-36.1Pb-1.4Ag solder. The fatigue test was designed to directly compare the fatigue life of the two cell types and measure the fatigue life improvement from using a low expansion Cu-Mo-Cu insert between the cell and copper heat spreader. In addition to the temperature cycle above, three additional temperature ranges were used: -50 to 150°C, 0 to 100°C, and 0 to 80°C to measure the fatigue life of bifacial cells at higher and lower values of shear strain. This will allow limited fatigue life estimates to be made in the future using the Coffin-Manson or Total Strain model.

Climax® Clad Cu-Mo-Cu sheet, which is a roll-bonded laminate of copper, molybdenum, and copper, has some very unique properties that make it ideal for solar cell soldering. It has the solderability of pure copper and the low thermal expansion properties that are ideal for soldering to silicon. It also has a higher thermal conductivity than aluminum, which makes it ideal for use as a heat sink. The conductivity and thermal expansion vary according to the thickness or percentage of copper in the laminate. The Climax® Clad sheet is available in copper thicknesses, on the top and bottom, of 5, 13, 20, 25, and 33%, which results in thermal expansions of 5.1, 5.7, 6.5, 7.3, and 8.6 ppm/°C. Custom ratios are also available. The thermal conductivity range is between 166 W/m·K for 5% copper to 311 W/m·K for the 33% copper laminate. Fatigue tests were conducted with 33% Cu-Mo-Cu using a sheet thickness of 0.0762-cm (30 mils).

Fatigue crack growth measurements were made using a through-transmission ultrasonic tester. This test equipment measures the transmission of ultrasonic waves through the solar cell, solder, and heat spreader. If any large voids or cracks (>1 mm) occur in the solder, then the ultrasonic waves will be attenuated and indicate a black area on the contour map of the cell. Fatigue crack growth was measured as a function of lost contact area under the cell using the colored pixel count from the contour map. Original cell contact area is first measured with no cycling. After cycling, the difference in the before and after area measurement is divided by the original area times 100 to yield percent contact area lost or percent fatigue crack growth. Control cell assemblies were used to

ensure the repeatability and validity of the measurements. Typically, the control sample was within 2% of its original contact area after each measurement. On two occasions anomalies occurred, and one out of five test cells lost or gained an excessive amount of contact area. Overall this proved to be a very reliable measurement technique.

TEST RESULTS

The point-contact cells are 100 microns thick and 0.85 cm. square. They also have a thin (about 2000 angstroms) gold metallized conductor pattern over nickel on the back to interconnect the alternating p and n point-diffusions. The width of the grid conductors are 125 microns with a spacing of 63 microns. The fatigue test results in Figure 2 show that with a five-cell sample size, an average of 78% of the contact area was lost after 788 cycles due to fatigue cracks. The five cells with 33% Cu-Mo-Cu inserts under them survived 2750 cycles before losing an average of 59% of the contact area to fatigue cracking. The Cu-Mo-Cu insert improved fatigue life by a factor of 4. The fatigue data also indicate that before fatigue crack propagation exceeded 10%, the distribution of crack growth values was very narrow, but as the fatigue cracks grew, the distribution became larger.

Fig. 2. Solder fatigue under point-contact cells with and without Cu-Mo-Cu inserts -40 to 110°C cycle

The bifacial cells used for LCF testing were 250 microns thick, 1.37 cm square, and have silver metallization on the back side. The fatigue test results in Figure 3 show that five of these cells lost an average of 57% of their contact area after 1250 cycles. The cells with 33% Cu-Mo-Cu only lost an average of 15% of their contact area after 1250 cycles. This is about a factor of 3 to 4 reduction in fatigue crack growth. The distribution of crack propagation values is quite narrow for cells soldered on Cu-Mo-Cu compared to cells soldered just on copper.

Fatigue tests were also conducted on the bifacial cells cycled at -50 to 150°C, 0 to 100°C, and 0 to 80°C. The 0 to 80°C temperature range provides fatigue life data that are more closely related to an actual operating temperature range. The other two temperature cycles provide LCF data at lower and higher strain values than in the previous

fatigue tests. Test results are plotted in Figure 4. The fatigue crack growth for the -50 to 150°C temperature cycle, which is 45%, is very close to the same value measured for the -40 to 110°C cycle at 948 cycles (Fig. 2). The fatigue crack growth for the 0 to 100°C cycle, is 20% after 1000 cycles. This is about half the 42% crack growth experienced by the cells in the -40 to 110°C cycle. Fatigue crack growth from the 0 to 80°C temperature cycle after 750 cycles is 8%, which is much less than the 32% crack growth resulting from the -40 to 110°C cycle group. The effect of reducing the cycle range and temperature to 0 to 80°C is a factor of 4 reduction in fatigue crack growth.

Fig. 3, Solder fatigue under bifacial cells with and without Cu-Mo-Cu inserts under the cell -40 to 110°C cycle

Fig. 4, Solder fatigue under bifacial cells temp cycled at -50 to 150°C, 0 to 100°C, and 0 to 80°C cycles

SOLDER MICROSTRUCTURE

Metallurgical cross sections of as-soldered and fatigued solder joints were made to identify and evaluate the changes that occurred in the solder. Figure 5 is a SEM micrograph of the as-soldered condition which exhibits the fine eutectic structure with no cracking. In Figure 6, heterogeneous coarsening occurs parallel to the direction of shear, and crack growth can be seen in the solder joint, which was cycled for 680 cycles at one cycle per day. In Figure 7, the solder joint was cycled for 788 cycles at 19 cycles per day. Heterogeneous coarsening was not as extensive

at this faster deformation rate. Cracks were observed to form intergranularly. This comparison illustrates the effect that deformation rate has on solder microstructure. At higher deformation rates there is less heterogeneous coarsening in the direction of shear, hence, less damage and fatigue cracking.

Fig. 5, As-Soldered Microstructure

Fig. 6, Fatigue Crack Growth (688 cycles at one cycle per day)

Fig. 7, Fatigue Crack Growth (788 cycles at 19 cycles per day)

FINITE ELEMENT STRAIN CALCULATIONS

Finite element stress analysis techniques were employed to predict the structural response of the concentrator cell assemblies due to manufacturing (cool down from the soldering temperature) and subsequent thermal cycling. As indicated above, the driving force for the development of stresses and strains which cause low cycle fatigue failure in the cell assemblies is the thermal expansion mismatch between various materials used in the assembly. The primary interest in these calculations was to predict the inelastic strains developed in the solder which are intended to be used to predict low cycle fatigue life of the assembly. Calculations were completed for point contact cells for both the baseline copper insert and the copper-molybdenum-copper low expansion insert for the four separate thermal cycles indicated in the experimental program.

The cell module assembly, including a portion of copper heat spreader, was idealized into 4,784 two-dimensional axisymmetric finite elements as shown in Figure 8. Although the actual solar cell and

Fig. 8, Finite Element Model

insert are square in shape and in reality require a three-dimensional analysis, the idealized axisymmetric geometry should result in a reasonable estimate of the stress and strain state in the assembly and will yield a very good comparison of the parameters evaluated in this study. The consequences of the two-dimensional assumptions are intended to be the subject of future research. In these calculations, the materials of the cell modules were assumed to be joined and stress free at the solidus temperature of the solder. The assembly was then uniformly cooled (no thermal gradients) to room temperature at a specific cooling rate and was then subsequently subjected to a single complete uniformly applied thermal cycle. The finite element calculations were obtained using the JAC2D (8) code running on a CRAY YMP computer.

For all finite element results presented in this paper, the silicon solar cell and the molybdenum-in-the-clad insert deform according to elastic constitutive laws. The copper insert, the copper-in-the-clad insert, and the copper heat spreader were all modeled using an elastic/plastic constitutive law incorporating a linear strain

hardening relationship. The constitutive relationship assumed for the 62.5%Sn-36.1%Pb-1.4%Ag solder was a minimum creep rate power law model where the minimum creep rate $\dot{\epsilon}_{min}$ is written as:

$$\dot{\epsilon}_{min} = A(\sigma)^n \exp\left(-\frac{Q}{RT}\right) \quad (1)$$

where σ is the applied stress, T is the absolute temperature, R is the universal gas constant, Q is the activation energy for creep, and A and n are constants. The power law creep model constants used in these calculations were actually for a eutectic tin/lead solder taken from Bourcier, et al. (9). Creep data for 62.5Sn-36.1Pb-1.4Ag solder was not available. The constants are as follows:

$$\begin{aligned} A &= 9.64E-11 \\ n &= 4.29 \\ Q/R &= 6.99E+3. \end{aligned}$$

The material properties of the other materials used in this study are given in Table 1.

TABLE 1
MATERIAL PROPERTIES

MAT'L.	TEMP C	YOUNG'S MODULUS Mpa	POISSON'S RATIO	YIELD STRESS Mpa	HARDEN'G MODULUS Mpa	CTE m/mC
COPPER		11.7E+5	0.3	68.9	1172	17.64E-6
MOLY		3.1E+5	0.3	NA	NA	5.4E-6
SILICON		1.31E+5	0.28	NA	NA	2.3E-6
SOLDER	-40	1.55E+4	0.38	NA	NA	25.0E-6
	25	1.49E+4	0.40			
	80	0.86E+4	0.40			
	120	0.73E+4	0.46			
	150	0.58E+4	0.49			
	180	0.07E+4	0.49			

The results obtained from the finite element calculations indicate that the strain distribution developed in the solder is quite complicated and is certainly not in uniform shear. The calculations indicated that for the baseline copper insert design, the maximum change in the creep shear strain in the 0.85-cm cell is 0.69% per cycle for the -40 to 110°C temperature range. For this case the maximum change in shear strain occurs in the solder between the copper insert and the cell. The maximum change in shear strain in the solder between the insert and the heat spreader for this temperature cycle is very low, 0.054% per cycle. The calculated maximum change in creep shear strain for the three additional thermal cycles are shown in Table 2. For the baseline design copper insert, these maximum values all occur in the solder between the insert and the cell.

The introduction of the clad insert into the assembly significantly reduced inelastic (creep) shear strain per cycle. For the -40 to 110°C temperature cycle, the maximum change in creep shear strain was 0.25% per cycle; however, this maximum occurs in the solder between the insert

and the heat spreader. The maximum change in creep shear strain in the solder between the insert and the cell is only 0.1% per cycle. The calculated maximum change in creep shear strain for the three additional thermal cycles are also shown in Table 2. For the clad insert design, these maximum values all occur in the solder between the insert and the heat spreader.

It is common practice to estimate the change in shear strain in a soldered assembly by simply calculating the dimensional change in the joined parts and dividing by the thickness of the solder as shown in Equation 2. To apply this equation, the assumption is made that the joined parts (the cell and the copper insert) are infinitely stiff. This method predicts a change in strain of 46% per cycle for the temperature range of -40 to 110°C. The finite element calculations indicate that substantial strains are developed in both the insert and the cell and that there is also significant bending in the assembly. The thermal deformation is accommodated by strains in the cell, insert, and by a multicomponent strain distribution in the solder layers. Therefore the assumptions required to apply the above shear strain estimate are inappropriate (Table 2). Calculating accurate strain values for the required solder joint geometry can be difficult. Consequently, the validity of fatigue life calculations that use strain are accordingly affected.

$$\Delta\epsilon = \frac{L \times \Delta T \times (\alpha_1 - \alpha_2)}{t} \times 100 \quad (2)$$

where

- $\Delta\epsilon$ = percent shear strain
 L = largest radial dimension of solder joint
 α_1 & α_2 = expansion coefficients of upper and lower materials in ppm
 ΔT = temperature excursion range °C
 t = solder joint thickness

TABLE 2

MAXIMUM SHEAR STRAIN PREDICTIONS
 (% strain per cycle)
 POINT CONTACT CELL 0.85 CM SQ

TEMP RANGE	FEA (1) COPPER	FEA (2) CLAD	EQ 2 COPPER
-50 to 150	4.15	0.30	62
-40 to 110	0.69	0.25	46
0 to 100	0.32	0.20	30
0 to 80	0.32	0.19	24

(1) - INSERT TO CELL SOLDER

(2) - INSERT TO HEAT SPREADER SOLDER

FATIGUE LIFE PREDICTIONS

Low-cycle fatigue life predictions using the basic Coffin-Manson equation, or the Total Strain Equation are the most popular models in use (4,5). They both require a plastic strain in association with the number of reversals to failure. (Eqs. 3, 4, 5 and Fig. 9). The Coffin-Manson equation is useful where strain values are in excess of 1%, but as strain decreases below 1%, significant creep and elastic strain effects begin to dominate fatigue crack growth. The solution to this limitation is to include Basquin's Equation for high cycle fatigue, which will incorporate the elastic strains that occur in medium to high cycle fatigue. The main advantage of these strain models are their simplicity. Their main limitation is that they are all curve fit models and not predictive. They also cannot account for variable creep strain and stress relaxation during hold times. The main application for these models are in laboratory experiments where the cyclic wave form is well defined and constant. Estimates of in-service fatigue life based on laboratory data is dependant on how well the laboratory data approximate the use environment.

Basic Coffin-Manson Equation

$$\frac{\Delta\epsilon_p}{2} = \epsilon_f' (2N_f)^c \quad (3)$$

Basquin's Equation

$$\sigma_a = \sigma_f' (2N_f)^b \quad (4)$$

Total Strain Equation

$$\epsilon_a = \frac{\Delta\epsilon_t}{2} = \frac{\sigma_f'}{E} (2N_f)^b + \epsilon_f' (2N_f)^c \quad (5)$$

- $2N_f$ = reversals to failure (1 cycle = 2 reversals)
 ϵ_f' = fatigue ductility coefficient
 ϵ_a = total strain amplitude
 $\Delta\epsilon_p/2$ = plastic strain amplitude
 $\Delta\epsilon_t/2$ = total strain amplitude
 E = elastic modulus
 c = fatigue ductility exponent (usually -0.5 to -0.7)
 b = fatigue strength exponent (usually -0.08 to -0.12)
 σ_f' = fatigue strength coefficient
 σ_a = true stress amplitude

Fig. 9, Fatigue Curve "Total Strain Model"

SUMMARY

The LCF test results indicate that significant improvements in fatigue life can be achieved by using the Cu-Mo-Cu insert between the cell and copper heat spreader to reduce solder shear strain. The number of cycles to failure N_f was increased by about a factor of 4 using the low expansion Cu-Mo-Cu insert. Solder joint metallization geometry also appears to be an important factor in fatigue life as seen by the significant reduction in cycles to failure that occurred using the point-contact cells with the back grid pattern. The LCF tests on bifacial cells using the 0 to 80°C cycle also resulted in a factor of 4 reduction in the percentage of contact area lost to fatigue cracks. This cycle reduced shear strain and temperature to improve fatigue life. The incorporation of the Cu-Mo-Cu insert, reduced cycle, and reduced temperature will result in a major increase in solder fatigue life under the solar cell.

Estimates of fatigue life will be made based on test data and Equations 3 and 5 when fatigue testing is complete. FEA strain values will be used for the required solder joint geometries and temperature cycles. The intent is to estimate when module life will be impacted by solder fatigue, and how well new cell assembly designs will resist solder fatigue.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the exceptional services of Phillip Walkington for the ultrasonic fatigue crack measurements, Alice Kilgo for metallography, and Frankie Potts for thermal cycling.

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