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A theoretical model for predicting LED product lifetime based on solder joint failure

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ABSTRACT

LED A-lamps are used in many types of lighting fixtures; however, these lamps can experience different thermal environments and use patterns (on-off switching), resulting in system life that varies in different applications. A recent study showed that on-off switching negatively affects LED system lifetime, and solder joint failure was the main reason. The goal of this study was to investigate and identify a theoretical model that can be used to predict LED A-lamp failure, when the failure is mainly due to solder joint failure. Although several models for solder joint fatigue failure exist in the electronics industry, the Engelmaier model is the most commonly used in industry standards. The study presented here showed that the Engelmaier model with modified fatigue ductility exponents provided a better fit to the experimental lifetime data for LED A-lamps. This paper describes the Engelmaier model prediction method for LED A-lamp failure.

Keywords: LED system life testing, lifetime prediction, solder joint fatigue

1. INTRODUCTION

Replacement lamps using light-emitting diode (LED) technology are displacing their traditional counterparts and have been gaining market share very rapidly. Long service life, in the timeframe of 25,000 hours, is one of the claimed benefits for these lamps. Because LED A-lamps are used in many types of lighting fixtures, including table lamps and ceiling-mounted fixtures, consumers expect them to last the claimed number of hours in any application. Depending on the application, these LED lamps can experience different thermal environments and on-off switching patterns. Therefore, it is possible for LED system life to vary from one application environment to the next. The results from a recent study showed that the present industry test procedure for LED lighting system lifetime measurement and the rating method are flawed.[1] The present industry standard requires manufacturers to test only one component, namely the LED package as per the LM-80 standard[2] and project the lumen maintenance lifetime (L70) based on TM-21.[3] In applications, the lamps are turned on and off, but in the test procedure lamps are tested by burning the lamps continuously on for 6000 hours. Moreover, the current test procedure considers only one failure type, namely, lumen depreciation.

The failures in LED lighting systems could be parametric or catastrophic. In parametric failure, light output gradually diminishes, and the failure criterion (L70) is defined as the time point at which lumen depreciation reaches 70% of the initial light output. Catastrophic failure is the complete cessation of light. In an earlier study we found that catastrophic failure is the dominant failure mechanism in commercial LED A-lamps.[1] The results of that study showed that, contrary to common belief, on-off switching negatively affects lifetime, and solder joint failure was the main reason.

The solder joint provides both mechanical and electrical connections between the LED package and the printed circuit board (PCB). Currently, most solder joints are Pb free and they contain Sn, Ag, and Cu alloys. The solder joint fatigue failure occurs as a result of the mismatch of the coefficient of thermal expansion (CTE) between the component and the substrate. On-off switching operation in an LED system induces cyclic thermal stresses on the solder joint due to the CTE mismatch between the LED package and the PCB. Consequently, smaller fatigue cracks are formed in the solder joint initially. During the operational life of the lamp, fatigue cracks grow and when they coalesce to make larger cracks, complete fracture could occur.[4] Many studies have shown that the fatigue life of surface mount solder joints can be characterized by the power law, where cyclic thermo-mechanical stress encourages the failure.[4,5] The goal of this study was to identify a model that can be used to predict LED A-lamp failure when solder joint failure is the main mechanism.

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2. EXPERIMENT

The studies conducted by our research group using integral LED lamps showed that delta temperature (ΔT) (defined as the difference between the uppermost and lowermost junction temperatures experienced by the lamp when they are switched on and off) and dwell time (on time at the maximum junction temperature) have the strongest correlation for catastrophic failure.[1] A commercially available 75W rated incandescent replacement LED A-lamp product was used in that study. The temperature profile experienced by the LED junction as a function of time is illustrated in Figure 1.[1] This figure demonstrates the parameters used in this study for setting up the experiment and analysis. The details of the experiment variables and the experimental setup are described in an earlier publication.[1]

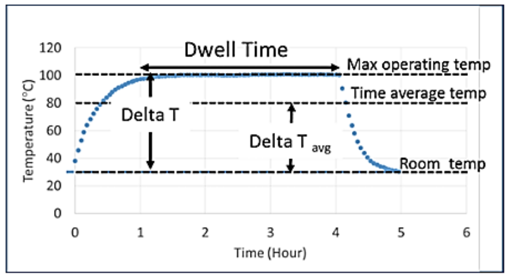

Figure 1. Temperature profile experienced by the LED junction [1]

3. RESULTS

The catastrophic failures of all LED A-lamp samples belonging to each test condition were reported in the earlier publication.[1] The median lifetime for each test condition was calculated by averaging the time to failure (TTF) values of the 5th and 6th lamps; the results are summarized in Table 1. In this analysis, we considered the test results from the on-off switching conditions only, and not the continuous operation. The reason for this consideration is the solder joints fail mainly due to the cyclic thermo-mechanical stresses. The results showed higher delta temperature resulted in a shorter time to failure. Moreover, a shorter dwell time resulted in a shorter time to failure for delta temperatures 80°C and 90°C. However, the trend is not clear in the delta temperature 100°C condition, most likely due to additional failure mechanisms. A post-failure analysis revealed that 84% of the lamp failures were due to solder joint failure between the LED package and the PCB, and the remaining 16% were due to driver failure. Hence, the objective of this study was to develop a theoretical model for predicting LED product lifetime based on the solder joint failure.

Table 1. Delta time-averaged temperatures and median life for different ΔT and dwell time conditions

	Delta time-averaged temperature (°C)		Time to failure (median life) (hours)	
ΔT/Dwell Condition	**2 hours**	**4 hours**	**2 hours**	**4 hours**
80°C	48	60	7,516	8,801
90°C	61	69	3,411	7,091
100°C	69	82	3,225	521

Solder joint fatigue models proposed in past literature can be divided into five categories: stress-based, strain-based, energy-based, damage-based, and empirical.[5] The stress-based methods use knowledge about solder geometry, dimensions, CTE mismatch, temperature difference, and Shear and Young's modulus of the materials. The strain-based models are subdivided as plastic strain and creep strain. Coffin-Manson and Engelmaier models are the most commonly used plastic strain-based fatigue models. The energy-based models use the area of the stress-strain hysteresis loop due to thermal cyclical stress to determine the fatigue damage. The damage-based fatigue models use damage parameters such as fatigue crack length. Finally, empirical methods are developed by curve fitting the experimental data obtained from solder joint thermal cycling stress tests.

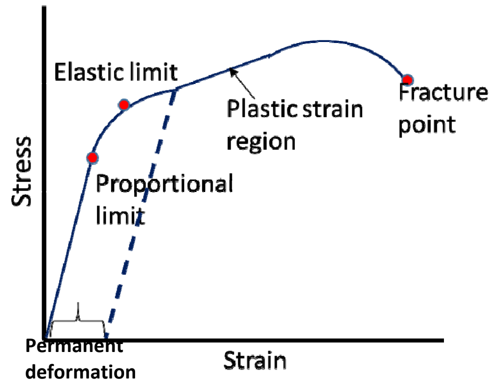

Figure 2. Typical stress-strain curve of a ductile metal (adopted from [6])

A typical stress-strain curve of a ductile metal is shown in Figure 2.[6] In the stress-strain curve, stress is linearly proportional to the strain up to the proportional limit. The elastic limit is the final point on the curve where the deformation is reversible. The region beyond the elastic limit is known as the plastic strain region and the deformations that occur in this region are permanent.

Although several methods for modeling solder joint fatigue failure exist in the electronics industry, the Engelmaier solder joint fatigue model is the most commonly used in several industry standards and was selected for this study. The Engelmaier model is based on plastic strain and is used for low cycle fatigue.[4] This model incorporates operational cyclic frequency and provides first order equations to compute the strain using simplifying assumptions on the geometry of the solder joint.

The Engelmaier model is given in equation 1. Fatigue ductility coefficient (ε_f') is a constant dependent of the material composition of the solder joint. For SnAgCu solder, it is considered as 0.325 in past literature.[5] Fatigue ductility exponent, c, is a function of the mean cyclic solder temperature and the cyclic frequency experienced by the solder joint. In the Engelmaier model, coefficients of c were empirically determined.

$$\mathbf{N_f = \frac{1}{2}\left[\frac{\Delta\gamma_t}{2\varepsilon_f'}\right]^{\frac{1}{c}}} \qquad \text{Equation 1}$$

N_f = cycles to failure
ε'_f = Fatigue ductility coefficient (0.325 for SnAgCu solder)
$\Delta\gamma_t$ = Total shear strain
c = Fatigue ductility exponent

$$\boldsymbol{c = -0.442 - 6.10^{-4} x \overline{T_s} + 1.74 x 10^{-2} x \ln(1 + f)} \qquad \text{Equation 2}$$

T_s = Mean cyclic solder temperature
f = Cyclic frequency (cycles/day)

$$\mathbf{\Delta\gamma = F\frac{L_D\Delta\alpha\Delta T}{h_s}} \qquad \text{Equation 3}$$

F= non-ideal factor
L_D=distance from the center of the component to the solder joint
h_s=solder height
$\Delta\alpha$=Coefficient of thermal expansion (CTE) mismatch
ΔT=temperature cycling range

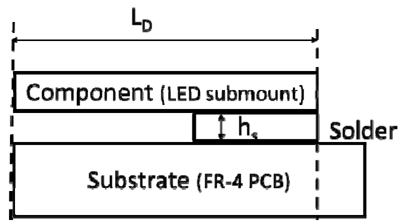

Figure 3. Solder attachment between a component and a substrate showing dimensions

The first order equation developed by Engelmaier to compute the strain range is shown in equation 3. Figure 3 shows the typical solder attachment between a component and a substrate with the dimensions used in equation 3. The non-ideal factor 'F', which is used to counter the second order effects being ignored in the model, is considered to be 0.5 based on past literature.[4]

Table 2. Dimensions and the parameter value used in the analysis

Parameter	Value
CTE of the component (α_1) (°C^{-1})	2.59E-06
CTE of the PCB (α_2) (°C^{-1})	1.60E-05
L_D (m)	2.25E-03
Solder height (h_s) (m)	1.02E-04

The dimensions of the LED package, solder thickness, and the coefficient of thermal expansion (CTE) values[7] used in the analysis are shown in Table 2. The fatigue ductility exponent 'c' and the strains were calculated for each test condition using the corresponding delta time-averaged temperature, the time-averaged temperature, and the cyclic frequency (cycles per day) using equations 2 and 3, respectively. Then the cycles to failure for each test condition were calculated using equation 1. A comparison between actual and predicted cycles to failure is shown in Figure 4.

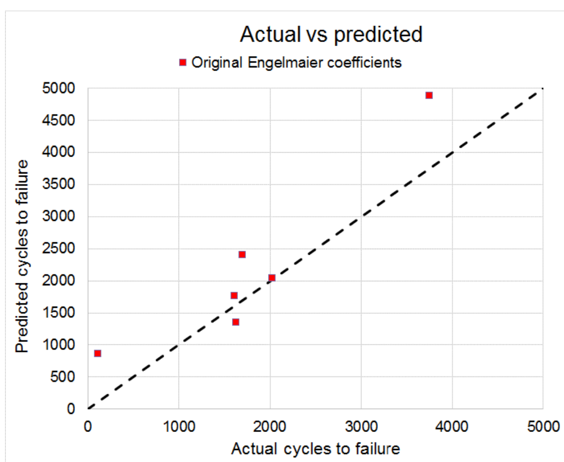

Figure 4. Comparison between actual and predicted cycles to failure with original Engelmaier coefficients

The cycles to failure prediction using the original Engelmaier coefficients showed a higher prediction compared to the cycles to failure measured in the experiment. In order to investigate whether better fit can be obtained using coefficients specific to this study, the fatigue ductility exponent 'c' values were calculated for three test conditions from equation 4 using the calculated strain values and the actual cycles to failure values.

$$c = \frac{\ln(\Delta\gamma_t) - \ln(2x0.325)}{\ln(2xN_f)}$$ **Equation 4**

A relationship between c and T_s and f was established, and the respective coefficients were determined using MATLAB curve fitting from the experimental data (cycle to failure, cyclic frequency, and the time-averaged temperature) for three conditions. The obtained curve fit is shown in Figure 5.

- Delta Temperature 80°C; 2 hrs
- Delta Temperature 80°C; 4 hrs
- Delta Temperature 100°C; 2 hrs

$$c = -0.4879 - 4.444x10^{-4}\overline{T_s} + 6.6668x10^{-3}\ln(1+f)$$ Equation 5

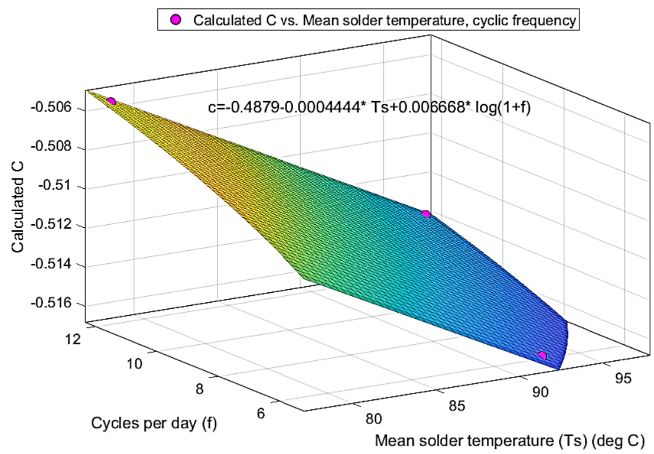

Figure 5. Curve fit for ‘c’ using mean solder temperature and cyclic frequency

The cycles to failure predictions were calculated again from equation 1 using the new ‘c’ values computed from equation 5, and the resulting values are shown in Figure 6 as modified coefficients. The actual and predicted cycles to failure for each test condition along with the prediction errors are summarized in Table 3, and a corresponding plot comparing actual and predicted cycles to failure is shown in Figure 6.

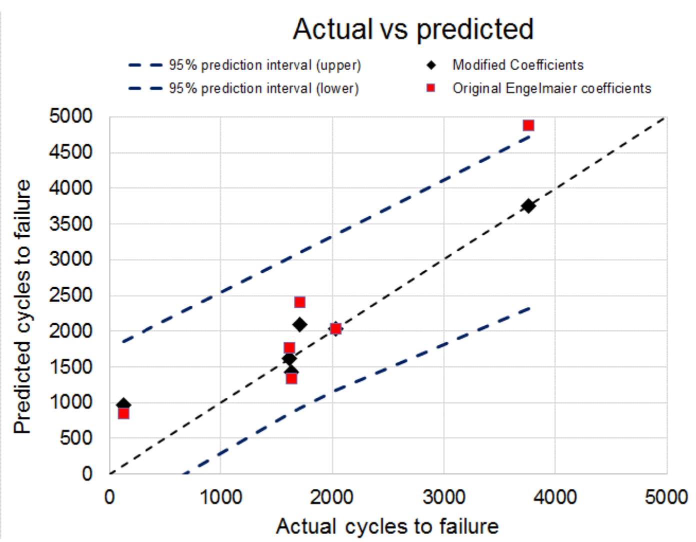

Figure 6. Comparison between actual and predicted cycles to failure with modified coefficients

Table 3. Actual and predicted cycles to failure values for different test conditions

Test condition	Actual failure (cycles)	Predicted failure (cycles)	Prediction error (%)
D80 2 hrs	3758	3758	0.0%
D80 4 hrs	2031	2033	0.1%
D90 2 hrs	1706	2097	22.9%
D90 4 hrs	1636	1433	12.4%
D100 2 hrs	1613	1613	0.0%
D100 4 hrs	120	974	711.6%

4. DISCUSSION

The cycles to failure experiment results and the prediction with the Engelmaier model and modified coefficients specific to the LED A-lamp life testing study explained in this paper showed better agreement. The largest deviation between actual and predicted cycles to failure values was observed in the D100 4 hrs condition. The actual cycles to failure for this test condition was 120 cycles. It is stated by Engelmaier that if the predicted life is less than 1000 cycles, then such a severe stress condition could introduce additional failure modes and mechanisms.[4] The estimated fatigue ductility exponent 'c' values in this experiment were in the range -0.5055 to -0.7253. It has been shown in past literature that c values for common engineering metals are in the range of -0.5 to -0.7.[4] The estimated c value for the D100 4 hrs condition is -0.7253, which is outside the above range. This could be an indication that additional failure mechanisms could have accelerated the failure in the D100 4 hrs condition.

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