Abstract: Temperature (thermal) cycling is a major cause of failures of electronic systems. This paper discusses the effect of the steady-state operating temperature, as controlled by parameters such as the coolant inlet temperature, on the fatigue life of electronic assemblies subjected to thermal cycling resulting from off-on power cycling. The power cycling fatigue life depends on the steady-state operating temperature $T_s$, as well as on the temperature range $\Delta T$ in the thermal cycle. The power cycling durability of copper plated through holes in circuit boards is very sensitive to the steady-state PTH operating temperature, because the strain ranges are in the portion of the copper S-N$_f$ (strain vs. number of cycles to failure) curve that is nearly horizontal. If the power is turned on at the same time the coolant flow is started, reducing the steady-state operating temperature can improve the durability. If the coolant is turned on for a substantial period before the power is turned on, reducing the coolant inlet temperature may degrade the durability for operation on hot days.

Key Words: Durability; electronic assemblies; power cycling; steady-state temperature

INTRODUCTION: Temperature is a key contributor to failures of electronic equipment [1, Chapter 4]. Failures result from:

- steady high temperature (hotter than normal room ambient temperature)
- steady low temperature (colder than normal room ambient temperature)
- temperature (thermal) cycling above and below ambient temperature.

Usually electronic equipment operates at temperatures above normal room ambient (20 to 25°C), and the focus is to keep the parts cool. The steady-state operating temperature $T_s$ is controlled by a number of design parameters including, for actively cooled equipment, the coolant inlet temperature [1, Chapter 8].
However, the effect on reliability of the steady-state operating temperature is controversial (see Morris and Reilly [2] and the references cited therein). Some state that:

- microelectronics reliability is independent of, or only weakly dependent on, the steady-state operating temperature \( T_s \)
- the dominant temperature dependence is on the temperature range \( \Delta T \) in a thermal cycle, which affects the number of thermal cycles to failure.

This paper shows that the fatigue life of electronic assemblies, subjected to thermal cycling resulting from off-on power cycling, depends on the steady-state operating temperature \( T_s \), as well as on the temperature range \( \Delta T \). The physical basis of the effect of the steady-state operating temperature on the power cycling durability of an assembly is described. The effect is illustrated by a thermal/structural/durability analysis of a representative electronic assembly.

**PHYSICAL BASIS**: During its service life, the system is powered repeatedly after being “soaked” at the ambient temperature, \( T_a \), and heats up to the steady-state operating temperature, \( T_s \). Each off-on power cycle produces a thermal cycle which damages the equipment. The thermal cycling fatigue damage accumulates and eventually will cause fracture, which in turn will result in an open circuit.

The steady-state operating temperature, \( T_s \), affects the temperature range in each off-on power cycle. The strain range of the materials in the assembly, and thus the damage, increases with increasing temperature range. The number of cycles to failure, \( N_f \), decreases with increasing strain range per cycle.

For actively cooled systems, 1) the power may be turned on at the same time the coolant flow is started or 2) the coolant may flow for a significant period before the power is turned on. In the first case, the equipment may heat up immediately when powered; in that case, the minimum temperature in the power cycle, \( T_m \), is the ambient temperature, \( T_a \). In the second case, the equipment temperature may approach the coolant inlet temperature prior to powering; on a hot day, \( T_m \) may be lower than \( T_a \). See Fig. 1.
EXAMPLE - PLATED THROUGH HOLE: Plated through holes (PTHs) electrically connect different layers of a printed wiring board (PWB). An axisymmetric representation of a PTH is shown in Fig. 2.

PTH failures during thermal cycling are caused by mismatches in the coefficient of thermal expansion (CTE) between the copper in the PTH barrel and the PWB laminate materials. The PWB laminate materials (polyimide in this case) expand much more rapidly with increasing temperature than the PTH barrel copper. (See Fig. 3.) Typically, the temperature excursions are not large enough to cause failure in a single cycle. Instead, fatigue can cause crack initiation leading to one of the principal electrical failure modes of a PTH - an open circuit resulting from cracking around the circumference of the PTH barrel. These cracks are shown in Fig. 2.

Analytical Approach: This section gives a brief overview of the approach used to evaluate the durability of a PTH.

1. **Thermal analysis**: Perform detailed finite-difference analysis [1, Chapter 8] to predict the steady-state operating temperatures within the assembly as a function of coolant inlet temperature. The analysis predicted that:
   - the difference between the steady-state operating temperature of the PTHs (the peak temperature of the PWB surface), $T_s$, and the coolant inlet temperature is 30°C
   - this difference is independent of the coolant inlet temperature.
2. **Thermomechanical stress/strain analysis**: Perform detailed thermomechanical finite element analysis (FEA) to predict the stresses and strains (elastic + plastic) in the PTH barrel copper as a function of temperature. All finite element models (FEM) are axisymmetric. Copper plasticity is represented by a bilinear kinematic-hardening stress-strain curve. The finite element model (FEM) accounts for the temperature dependence of the properties of copper and the PWB composite. The decrease of copper yield stress with increasing temperature is accounted for. Non-linear strains are calculated at each temperature in the thermal environment of the PTH.

3. **Fatigue analysis**: Predict the thermal fatigue life for the PTH copper using using Engelmaier’s modified Coffin-Manson approach, with the maximum equivalent non-linear strains calculated in step 2 as an input. Using Engelmaier’s equation [3] (a modified Coffin-Manson approach), the number of cycles to failure expected for each exposure level is estimated. Then the fatigue life resulting from the combinations of individual thermal exposures within the environment is determined using the Palmgren-Miner linear damage accumulation methodology.

Failure modes other than fatigue in the barrel, such as delamination of the PWB or debonding of the barrel and pad from the laminate, are not considered.

**Evaluation of Effect of Copper Plating Quality**: Copper plating is assumed to be of high quality without defects that cause localized strain concentrations such as flaws, voids, localized thickness variations, and lack of adhesion. Variations in plating quality are addressed by use of a quality factor, $K_q$, discussed below. Copper quality is represented by $K_q$ and attempts to account for defects in the plating such as flaws, voids, localized thickness variations, and lack of adhesion which induce strain concentrations. The factor $10/K_q$ functions as a strain multiplier:

$$\frac{\varepsilon_{\text{effective}}}{\varepsilon} = \frac{10}{K_q}$$

Although $K_q$ can range from 0 (infinitely poor plating quality) to 10 (perfect plating quality), it usually falls in the range of 5 to 10. For comparison, a value of $K_q = 7$ results in 43% higher strains than $K_q = 10$. 
Figure 2. Cross-Section of a Plated Through Hole

Figure 3. Thermal Growth of Polyimide Resin and Electrodeposited Copper
Fatigue Life Calculation: The maximum equivalent strains calculated in the FEA are used in Engelmaier’s modified Coffin-Manson approach to predict fatigue life. Life for each thermal exposure is calculated using these strains in the equation below and solving iteratively.

\[ N_f^{-0.6} D_f^{0.75} + \left( \frac{S_u}{E_{cu}} \right) \left[ \exp \left( \frac{D_f}{0.36} \right) \right] \chi - \Delta \varepsilon = 0 \tag{1} \]

where

- \( N_f \) = expected mean fatigue life N(50%), cycles to failure
- \( D_f \) = fracture strain, fatigue ductility of barrel copper (baseline = 30%)
- \( S_u \) = ultimate tensile strength of barrel copper (baseline = 40,000 psi)
- \( E_{cu} \) = copper modulus of elasticity
- \( \Delta \varepsilon \) = total cyclic strain range = \(| \varepsilon(T_1) - \varepsilon(T_2) |\)
- \( T_1 \) = first temperature of thermal exposure
- \( T_2 \) = second temperature of thermal exposure
- \( \chi = 0.1785 \log \left( \frac{10^5}{N_f} \right) \)

The relationship of fatigue life and total cyclic strain range in Eq. 1 may be graphically displayed as shown in Fig. 4 for the baseline copper material properties.

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**Figure 4. Strain Range vs. Mean Cycles to Failure for Baseline Copper Property Values**
Evaluation of the Effects of Multiple Exposures: Linear cumulative damage theories can be used to approximate the influence of multiple thermal exposure types. Eq. 2 is the Palmgren-Miner linear damage accumulation expression:

\[
D = \sum_{i=1}^{j} \left( \frac{n_i}{N_i} \right)
\]

where
- \(i\) = exposure type number
- \(j\) = total number of exposure types
- \(D\) = damage value
- \(n_i\) = cycles occurring in exposure \(i\)
- \(N_i\) = life predicted for an exposure \(i\)

The Palmgren-Miner theory is an accepted means of combining the effects of multiple fatigue exposures. The relation linearly sums the ratios of experienced cycles to predicted cycles to failure for each of the exposure types within a thermal environment. The cumulative total damage for the environment is then compared to an allowable damage value, usually 0.6 to 1.0.

Results: Calculations were performed for:
- Minimum PTH temperatures, \(T_m\), between -40°C and +40°C
- Steady-state PTH operating temperatures, \(T_s\), between 45°C and 85°C
- coolant inlet temperatures of 15°C and 35°C, which correspond to \(T_s = 45°C\) and 65°C, respectively.

The results are shown in Table I and Figs. 5-8: predicted numbers of cycles to failure, \(N_f\) (Note: For lifetimes and cycle rates of military and commercial systems, only values of \(N_f\) smaller than about \(10^6\) are significant. For example, off-on power cycling every hour for 20 years would produce \(2 \times 10^5\) cycles. Some of the values of \(N_f\) for this example are \(>> 10^6\); however, they illustrate the trends.) Figs. 5 and 6 show \(N_f\) vs. \(T_s\) for \(T_m = -40\) and 25°C, respectively. Fig. 7 shows \(N_f\) vs. \(T_m\) for \(T_s = 45°C\) and 65°C. For the case in which the power is turned on at the same time the coolant flow is started and the system heats up immediately, \(T_m = T_a\). Fig. 8 is the same as Fig. 7 for the limiting case in which the coolant is turned on for a substantial period, and the equipment temperature reaches the coolant inlet temperature, before the power is turned on.
Table I. Example of Effects of Steady-State Operating Temperature on Thermal Cycling Fatigue of Plated Through Holes in Printed Wiring Boards

<table>
<thead>
<tr>
<th>Minimum PTH temperature, $T_m$ ($^\circ$C)</th>
<th>Steady-State PTH Operating Temp., $T_s$ ($^\circ$C)</th>
<th>Copper strain range per cycle, $\varepsilon_{Ts} - \varepsilon_{Tm}$</th>
<th>Thermal cycles to failure, $N_f$</th>
<th>Ratio, $N_f(T_s=45^\circ$C) / $N_f(T_s=65^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40</td>
<td>45</td>
<td>0.0076</td>
<td>$3.7 \times 10^3$</td>
<td>1.4</td>
</tr>
<tr>
<td>-40</td>
<td>65</td>
<td>0.0084</td>
<td>$2.7 \times 10^3$</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>45</td>
<td>0.0016</td>
<td>$3.4 \times 10^7$</td>
<td>34.</td>
</tr>
<tr>
<td>10</td>
<td>65</td>
<td>0.0024</td>
<td>$1.0 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>45</td>
<td>0.0002</td>
<td>$2.5 \times 10^{15}$</td>
<td>1,300,000.</td>
</tr>
<tr>
<td>40</td>
<td>65</td>
<td>0.0011</td>
<td>$1.9 \times 10^9$</td>
<td></td>
</tr>
</tbody>
</table>

CONCLUSIONS

- If the power is turned on at the same time the coolant flow is started, reducing the steady-state operating temperature can improve the durability.
- If the coolant is turned on for a substantial period before the power is turned on, reducing the coolant inlet temperature may degrade the durability for operation on hot days. For example, Fig. 8 shows that, for ambient temperatures higher than $33^\circ$C, the number of cycles to failure is smaller for a $15^\circ$C coolant than for a $35^\circ$C coolant.
- The power cycling durability is very sensitive to the steady-state PTH operating temperature, because the strain ranges are in the portion of the copper S-N$_f$ (strain vs. number of cycles to failure) curve that is nearly horizontal. For example, for an initial temperature of $-20^\circ$C, a $20^\circ$C increase in the operating temperature (from $45^\circ$C to $65^\circ$C) increases the strain by a factor of 1.3 (from 0.0030 to 0.0038), which decreases the number of cycles to failure by a factor of 4 (from $2.3 \times 10^5$ to $5.6 \times 10^4$).

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REFERENCES
