26. Effect of PCB Bending Stiffness on Wire Stresses

26.1 Introduction

When axial leaded devices on a PCB are exposed to thermal cycling environments, overturning moments can occur which may force the PCB to bend as shown in Figure 26.1.

In the previous sample problems, the bending effects of the PCBs were not included in the force and displacement relations. Since bending in the PCB can occur during temperature cycling, the magnitude of these effects should be evaluated.

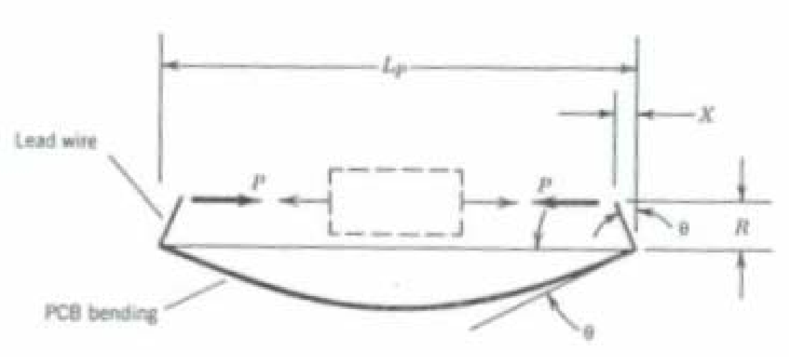

Figure 26.1 High axial loads in lead wires can force the PCS to bend

The Figure 26.1 shows that when the PCB bends, the magnitude of the horizontal load will be reduced. These relations can be obtained from Equation 25.2 by considering bending in the vertical member of the lead wire, and rotation of the PCB which will produce rotation of the vertical lead wire. The horizontal displacement expected at the top of the wire will be the sum of the wire bending and the PCB rotation, as shown in Equation.26.1, when the horizontal and vertical legs of the wire are the same length.

$$X = \frac{P L_W^3}{7.5 E_W I_W} + \mathrm{R}\theta \qquad (26.1)$$

Example: Determine the axial force in the lead wire for the resistor shown in Figure 25.6, when bending of the PCB is included in the analysis over a temperature cycling range from -40 to +80 °C. As defined in the example of section 25.4.

Solution:

The axial load in the lead wire induced by the different TCE will produce an overturning moment in the PCB and force it to bend, as shown in Figure 26.1. Considering the pivot point to be at the lead wire solder joint, the angular rotation of the lead wire (for small angles) must be the same as the angular rotation of the PCB. The PCB angular rotation will be as shown in Equation 26.2.

$$\theta = \frac{ML_P}{2E_P I_P} \tag{26.2}$$

Substitute Equation 26.2 into Equation 26.1 to obtain the combined deflection of the bending wire and the rotating PCB.

$$X = \frac{PL_W^3}{7.5E_W I_W} + \frac{RML_P}{2E_P I_P} \tag{26.3}$$

Reference subscripts W and P are added for the wire and PCB respectively.

Where:
$X = 0.000264$ in
$E_W = 16 \times 10^6$ Ib/in^2 (copper wire modulus elasticity)
$I_W = \pi (d^4)/4 = 1.917 \times 10^{-8}$ in^4
$d = 0.025$ in
R = height of wire plus one wire diameter into the PCB for wire in bending
$= 0.1 + 0.025 = 0.125$ in (moment arm length)
L_W = effective wire length = length of wire plus one wire diameter
$= 0.1 + 0.025 = 0.125$ in
$E_P = 1.95 \times 10^6$ Ib/in^2 (PCB modulus of elasticity)
L_P = length of PCB between component lead wires
$= 1 + 2(0.1) = 1.2$ in (PCB length)
$h = 0.062$ in (PCB thickness)
b = effective width of PCB for bending = 30 x h = (30) (0.062) = 1.86 in (effective width of PCB assuming no other similar components on PCB)
$I_P = bh^3/12 = (1.86)(0.062)^3/12 = 3.694 \times 10^{-5}$ in^4
M = RP = 0.125 P (bending moment on PCB)
Substitute into Equation 26.3 to get the wire load when PCB bends:

$$0.000264 = \frac{P(0.125)^3}{7.5(16\text{x}10^6)(1.917\text{x}10^{-8})} + \frac{(0.125)(0.125P)(1.2)}{2(1.95\text{x}10^6)(3.69\text{x}10^{-5})}$$

$$P = 0.269 \text{ Ib}$$

When compare the results with the previous example of section 25.4. When neglect the bending of the PCB in the analysis, the wire force of 0.311 pound will be developed.

When the bending of the PCB is included in the analysis, the wire force of 0.269 pound will be developed. This means that the bending action of the PCB will reduce the wire load by about 13%.

26.2 Fatigue Life and Vibration Environments

26.2.1 Introduction to Fatigue Generation

Electronic assemblies are used in many commercial, industrial, and military applications worldwide. The common element in the vast majority of these systems is that power is turned on to perform a function and then turned off after the function has been completed. This turn-on and turn-off process introduces alternating stresses in the structural elements as the assembly heats up and then cools down. Every stress cycle experienced by the electronic system will use up a small part of its total life. When enough stress cycles have been experienced, the fatigue life will be used up and cracks will develop in structural elements such as solder joints, plated through holes, and electrical lead wires, resulting in failures**.**

Materials can fracture when they are subjected to repeated stresses that are considerably less than their ultimate static strength. The failure appears to be due to submicroscopic cracks that grow into visible cracks, which then leads to a complete rupture under repeated loadings**.**

The appearance of a small crack does not always mean that a failure will occur. Sometimes a small crack will just stop growing, or grow so slowly that a failure does not occur. When a crack is observed, it is best to be safe and to assume that the crack will eventually result in a fatigue failure. If the crack is in a major structural element, then the element should be repaired or replaced.

Fatigue can also be generated in electronic systems by shock and vibration. It is probably safe to say that all electronic equipment will be subjected to some type of vibration at some time in its life. If the vibration is not associated with the end use of the product, then the vibration will probably be due to the transportation of the product from the manufacturer to the consumer**.**

Thermal stresses can develop in an electronic assembly while it is stored or sitting on a shelf, with no electrical operation. Temperature changes can still occur within the assembly, as the local ambient temperature changes from day to night.

When electronic systems are associated with moving vehicles or machinery such as automobiles, airplanes, washing machines, or blenders, then vibration cycling fatigue can develop as well as thermal cycling fatigue. These two fatigue effects can combine to produce-more rapid fatigue failures. Small fractures may be initiated during the thermal cycling environment, but they do not propagate rapidly since the thermal cycling rate is very low (1 to 10 cycles per day). Vibration environments, on the other hand, often produce several hundred cycles per second, so small cracks can grow more rapidly in vibration until a full fracture occurs.

When structural failures are experienced during vibration, it is natural to assume that vibration caused the failures. The corrective action would then be based upon structural dynamics. This may not be true, however, if there is a previous history of exposure to any thermal cycling environments. An examination of the various failures experienced in military electronic equipment shows that about 80% of the failures are due to thermal cycling, while the remaining 20% are due to vibration and shock. Any structural changes made to correct a deficiency involving vibration may not stop crack initiation in a thermal cycling environment. It is therefore important to understand the difference between thermal cycling failures and vibration cycling failures, to ensure the reliability of an electronic system that is required to operate in both environments.

Field experience with military types of electronic equipment shows that the greatest number of failures typically occur in the electrical interconnect system. About 30% of all failures occur in the connectors, master interconnecting boards, cables, and harnesses. These failures are produced by a combination of relative motion resulting from thermal cycling, vibration, shock, and rough handling.

26.2.2 Slow Cycle Fatigue and Rapid Cycle Fatigue

Fatigue properties are typically obtained from controlled stress cycle tests, using precision-machined and polished test specimens that are tested to failure over a wide stress range. The data points obtained are plotted on log-log paper with stress on the vertical axis and the number of cycles to fail on the horizontal axis. A straight line that represents the best average fatigue properties for that specimen is then drawn through the various scattered points, as shown in Figure 26.2.

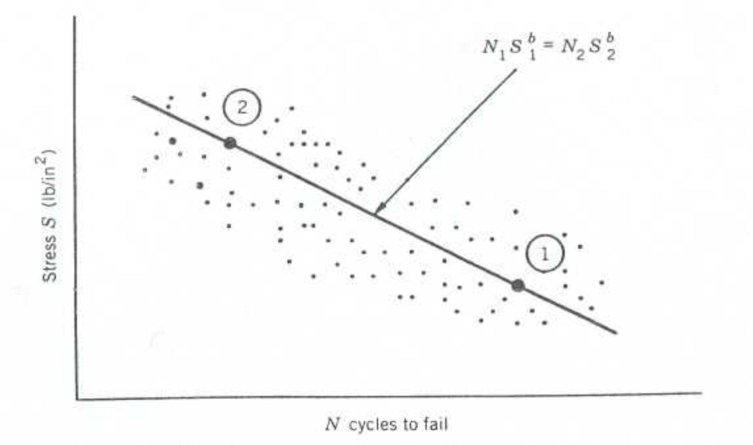

Figure 26.2 Typical S-N fatigue curves

The fatigue life can be estimated from the sloped portion of the curved based on the relation.

$$N_1 S_1^b = N_2 S_2^b \tag{26.4}$$

Where:
N= number of stress cycles to produce a fatigue failure
S = stress level at which these failures will occur
b = fatigue exponent related to the slope of the line

The b exponent shows the fatigue properties of each material, so it is useful in predicting the fatigue life of other members fabricated of the same material when exposed to similar environments. The slope of the fatigue curve must reflect the condition of the structure at critical areas such as holes, notches, and sharp changes in the cross section, which are defined as stress concentration areas. These stress concentration factors are not usually considered unless 5000 or more stress cycles are involved. Stress concentrations are not usually considered for very ductile materials, since these materials can often strain relieve themselves by plastically deforming.

Test data on solders shows that the frequency of the applied alternating load has a significant affect on the fatigue life, as shown in Figure 26.3. Where the effects of slow cycle fatigue and rapid cycle fatigue appears. The solder joint is significantly weaker for stresses that alternate at 0.06 cycle per minute compared with stresses that alternate at 5 cycles per minute under the same temperature conditions.

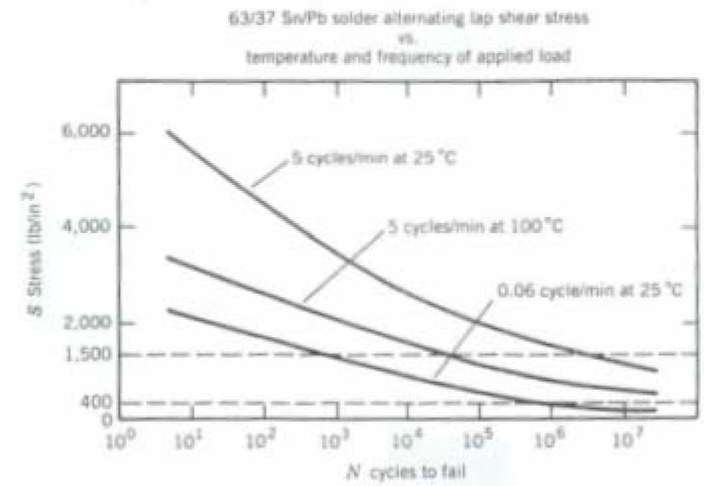

Figure 26.3 Solder subjected to slow cycle fatigue is weaker than solder in rapid cycle fatigue, especially at high temperatures.

Instead of a single-solder-joint fatigue curve, a dual curve is recommended, which shows the average properties for slow cycle fatigue and the average properties for rapid cycle fatigue. This dual-curve-concept recommendation is shown in Figure 26.4.

The slow cycle fatigue data portion of the solder curve was based upon a wide variety of temperature cycling tests, from -55 to +95 °C, and in some cases to + 125 °C, on a broad range of electronic circuit boards and chassis assemblies. The rapid cycle fatigue data portion of the solder curve was based upon random vibration and sinusoidal vibration tests, plus field exposure on many electronic boxes.

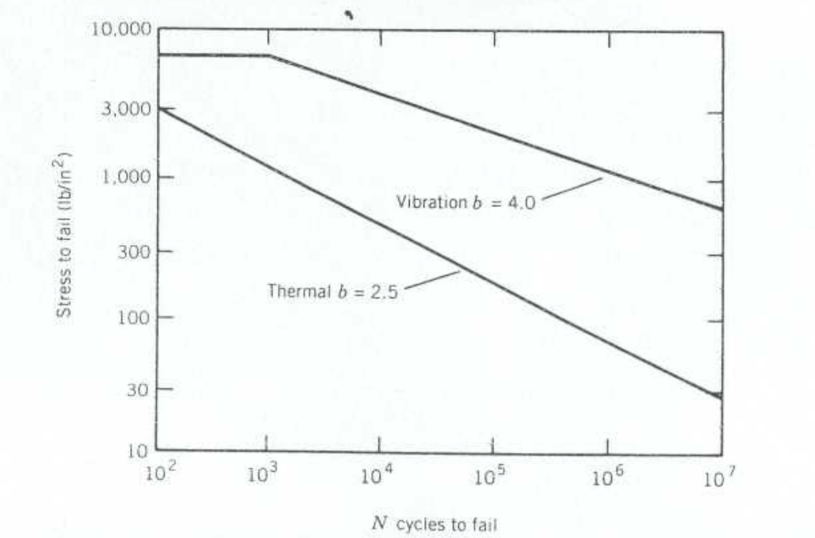

Figure 26.4 Vibration and thermal cycle fatigue, 63/37 solder, (vibration at room temperature)

Example: Determine the approximate fatigue life expected for the solder joints on the surface mounted transformer shown in sample solved example in section 25.2. For two different conditions as follows:

A) Original rapid temperature cycling from -55 to +95 °C, which resulted in a solder joint

shear stress of 1434 psi.

B) Revised rapid temperature cycling from -25 to +75 °C.

Solution:

PART (A)
An examination of the solder joint fatigue curve has shown in Figure 26.4 for thermal cycling conditions with 1434 psi solder shear stress.

Approximate solder fatigue life = 650 cycles

At 650 the cracks may be expected in some of the solder joints when the solder shear stress level is about 1434 psi.

This does not mean that electrical failures will occur instantly. It means that visible cracks may have developed and that these cracks can continue to grow in this environment, so a catastrophic failure is not far away.

PART (B)
When the temperature cycling range is changed, the fatigue life of the solder joint can be approximated by assuming a linear system, so the stress is directly proportional to the temperature change. The high and low temperatures to the neutral points are:

Condition (A) $$\frac{95 - (-55)}{2} = 75\ °\mathrm{C}$$

Condition (B) $$\frac{75 - (-25)}{2} = 50\ °\mathrm{C}$$

Using a linear ratio of the temperature change, the solder joint shear stress for the 50 °C temperature change will be:

$$S_S = \frac{50}{75}(1434) = 956\ \ \mathrm{Ib/in}^2$$

By Figure26.4 the approximate fatigue life is

Life = 1600 cycles to fail

Another method can be used to obtain the approximate fatigue life of the solder joint using Equation 26.4, along with the exponent b of 2.5, which represents the slope of the thermal fatigue curve for solder. A reference point must be obtained from Figure 26.4 to start the process. Any convenient starting point can be selected, such as 200 psi, where the fatigue life is 80,000 cycles to fail. This will be selected as point 2 on the fatigue curve.

Changing Equation 26.4 slightly to solve for N_1 cycles to fail and using the slow cycle fatigue exponent b with a value of 2.5:

$$N_1 = N_2 (S_2 / S_1)^{2.5}$$

Where:
N_2 = 80,000 (cycles to fail at reference point 2)
S_2 = 200 lb/in^2 (stress to fail at reference point 2)
S_1 = 956 lb/in^2 (stress resulting from 50 °C temperature change from condition B)

Substitute into Equation 26.4, to get the fatigue life for condition B is:

$$N_1 = 80000(200/956)^{2.5} = 1601\ \ \text{cycles to fail}$$