Part E: Analysis of Thermal Failure of Electronic Components

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25. Analysis of Thermal Stresses and Strain

25.1 Introduction

For many years the reliability of an electronic system was based, to a great extent, upon the junction temperatures of the semiconductor devices. Substantial efforts were made in the fabrication methods, mounting methods, and cooling techniques of the electronic devices to reduce these hot spot temperatures below 100 °C. This has produced a significant improvement in the reliability and effective operating life of the equipment. However, the electronic failure rates are still too high. Additional reductions in the failure rates must be achieved to further improve the reliability of our electronic equipment.

Some of the failure mechanisms that can cause malfunctions in electronic systems are examined in this chapter. Experience has shown that most of these failures are produced by a mismatch in the thermal coefficients of expansion (TCE) of the different types of materials typically used in electronic assemblies. The mismatch often generates high forces and stresses, which produce fractures and cracks in the electronic components and assemblies.

An examination of a large number of avionics failures has shown that most of them are mechanical in nature. They typically involve fractures in solder joints, electrical lead wires, plated throughholes (PTH), electrical cables, connectors, adhesive bonded joints, and hermetic seals. These failures are often produced by various combinations of thermal, vibration, shock, humidity, and salt environments, combined with poor manufacturing processes and poor design practices. These failures must be reduced in order to achieve a substantial improvement in the system reliability.

25.2 Thermal Expansion Effects in Electronic Equipments

Electronic assemblies utilize a wide variety of plastics and metals in the fabrication and manufacturing of their products. These materials can have significant differences in their thermal TCE, which may result in high strains and stresses in the lead wires, solder joints, and PTH if these factors are not understood or if they are ignored. Temperature changes will produce dimensional changes in almost all materials normally used in the assembly of electronic chassis and PCBs. Dimensional changes can occur due to power cycling where the power is turned on and off, which induces temperature changes within the electronic assembly. This can also be caused by thermal cycling, where the outside ambient temperature changes and the thermal lag within the chassis forces thermal gradients to develop because of different mass effects. These dimensional changes, which can occur along the X, Y, or Z axes of the electronic assemblies, can produce a wide variety of failures in the structural elements of these assemblies.

Consider a surface mounted transformer on a PCB, as shown in Figure 25.1. Thermal expansion differences between the component and the PCB along the X and Y axes (in the plane of the PCB) can produce failures in this subassembly after 12 thermal cycles from -55 to +95 °C. The failures will not be in the lead wires or in the solder joints. Instead, the failures will occur in the solder pads, which will be lifted off the surface of the PCB by overturning moments in the lead wires. These moments are caused by the expansion differences between the transformer and the PCB because each material has a different TCE.

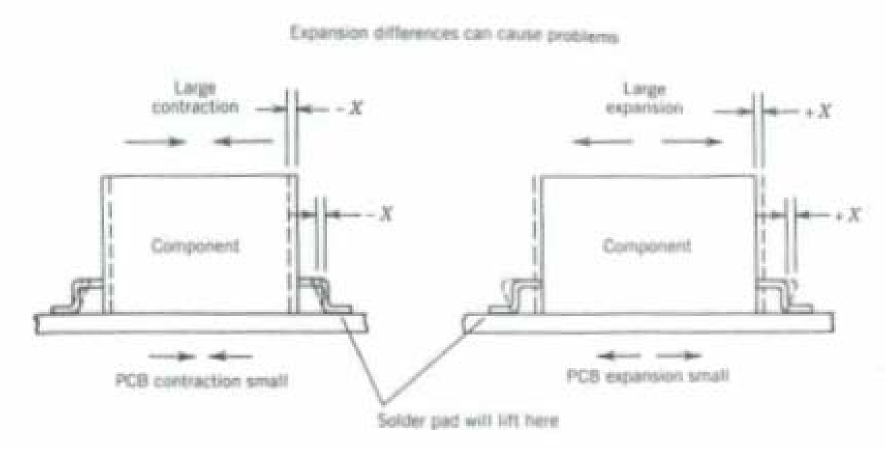

Figure 25.1 Surface mounted transformer where differences in expansion produce bending in the lead wires

Although epoxy is used in the PCB and for potting the transformer, the PCB contains glass fibers which have a low TCE. This reduces the TCE of the PCB in the X and Y planes, so the PCB expands and shrinks less than the transformer. This expansion difference produces the high forces in the lead wires. The wires transfer the load to the solder pads, lifting the pads, which are only cemented to the surface of the PCB.

Plated throughholes can be added to anchor the pads to prevent the pads from lifting off the PCB. The fatigue life of the assembly will now be increased to about 150 thermal cycles from -55 to +95 °C, where solder joint shear failures can now be expected.

Example: Determine the deflections and thermal stresses expected in the lead wires and solder joints of the surface mounted transformer shown in Figure 25.2, when it is mounted on an aluminum composite PCB which experiences in plane (X and Y) thermal expansion during rapid temperature cycling tests over a temperature range from -55 to +95 °C, with no electrical operation.

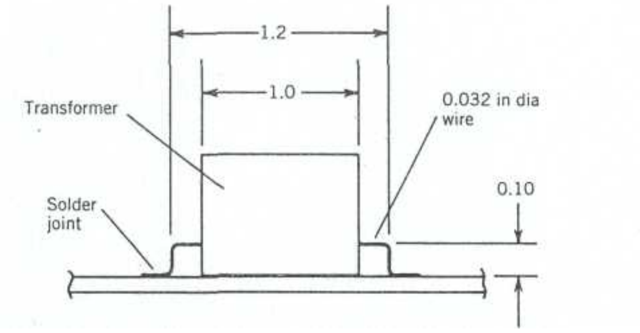

Figure 25.2 Dimensions of a surface mounted transformer

Solution:

Thermal expansion differences between the transformer and the PCB in the X-Y plane will produce a force on the lead wires and cause them to bend. This same force will produce a shear stress in the solder joint at the junction of the lead wire and the PCB. Since all masses tend to expand with respect to their centroid (or center of mass) and the proper length must be used in the expansion calculations. For a symmetrical structure, the effective length is simply half of the total length. Average physical properties must be used for the TCE of the transformer, which has an epoxy potting outer shell around a copper-iron core. This is also true for the PCB, which has an aluminum heat sink laminated between two epoxy fiberglass circuit boards, so an average TCE must be used for this subassembly.

The temperature is cycled over a range from -55 to +95 °C, for a total difference of 150 °C in this sample problem. However, the stresses are determined for a temperature range of only 75 °C, which is half of the total temperature range experienced. The 75 °C temperature range is used because it represents the stresses that will be developed during cycling from a neutral stress point to the maximum positive stresses, and from a neutral stress point to the maximum negative stress.

In this case the neutral stress point would be at 20 °C. Increasing the temperature 75 °C would bring the temperature to +95 °C. Decreasing the temperature 75 °C from the neutral point of 20 °C would bring the temperature down to -55 °C.
The solution divided into three parts:

1) Determine the expansion differences between the transformer and the PCB in X-Y planes is

$$X = (a_T - a_P)\, b\, \Delta t \qquad (25.1)$$

Where:

a_T = average TCE of transformer, considering a mixture of epoxy potting copper, and iron core

in and PCB in X-Y plane (Z axis expansion are ignored here)
= 35×10^{-6} in/in/°C or 35 parts per million/°C (35 ppm/°C)

a_P = average TCE of composite PCB with epoxy fiberglass and aluminum heat sink core in X-Y
planes
= 20×10^{-6} in/in/°C or 20 parts per million/°C (20 ppm/°C)

$b = 1.2/2 = 0.6$ in (effective length of transformer, including wire length with the transformer)

$\Delta t = 95-(-55) = 150$ °C (peak to peak temperature range)

$\Delta t = 150/2 = 75$ °C (neutral point to high and low temperature)

Substituting in Equation 25.1 yields to

$$X = (35-20) \times 10^{-6} (0.6)(75) = 0.000675 \text{ in}$$

2) Determine the horizontal force induced in the wire as it is forced to bend through this deflection. The wire geometry is shown in the following Figure 25.3.

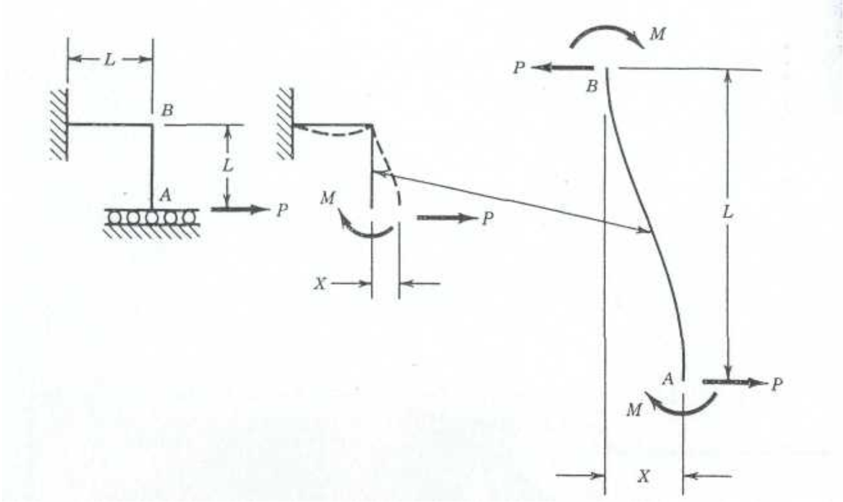

Figure 25.3 Deflection forces the lead wire to bend

The horizontal displacement of a square frame with clamped ends, with bending of both wire legs due to the action of the lateral force (P), can be determined from the following equation

$$X = \frac{PL_W^3}{7.5E_W I_W} \tag{25.2}$$

Where:
$X = 0.000675$ in (wire displacement in X-Y plane)
$L_W = 0.1$ in (vertical and horizontal wire length)
$I_W = \dfrac{\pi d^4}{64} = \dfrac{\pi(0.032)^4}{64} = 0.051\text{x}10^{-6}\text{in}^4$ (wire inertia)
$E_W = 16\text{x}10^6$ psi (modulus of elasticity, copper wire)

Substituting in Equation 25.2 yields to

$$P = \frac{7.5(0.000675)(16\text{x}10^6)(0.051\text{x}10^{-6})}{(0.1)^3} = 4.13\ \text{Ib}$$

3) Determine the bending stress in the lead wire and the shear stress in the solder joint.

The bending moment (P) in the wire at the solder joint can be determined from Figure 25.2, by summing up the bending moments for the wire frame.

$$\begin{aligned} M &= 1.2PL_W \quad \text{(wire bending moment)} \\ &= 1.2(4.13\text{x}0.10) = 0.495 \text{ lb in} \end{aligned} \tag{25.3}$$

Then the bending stress (S_b) in the wire can be obtained as in Equation 25.4

$$S_b = \frac{\text{KMC}}{\text{I}_\text{W}} \tag{25.4}$$

Where:
K = Stress concentration factor
   = 1 here
C = Wire radius to neutral axis
   = 0.032/2 = 0.016 in
Substituting in Equation 25.4 yields to

$$S_b = \frac{(0.459)(0.016)}{0.051\ \mathrm{x}10^{-6}} = 155294\ \mathrm{Ib/in}^2$$

This far exceeds the ultimate tensile stress of 45,000 psi for the copper lead wire, which means that the wire will be in the plastic bending range. However, testing experience with this condition shows that the probability of a wire failure is low (if there are no sharp cuts in the wire) due to the low number of stress cycles normally expected for this type of environment.

The direct shear stress (S_s) in the solder joint can be obtained from the solder pad area estimated to be about 0.09 in x 0.032 in. This direct shear stress does not include solder joint stresses produced by the overturning moment. Both stresses may be combined to obtain the maximum or the Von Mises stress. Only the shear stresses were used here to determine the approximate fatigue life of the solder joint. Stress concentrations are not considered here because the solder is so plastic.

$$\mathrm{S_s} = \frac{P}{A} \qquad (25.5)$$

Where: P= 4.13 Ib
A= 0.09 in x 0.032 in = 0.00288 in^2

Then the direct shear stress is

$$\mathrm{S_s} = \frac{4.13}{0.00288} = 1434\ \mathrm{Ib/in}^2$$

25.3 Reducing the Thermal Expansion Forces and Stresses

Lower forces and stresses in the electrical lead wires and solder joints will lead to a longer life with a higher reliability. The Equation 25.2 shows that the forces in the lead wires can be reduced by (a) decreasing the moment of inertia I, (b) decreasing the deflection of the wire X, or (c) increasing the length of the wire L.

(a) Decreasing the moment of inertia I

The moment of inertia of the component wire can be reduced by coining (squeezing or rolling) the round wire into a flat thin rectangular cross section. This will decrease the force in the wire, which will decrease the wire bending stress and the solder joint shear stress. Coining will also increase the width of the lead wire at the solder joint, which will increase the solder joint area and further reduce the solder joint stress. MIL-STD-2000 solder specification requires surface mounted components, with axial leads, to have their wires coined before they are soldered to the circuit boards.

Coining may be expensive since special machines are required for this operation. For a large manufacturing facility, where millions of components are involved, the coining costs for each component will be relatively small. However, for a small company the cost of the coining equipment can be too great, so other ways for mounting the components may have to be examined.

In the previous sample problem, if the lead wires are coined to a cross section that measures 0.010 in thick and 0.080 in wide (which maintains the same cross-sectional area), the forces and stresses will be reduced. The reduction will be directly related to the different moments of inertia for the wire cross sections, as shown in Equation 25.2. The new moment of inertia becomes.

$$\mathrm{I} = \frac{(0.08)(0.01)^3}{12} = 6.667 \ \mathrm{x}10^{-9} \ \mathrm{in}^4$$

From Equation 25.2 the new shear force is

$$P = \frac{7.5(0.000675)(16\mathrm{x}10^6)(6.667\mathrm{x}10^{-9})}{(0.1)^3} = 0.54 \ \mathrm{Ib}$$

Substituting in Equation 25.5.With 0.09 in x 0.08 in estimated area yields to

$$\mathrm{S_s} = \frac{0.54}{(0.09)(0.08)} = 75 \ \mathrm{Ib/in}^2$$

This low solder shear stress will provide a good fatigue life.

(b) Decreasing the deflection of the wire X

Wire deflections can be reduced by reducing the relative differences in the TCE between the component body and the PCB. In this application, the transformer has a TCE that is much greater than the TCE of the PCB, so the transformer expands and shrinks more than the PCB, producing high forces in the wires. Expansion differences can be reduced by increasing the TCE of the PCB or by reducing the TCE of the transformer, so the mismatch between them is reduced. It is a far easier task to reduce the TCE of the transformer by simply adding calcium carbonate or aluminum oxide powder to the epoxy solution before encapsulating the transformer. The reduction in the transformer TCE will be related to the amount of material added to the epoxy solution. An overall reduction in the transformer TCE of about 10% or 3.5 ppm/°C can be achieved. This will reduce the difference in the TCE as shown in Equation. 25.1. From 35 - 20 = 15, to 31.5 - 20 = 11.5 ppm/ °C. This ratio is 11.5/15 = 0.766.

This means that the forces and stresses will only be 76.6% of the levels previously shown, when the transformer TCE is reduced by 10%.

(c) Increasing the length of the wire L

Increasing the wire length will rapidly reduce the forces developed in the lead wires, because a cubic function is involved here. The wire length can be increased by using camel humps or loops as shown in Figure 25.4.

If the wire length increased 50% to a length of 0.15 in, the wire force will be reduced to 1.22 pounds. This will reduce the bending stress to 68900 psi and solder shear stress to 424 psi.

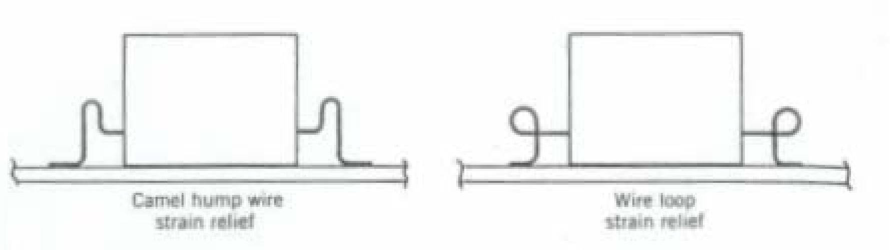

Figure 25.4 Methods for increasing the wire length to decrease the forces and stresses in the solder joints

25.4 X-Y Thermal Expansion Stresses for Throughhole Mounting

A large number of components such as resistors, capacitors, diodes, flat packs, and hybrids are fabricated with axial leads. Wire-forming tools are then used to bend the leads 90° for insertion in throughhole PCBs for flow soldering. During exposure to thermal cycling environments, the PCB typically ' has a higher TCE than the component in the X-Y plane, so the PCB will expand more than the component. Since the wire in an axially leaded component has a relatively low bending stiffness, virtually all of the deflection difference between the PCB and the component will be taken up by the bending in the wire, as shown in Figure 25.5.

A bending moment will be developed in the wire, at the PCB solder joint, which will produce a shear tear-out stress in the solder joint. This solder joint stress should be limited to a value of about 400 psi to ensure a long trouble-free operating life.

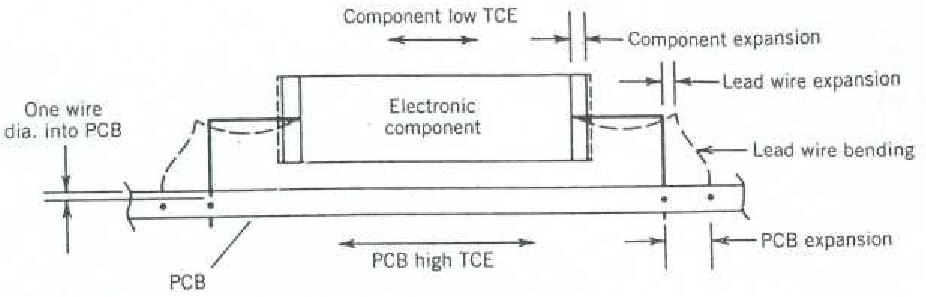

Figure 25.5 Deflection in throughhole technique

Example: Determine the stresses in the lead wires and solder joints of the axial leaded resistor, throughhole mounted as shown in Figure 25.6, due to a mismatch in the thermal expansion of the epoxy fiberglass PCB in the X-Y plane over a temperature cycling range from -40 to +80 °C.

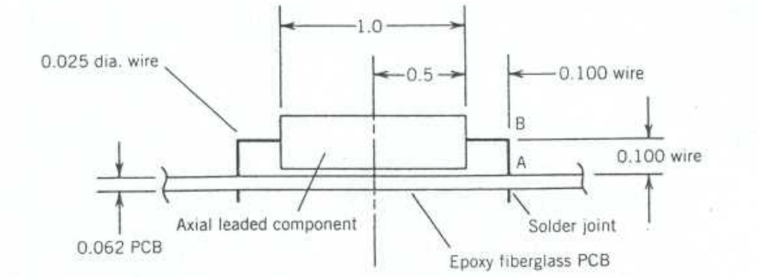

Figure 25.6 Dimensions of an axial leaded resistor throughhole mounted in a PCB

Solution:

The thermal expansion of the PCB will be greater than the expansion of the resistor because the TCE of the PCB is greater than the TCE of the resistor. The expansion differences will force the vertical leg of the resistor lead wire to bend. This action will produce bending and shear stresses in the lead wires, and shear tear-out stresses in the solder joints.

The expansion of the PCB must be equal to the expansions of the resistor body plus the horizontal expansion of the lead wire, plus the bending deflection of the vertical leg of the lead wire. This can be expressed in a simplified form as shown in the following equation.

$$X_p = X_R + X_H + X_W \tag{25.6}$$

Where:
X_p= Thermal expansion of PCB along X axis
X_R = Thermal expansion of resistor body along X axis
X_H = Thermal expansion of horizontal lead wire leg
X_W = Bending of vertical lead wire leg along X axis

The expansion differences force the wire legs to bend, which produces a horizontal force in the wire. The magnitude of this force can be obtained from the bending displacement produced in the vertical leg of the wire. This bending displacement can be obtained from Equation 25.7 as shown below.

$$X_W = a_P L_P \Delta t - a_R L_R \Delta t - a_H L_H \Delta t \tag{25.7}$$

Where:
a_P = 15 x 10^{-}6 in/in/°C (TCE of PCB in X-Y plane)
L_P = 0.5 + 0.1 = 0.6 in (effective length of PCB)
Δt = 80-(-40) = 120 °C (total temperature range)
Δt = 120/2 = 60 °C (neutral to peak value for a rapid temperature cycle)
a_R = 6 x 10^{-6} in/in/°C (TCE of carbon composition resistor)
L_R = 0.5 in (half of resistor body length)
a_H = 16 x 10^{-6} in/in/°C (TCE of horizontal copper wire
L_H = 0.1 in (horizontal length of lead wire)

Substitute into Equation 25.7 yields to:

$$\begin{aligned} X_W &= (15x\,10^{-6})(0.6)(60) - (6x\,10^{-6})(0.5)(60) - (16x\,10^{-6})(0.1)(60) \\ &= 0.000264 \text{ in} \end{aligned}$$

This represents the bending displacement of the lead wire. The force produced in the wire due to this bending deflection can be determined from the following Equation 25.8, for a square frame, where the lengths of both legs are equal.

$$P = \frac{7.5E_W I_W X_W}{L_W^3} \tag{25.8}$$

The wire extends into the PCB, and it also extends into the resistor body, which makes the effective wire length slightly longer than the exposed wire length. Test data on similar electronic subassemblies show that for wires in bending, the lead wire appears to extend about one wire diameter into the component body and one wire diameter into the PCB. This approximation is used in the sample problem to obtain the effective length of the lead wire.

L_W = effective wire length = exposed length plus one wire diameter
$= 0.1 + 0.025 = 0.125$ in
$E_W = 16 \times 10^6$ Ib/in^2 (copper wire modulus elasticity)
$X_W = 0.000264$ in
$I_W = \pi\,(d^4)/4 = 1.917 \times 10^{-8}$ in^4

Substitute into Equation 25.8 yields to:

$$P = \frac{7.5(16x\,10^6)(1.917x\,10^{-8})0.000264)}{(0.125)^3} = 0.311\,\text{Ib}$$

Then the bending moment in the lead wire, at the solder joint is

$$M = 1.2PL_W = 1.2(0.311)\,(0.125) = 0.0466 \text{ Ib in}$$

Then the bending stress in the lead wire can be obtained from equation 25.4. Since the number of stress cycles over this wide temperature range is expected to be low, so fatigue is not a factor. So that stress concentration factor is not used here.

Where:
C = Wire radius to neutral axis
$= d/2 = 0.025/2 = 0.0125$ in

Substitute into Equation 25.4 yields to:

$$S_b = \frac{(0.0466)(0.0125)}{1.917\,x10^{-8}} = 30386\,\text{Ib/in}^2$$

Since this stress is well below the ultimate stress of 45,000 psi for copper wire, the condition is acceptable.

The overturning moment developed in the lead wire may lead to shear tear-out failures in the solder joint, as shown in Figure 25.7. Test data show that these failures do not always occur at the surface of the lead wire, where the shear area is minimum.

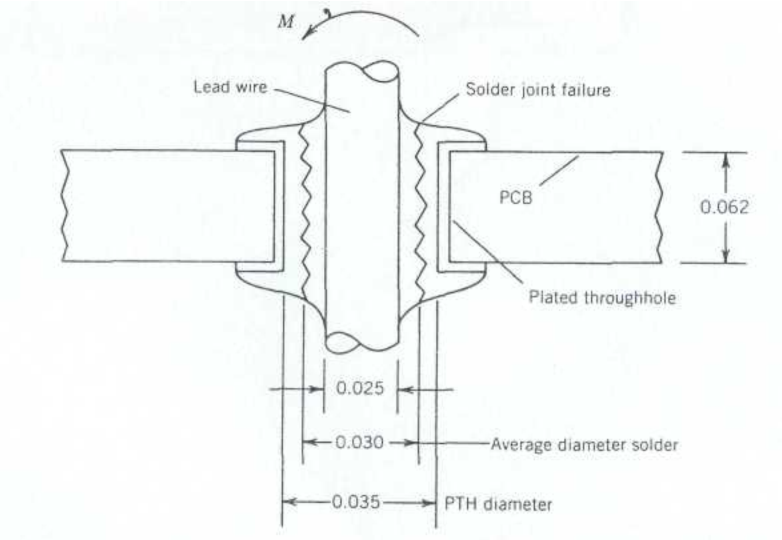

Figure 25.7 Typical solder joint failure in a throughhole PCB mounting

Many of the solder joint failures seem to occur in an area between the wire and the PTH in the PCB as shown in Figure 25.8. An average area based upon the diameter of the wire and the diameter of the PTH can be used to find the average area of the solder joint for this condition.

The magnitude of the shear tear-out stress can be obtained from Equation 25.9.

$$S_{ST} = \frac{M}{A_S h} \qquad (25.9)$$

Where:
M = 0.0466 Ib in (overturning moment in solder joint)
h = 0.062 in (solder joint height, use PCB thickness)
$d_{av.}$= (0.025+0.035)/2 = 0.03 in
$A_S = \pi\,(0.03)^2/4 = 0.000707\ \text{in}^2$
Then the shear stress is:

$$S_{ST} = \frac{0.0466}{(0.000707)(0.062)} = 1063.3\,\frac{\text{Ib}}{\text{in}^2}$$

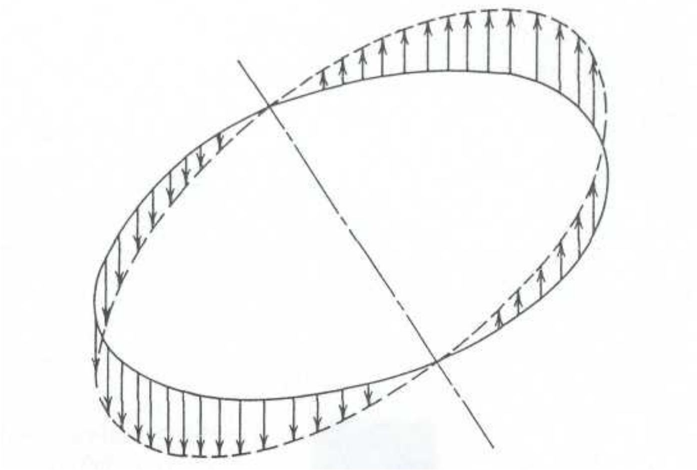

Figure 25.8 Shear tear-out stress pattern in the solder joint of a throughhole lead wire