Mechanical Engineering for Electronics

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Abstract

Schlumberger drilling tools are exposed to very hard loading conditions (shocks, vibrations, thermal cycling) while performing a job. As these tools are full of electronics, issues can quickly come from electronics failure. Mechanisms of failure occurring in electronics are very complex but can be predicted in some cases.

The first part of the thesis describes in which context mechanical engineering applied to electronics is used in Schlumberger. The different kinds of failure which will be investigated in the report are presented in this part.

The second part deals with fatigue models used in electronics. From classical methods used in mechanical engineering to calculate a material fatigue life, fatigue models are adapted and formulated for special applications.

The third part investigates the issue of capacitor flex-cracking which occurs when boards do not remain flat during loadings (shocks or thermal cycling). Root causes of this mechanism of failure are investigated in this part to find key points where improvements have to be made to avoid failure.

The fourth part presents a common failure which deals with Plated Through Holes (PTHs) issues. A simple model of investigations is established.

The fifth part deals with fatigue life of leadless components (resistors) under thermal cycling. Even if the failure is revealed during shock tests, the damage is mostly created during the thermal cycles applied on the board prior to shock. The effect of the size of the component is discussed in this part.

The last part deals with modal analysis on a given board in order to be able to reduce the impact and the damage of shocks applied on this board. Simulation and experimental modal analysis are compared in order to see the influence of certain parameters on the natural frequencies of the board.
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I. Schlumberger presentation

1. The company

Schlumberger is a leading international company providing oilfield services. Founded by the Schlumberger brothers in 1927 in Alsace, France, the company is today hiring more than 110,000 people of more than 140 different nationalities and is present in about 80 countries in the world. The company is a specialist in all the steps from hydrocarbon prospection to the exploitation (petrol, oil or gas) and drilling.

2. Product Center in Clamart

The Schlumberger Riboud Product Center (SRPC) is the biggest technologic center of its kind in Europe and employs 500 scientists. One of the main missions of the technologic center is to develop and manufacture the drilling tools which will be sent into the field to perform job.

a) Drilling tools

In order to drill a hole in the earth to extract hydrocarbon, scientists must obtain plenty of information concerning the environment in which oil slick is situated. Therefore, drilling tools created by Schlumberger are equipped with a multitude of electronics in order to acquire data while drilling the hole. Electronics embedded in the drilling tools is experiencing very harsh conditions in terms of shocks, vibrations and thermal cycles. These conditions are among the worst seen by electronics in industry. It is a fact that failure of electronics in drilling tools exists and Schlumberger’s interest is to understand the occurrence of failure and find solutions to avoid it.

b) Simulation and modeling group

Within the technologic center of Clamart, the simulation and modeling group is in charge of understanding, simulating and providing solutions to avoid failure encountered by the drilling tools in qualification tests or on the field. Their clients are essentially the project engineers designing drilling tools and experiencing difficulties to understand and find solutions for recurrent failure.

To understand these failures, engineers of the simulation and modeling group essentially perform simulations with finite elements software which permits investigations numerically of different designs in order to find the one which is the most suitable to avoid failure. However, finite elements simulations take a lot of time from its preparation to the end of run especially for simulations involving shock loading. Thus, it is interesting to know whether other tools than finite elements software can be used to predict failure of drilling tools.

c) Context of the internship

Many failures investigated by the modeling and simulation group concerns electronic components on electronic boards. As the investigation of electronics failure under shocks, vibrations and thermal cycling requires a strong and special experience which is not implemented in finite elements software, Schlumberger decided to investigate in more detail the mechanisms of failure involved. In order to do so, simple models to describe the mechanisms of failure have been created.
3. Mechanical context

a) Modeling electronic boards

To understand how mechanical engineering is used in electronics, it is important to be familiar with the mechanical context of components. An electronic board is a superposition of conductive and non-conductive layers. The material for the conductive layer is mostly copper. For the non-conductive layers, different dielectrics are used. The mechanical properties and parameters like Young’s modulus, Poisson’s ratio, coefficient of thermal expansion, of copper and dielectrics are different which can lead to some issues when the board is loaded. Components are soldered on this board. The way of attaching the components varies from one component to another as seen in Figure 1. Some components have leads with different shapes (Jlead or Gullwing) whereas others are directly soldered from their extremities to the board; these are called leadless components such as resistors. Finally, some others have pins which are soldered in a hole going from one side of the board to the other side. These holes are called Plated Through Holes (PTH) and the components are called Through Hole Components, in opposition to the Surface Mounted Components (SMC) described before.

Figure 1 - Component leads on electronic board.

b) Origin of failure

When a drilling tool is in operation, electronic boards with components attached on them are experiencing very hard conditions due to thermal cycling, shocks or vibrations. Under loading, the board is experiencing displacements which, due to the different mechanical properties of the materials (copper, dielectrics, solder, component lead and component packaging), can lead to displacement mismatch causing failure. For Jlead or Gullwing components, cracks can occur in the solder. For leadless components, cracks can occur in the component packaging. For through hole components, cracks can be observed in the periphery of the hole drilled in the board and called plating or barrel. Electronic failure can appear immediately when applying loading or due to fatigue. Thus, it is interesting to be able to predict when cracks will appear. However, it is important to note that, in practice, some cracks can be present without being detectable electrically. Thus, crack apparition and electronic failure does not occur systematically at the same time. Predicting materials fatigue life in mechanical engineering is widely used today and it is interesting to see how this knowledge is applied to the practical case of electronics. Some already known fatigue models are just applied to the practical case, whereas some others have been created for special applications.
II. Fatigue models

1. Wöhler curve

In order to predict a material fatigue life under cyclic load, the Wöhler curve (also called S-N curve) is a useful tool for describing material properties. This curve plots for a given stress amplitude (on the vertical axis) applied to the material during a load cycle, the number of cycles (on the horizontal axis) which can be applied before the material fails. It has been observed that the stress amplitude is not always a suitable parameter in characterizing fatigue failure. In particular, this holds true for low cycle fatigue where the strain range may replace the stress amplitude. A similar curve is also used in electronics. Instead of looking at the stress amplitude one looks at the strain range experienced by the material during a load cycle. A typical fatigue curve used in electronics is presented in Figure 2. The idea has been borrowed from low cycle fatigue in engineering [2].

One can divide the strain range into a plastic part and an elastic part. It is not always an easy matter to distinguish between them. In electronics, low cycle fatigue may cause fatigue due to thermal cycling whereas failure due to high cycle fatigue is caused by shocks or vibrations.

![Fatigue curve for electronics.](image)

2. Thermal cycling

Under thermal cycling, fatigue failure essentially occurs in the solder. Thus, fatigue models are focused on the solder material and the constraints it endures during a thermal cycle. This kind of failure primarily comes from a Coefficient of Thermal Expansion (CTE) mismatch between the component, the solder and the board. To calculate the fatigue life of the component (the number of cycles \( N_f \) before failure) under thermal cycling from the plastic strain range experienced by the solder (or, generally speaking, the material in which cracks appear) over one cycle, the Engelmaier model is used. It can be formulated in two ways [6]. The first version is

\[
N_f = \frac{1}{2} \left( \frac{\Delta \varepsilon_p}{2 \varepsilon_f} \right)^{1/2}
\]

where:

- \( \varepsilon_f \) is the solder ductility coefficient depending on the solder material and is calculated experimentally,
- \( c \) is the solder ductility exponent (typically \(-0.2 < c < 0\)) calculated as

\[
c = -0.442 - 0.0006T_s + 0.0174 \ln \left( 1 + \frac{360}{t_D} \right)
\]

where,

- \( T_s \) is the mean temperature of the thermal cycle,
- \( t_D \) is the dwell time at the maximum temperature during the soldering process.
The second version of the Engelmaier model is formulated as

\[ N_f = \beta \left( \frac{\Delta e_p}{2} \right)^{-1} \]  

(2)

where \( \beta \) is a coefficient depending whether the solder is a tin-lead solder or a lead-free solder.

From a theoretical point of view, the first formulation for the Engelmaier model seems to be more precise and adaptable to the solder material, according to the review performed in [6].

3. Shocks and Vibrations

a) Steinberg’s equation

Steinberg’s equation claims that for a board simply supported on four edges, the maximum out-of-plane displacement that is allowed for a component on this board under vibrations according to [2] is

\[ d = \frac{0.00022B}{ct\sqrt{L}} \]  

(3)

where:
- \( d \) is the allowable displacement in inches (relative displacement between board and component),
- \( B \) is the board length in inches,
- \( c \) is a parameter depending on the component:
  - 1.0 for standard components with two rows of pins (DIP),
  - 1.26 for DIP with side brazed leads component,
  - 2.25 for rectangular Surface Mounted Components with attaches on the four edges.
- \( t \) is the board thickness in inches,
- \( L \) is the component length in inches.

b) Fatigue life under vibrations

To predict the fatigue life of a component on a board under vibrations, the Basquin’s model should be used, [2]

\[ \sigma N^b = \text{constant} \]  

(4)

where \( \sigma \) is the stress amplitude applied on the component leads, \( N \) is the number of vibration cycles applied before failure and \( b \) the Basquin constant (usually set equal to 6.4 for electronics materials used for pins and solders).

Assuming that displacements and stresses are proportional, the Basquin equation can be written as

\[ Z N^b = \text{constant} \]  

(5)

where \( Z \) is the relative displacement between the board and the component.

Thus, the Basquin equation relates the life times for two different displacements in the following way

\[ Z_1 N_{1}^b = Z_2 N_{2}^b \]  

(6)

\[ N_2 = N_1 \left( \frac{Z_1}{Z_2} \right)^{3/\beta} \]  

(7)

Assuming that the relative displacement \( Z_2 \) applied to the component is known, one can use a reference case to calculate the fatigue life \( N_2 \) of the component. This reference case is the following

\[ Z_1 = d \quad \text{and} \quad N_1 = 10E6 \text{ for harmonic vibrations} \]
\[ N_1 = 20E6 \text{ for random vibrations} \]  

(8)
There are several ways of calculating this displacement $Z_2$.

As equation (7) describes the worst case when the component is located at the center of the board where the curvature is maximum, one can modify this equation so as to include the board curvature $R$ at the location of the component [2]

$$N_2 = N_1 \left( \frac{Z_1}{Z_2 R} \right)^{1/b} \quad \text{(9)}$$

c) Criterion with shocks

Concerning shock loading, the criterion decides whether a component is able to resist a certain shock level (shock acceleration). For a rectangular board simply supported on its four edges, the maximum out-of-plane displacement (relative displacement between the board and the component) can be calculated as [13]

$$Z_{\text{max}} = \frac{A_{sh} P_F}{f_n^2} R \quad \text{(10)}$$

where:
- $Z_{\text{max}}$ is the maximum relative displacement between the board and the component in inches,
- $A_{sh}$ is the shock acceleration in inches/second$^2$,
- $P_F$ is the amplification factor,
- $f_n$ is the board first natural frequency,
- $R$ is the relative board curvature (ratio of the local board curvature over the maximum board curvature) at the location of the component ($0 < R < 1$).

Empirical laws reveal that a component can resist a shock if the maximum relative displacement between the board and the component during the shock is lower than an empirical value [13]

$$Z_{\text{max}} < Z_{\text{allow}} = 6d \quad \text{(11)}$$

where $d$ depends on board geometry and is calculated according to (3).

This is valid for a single shock. For repeated shocks, one can treat them as vibrations and formula (9) can be applied.

$f_n$ and $R$ are usually calculated by means of modal analysis with a finite elements software. In selecting elements for the calculation, one must be observant. For example, when using brick elements for calculating natural frequencies of plates, a computational trouble called shear locking can appear and virtually rigidify the plate more artificially.

The amplification factor $P_F$ is used to reflect the conditions in which shocks are performed. The board with components soldered onto it is seen as a mechanical system which can be modeled by mass-spring-damping system which has its own natural frequency $f_n$. One defines a shock as a periodic acceleration varying with time which is applied to the system. Depending on the frequency of the input acceleration (shock), the output acceleration (and so displacements of the board) can be amplified or attenuated by the system. To take this effect into account, the amplification factor $P_F$ has been introduced. This parameter depends on the shock characteristics such as shape, duration, intensity or shock condition (impact or impulsion, with or without bounce) but also on the board characteristics on which the shock is applied. It can vary from 0.5 to 2 and the highest value is taken for calculations in order to consider the worst situation.
III. Capacitor flex-cracking

1. Phenomenon

The flex-cracking phenomenon concerns capacitors (MLCC) soldered on a board (also called substrate) and is illustrated in Figure 3. When deflection is applied on the substrate leading to a curvature under the capacitor, tensile stress is developed in the capacitor due to deformation of the pad and the solder. If this tensile stress is too high, the termination is pulled out creating a crack in the capacitor. These cracks have a direction with an angle of approximately 45° with respect to the substrate and are typical of flex-cracking. When a crack is propagating in the capacitor, it creates interconnects between the conductive plates and the failure can be detected electrically. However, if the initiation of the crack remains in the capacitor termination it cannot be detected electrically.

2. Parameters involved in flex-cracking

The model used by the software for flex-cracking is empirical and has been developed and calibrated with a number of experiments. It concerns low cycle fatigue and gives a probability of failure for the capacitor from input parameters divided into four categories:

- geometrical parameters, described in Figure 4,
- capacitor manufacturer,
- materials (Young’s modulus of substrate and solder),
- curvature (inverse of radius of curvature) under component.
3. **Study case**

In order to study the flex-cracking phenomenon one considers a simplified example of a board of length $L_b$ which is simply supported at its ends. A deflection $\delta$ is applied at the center of the board where a capacitor of length $L_c$ is soldered (Figure 5).

![Figure 5 - Flex-cracking study case.](image)

**a) Curvature**

As the curvature is the initial reason leading to failure, this curvature must be connected with deflection, see Figure 6.

![Figure 6 - Curvature calculations.](image)

We can approximate the shape of the board by a polynomial equation of the second order

$$y = ax^2 + bx + c$$  \hspace{1cm} (12)

Three boundary conditions,

$$y(x = 0) = \delta \text{ and } y \left( x = \pm \frac{L_b}{2} \right) = 0$$  \hspace{1cm} (13)

give

$$a = -\frac{4\delta}{L_b^2} \text{ and } b = 0 \text{ and } c = \delta$$  \hspace{1cm} (14)

Thus, the curvature (inverse of radius of curvature) of the board can be expressed as

$$\gamma(x) = \frac{\frac{d^2y}{dx^2}}{\left(1 + \left(\frac{dy}{dx}\right)^2\right)^{3/2}} = \frac{2a}{(1 + (2ax + b)^2)^{3/2}}$$  \hspace{1cm} (15)
The maximum curvature is reached for the case \((x = 0)\) where we have

\[
\gamma_{\text{max}} = \gamma(x = 0) = 2a = -\frac{8\delta}{L_b^2}
\]

(16)

the negative value is due to a concave function. Thus, the radius of curvature under the component becomes

\[
\rho = \left|\frac{1}{\gamma_{\text{max}}}\right| = \frac{L_b^2}{8\delta}
\]

(17)

b) Stress analysis

To give analytically the stress level experienced by the solder, the model in Figure 5 is completed by the model below where the solder joints are modeled by means of beams.

Assuming that deflection is small, the angle \(2\theta\) between the two extremities of the capacitor can be calculated as

\[
2\theta = \frac{L_c}{\rho}
\]

(18)

The solder beams are experiencing bending (Figure 8). A bending moment \(M_0\) is applied by the capacitor on the solder. One assumes that the angle \(\varphi\) between the solder and the capacitor remains equal to zero (i.e. rigid clamping). A second moment \(M_1\) will arise between the board and the solder. The angle between the solder and the board is assumed to be \(\theta\) due to the geometry of the problem.
From beam theory, the relation between the moment applied on the solder modeled by a beam, and the angle of the beam is given by

$$
\begin{align*}
\varphi &= 0 = \frac{M_0}{3EI} + \frac{M_1}{6EI} \\
\theta &= \frac{M_0}{6EI} - \frac{M_1}{3EI}
\end{align*}
$$

(19)

where $E$ is the Young’s modulus of the solder and $i = \frac{W_c l^4}{12}$ is the moment of inertia in bending of the solder. The solutions are

$$
M_0 = -\frac{2\theta Ei}{h} \\
M_1 = -2M_0
$$

(20)

(21)

Thus, maximum stress experienced by the solder during flex-cracking becomes

$$
\sigma_{\text{max}} = \frac{\left|M_0\right| T_c}{I} = \frac{\theta Ei T_c}{hl}
$$

(22)

where $I = \frac{W_c T_c^3}{12}$ is the moment of inertia in bending of the capacitor. So the stress experienced by the capacitor can be expressed as a function of the deflection as

$$
\sigma_{\text{max}} = \frac{4EI_c T_c W_c l^3}{hL_b W_c T_c^3} \delta
$$

(23)

c) Fatigue life

As flex-cracking failure is observed experimentally in high cycle fatigue, the value given in equation (23) can be used directly in the Basquin’s model of equation (4) to calculate the stress experienced by the capacitor.

Results of fatigue life from Basquin’s model and some experiments are provided in Figure 9 for capacitors of different sizes. In the experiments, three capacitors were located at the center of a board experiencing a deflection. Since capacitor sizes are normalized, results are represented with a variation of the capacitor length but, in fact, all other dimensions also vary. It can be seen that theory describes the same tendency (with capacitor length increase) as observed in experiments even though results from theory are higher than experiments. It can be explained by the fact that the model described above does not consider the presence of defects in capacitors.

![Figure 9 - Capacitor fatigue life under flex-cracking.](image-url)
4. Effect of solder shape

The solder shape plays an important role on the capacitor fatigue life. To investigate this effect, one performed several Finite element simulations with Abaqus. As the yield stress is reached in the solder, the Engelmaier model is used to determine the solder fatigue life.

d) Parameters

One performed simulations on a 2D model with a board of length 200 mm and thickness 4 mm. The soldered capacitor has a length of 10 mm and a height of 2 mm. A deflection of 1 mm is applied on the center of the board, whereas the extremities of the board are simply supported. Due to symmetry, it is sufficient to model one half of the arrangement. The effects of the solder height (0.5 mm, 1 mm or 1.5 mm) as well as the shape of the solder (nominal starved or bulbous) were investigated.

![Figure 10 - Solder shape parameters.](image)

**Figure 10 - Solder shape parameters.**

d) Parameters

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e) FEA model

The mesh used for the simulations is presented in Figure 11 with the material properties. Only the plastic behavior of the solder has been considered.

![Figure 11 - Model for finite elements analysis.](image)

**Figure 11 - Model for finite elements analysis.**

f) Results

For comparing results, interest was focused on the maximum plastic strain in the solder. As presented above, this plastic strain is the mechanism of failure and can be linked to the capacitor fatigue life by the Engelmaier model in equation (1). The plastic strain range for the different solder shapes with a solder height of 1 mm is presented in Figure 12, Figure 13 and Figure 14. The effect of the solder shape and height is presented in Figure 15.
Figure 12 – Plastic strain for nominal shape of solder of 1mm height (plastic strain range = 4.7 %).

Figure 13 – Plastic strain for starved shape solder of 1mm height (max capacitor stress = 4.5 %).

Figure 14 – Plastic strain for bulbous shape of solder of 1mm height (max capacitor stress = 4.9 %).
Solder fatigue life corresponds to the number of times the deflection on the board can be applied before the solder fails. There is no experimental result testing the effect of the solder shape and height on the same component on the same because of costs. However, the fatigue life calculated with simulations and the Engelmaier model appears to be high. This can be due to the fact that other phenomena than the ones modeled by the Engelmaier model are involved. Even without experimental results, simulations give a good tendency of the effect of the solder shape and height. Increasing the solder height increases the plastic strain range of the solder and so decreases the solder fatigue life. Moreover, a starved solder is more suitable to increase the fatigue life. This tendency has been observed punctually on several boards where the soldering process had not been done correctly. Components soldered with an excess of solder paste, leading to a high solder height and a bulbous shape, have experienced failure before the ones soldered with a correct soldering process.
IV. Plated Through Hole failure

1. Issues

Plated Through Holes (PTH) are important components on electronic boards. PTHs allow creating connections between different layers of the board and the pins of the components. The inside of the PTH is plated with a conductive material to create the connections. This part of the PTH is called the barrel. The plating material is mostly copper. The copper layers of the board are separated by dielectric layers whose expansion (in the direction orthogonal to the board) is much higher than the one of the plating material. Thus, during thermal cycling, the expansion of the dielectric of the board tends to extend the barrel (in the direction orthogonal to the board) creating tensile stress which can lead to failure due to fatigue.

2. PTH failure parameters

In order to describe finely the mechanism involved in PTH failure, many parameters have to be taken into account. These parameters are presented on Figure 16.

3. Study case

In order to investigate PTH failure, a simplified model is studied where the board is modeled by a stack-up of copper layers and dielectric layers.

a) Board deformation

When the board is subjected to thermal cycling, each layer will expand in the direction orthogonal to the board leading to a global board deformation which is the sum of the deformation of all layers. Consider a general stack-up with \( n \) layers of thickness \( t_i \) (total thickness \( t \)) and cross section area \( A_{\text{layers}} \). Each layer has a Coefficient of Thermal Expansion equal to \( \alpha_i \) and a Young’s modulus equal to \( E_i \). In parallel, the barrel on the PTH of cross section area \( A_{\text{barrel}} \) has a Coefficient of Thermal Expansion equal \( \alpha_{\text{barrel}} \) and a Young’s modulus \( E_{\text{barrel}} \).
One needs to calculate the strain in the barrel to apply the Engelmaier model. According to Hooke’s law, when a change of temperature $\Delta T$ is applied, the stress in the barrel is given by

$$\varepsilon_{\text{barrel}} = \frac{\sigma_{\text{barrel}}}{E_{\text{barrel}}} + \alpha_{\text{barrel}} \Delta T$$

where $\sigma_{\text{barrel}}$ is the tensile stress experienced by the barrel.

In the stack-up, the change of thickness is calculated as

$$\Delta t = \sum_i \Delta t_i = \sum_i \varepsilon_i t_i = \sum_i \left[ \frac{\sigma_{\text{layers}}}{E_i} + \alpha_i \Delta T \right] t_i = \sigma_{\text{layers}} \sum_i \frac{t_i}{E_i} + \Delta T \sum_i \alpha_i t_i$$

where $\sigma_{\text{layers}}$ is the common tensile stress experienced by the layers.

As the change of thickness is the same in the barrel one gets

$$\Delta t = \varepsilon_{\text{barrel}} t = \left[ \frac{\sigma_{\text{barrel}}}{E_{\text{barrel}}} + \alpha_{\text{barrel}} \Delta T \right] t$$

Claiming that equations (25) and (26) are equal and with the equilibrium equation

$$\sigma_{\text{barrel}} A_{\text{barrel}} + \sigma_{\text{layers}} A_{\text{layers}} = 0$$

one can calculate $\sigma_{\text{barrel}}$ and so $\varepsilon_{\text{barrel}}$ by means of equation (24), one gets

$$\varepsilon_{\text{barrel}} = \left[ \frac{\sum_i \alpha_i t_i - \alpha_{\text{barrel}} t}{t + E_{\text{barrel}} A_{\text{barrel}} \sum_i \frac{t_i}{E_i}} + \alpha_{\text{barrel}} \right] \Delta T$$

**b) Fatigue life**

To calculate the fatigue life of the PTH one should use the Engelmaier model defined by equations (1) or (2). First, the plastic strain range $\Delta \varepsilon_p$ experienced by the barrel during a thermal cycle is calculated. In order to do so one considers that the barrel constitutive material has an elastic-plastic behavior with a yield stress $\sigma_Y$, and plastic deformations occur when $\varepsilon_{\text{barrel}}$ reaches a value higher than

$$\varepsilon_Y = \frac{\sigma_Y}{E_{\text{barrel}}}$$
If \( \varepsilon_{\text{barrel}} \) is lower than \( \varepsilon_Y \), there is no plastic deformation and no risk of low cycle fatigue. If the board deformation \( \varepsilon \) is higher than \( \varepsilon_Y \), equations (28) and (29) are used to calculate the plastic strain range in the barrel.

The results for the fatigue life from theory and experiments are presented in Figure 18. Experiments were performed on three different PTHs on the same board with a representative thermal cycle applied. The three PTH differ with respect to their plating thickness.

It is concluded that the tendency of the fatigue life with respect the diameter ratio is the same with theory as observed in the experiments. The increase of the fatigue life with the increase of the thickness can be easily understood as stresses in the barrel decrease when the cross section area of the barrel increases. It is also noted that the model is more accurate for thick barrels.

![Figure 18 - PTH fatigue life.](image-url)
V. Leadless components under thermal cycling

1. Problem description

When new drilling tools are designed and manufactured by Schlumberger engineers, these tools have to be approved before being sent into the field to perform a job. To be approved, the tools have to pass several qualification tests which recreate the conditions the tool would see on the field during operation. These tests can be divided into three categories: thermal cycling, shocks and hot shocks. The latter is a test where shocks are applied simultaneously with thermal cycling.

In these tests, failure on leadless components (resistors) occurs mostly during shock tests or hot shock tests. It was thought at first that this failure was due to a bad board design leading to weakness (in some sense) with respect to shocks. Finite Element Analyses for shocks were performed for different boards but did not reveal any risk of failure. Moreover, one observed that in shock tests, failure occurred only on boards which had experienced thermal cycling test before the shock test. It was also observed that boards which did not experience thermal cycling before the shock test did not fail. It was then assumed that failure was initiated during thermal cycling but could not be detected electrically and was revealed during shocks. It was therefore decided to perform simulations to evaluate the damage induced in the solder of leadless components during thermal cycling.

2. Study case

a) Model

In order to make plausible the assumption that the failure observed during shock tests comes initially from thermal cycling applied to the board before the shock test, a special board developed by Schlumberger was investigated. As board designs are strictly confidential one may instead consider the virtual case presented in Figure 19 which bears some resemblance with the real case. In Figure 19, one can see the first mode shape of the board with two resistors R1 and R2 located at the same place on the board where displacements of the first mode are maximum. In experiments, resistor R1 fails during shocks after thermal cycling whereas this is not the case for resistor R2 which remains in function after thermal cycling and shocks. As both resistors are located on the same place on the board, they should be subjected to the same loading during shocks. The only difference between them comes from the size of the resistors as resistor R1 is 56% longer than resistor R2.
b) Investigations

It was decided to analyze a simple model to evaluate the plastic strain range experienced by the solder of a leadless component during a thermal cycle. The solder under the component is simply modeled by two direct attachments on the board. The model is free from stress initially and the deformed configuration is given in Figure 20.

One assumes that the component has a Coefficient of Thermal Expansion $\alpha_c$. Under a change of temperature $\Delta T$, the displacement of the component becomes

$$\delta_c = \alpha_c L \Delta T$$

Similarly, assuming that the board has a Coefficient of Thermal Expansion $\alpha_b$, the same change of temperature $\Delta T$, will lead to a board displacement of

$$\delta_b = \alpha_b L \Delta T$$

Finally, the relative displacement between the board and the component is calculated as

$$\Delta L = \delta_c - \delta_b = (\alpha_c - \alpha_b) L \Delta T$$

Thus the shear stress experienced by the solder during a thermal cycle is calculated as

$$\tau = G \frac{\Delta L}{2h} = G \frac{(\alpha_c - \alpha_b) L \Delta T}{2h}$$

Thus an increase of 56% in the component length, leads to an increase of 56% of the shear stress experienced by the solder.

c) Fatigue life

For finding the fatigue life of the solder, one may use the Engelmaier model defined in equations (1) and (2). The plastic strain range experienced by the solder from the shear stress is calculated by means of (32). One can assume that the solder has an elastic-plastic behavior with a shear modulus $G$ and a plastic modulus $H$(strain hardening), see Figure 21.
Thus, when the shear stress \( \tau \) is higher than the yield shear \( \tau_Y \), plastic strain is developed, and the plastic strain range can be calculated as

\[
\Delta \varepsilon_p = \frac{\Delta \gamma_p}{2} = \frac{\tau - \tau_Y}{2G}
\]

This model has been implemented and results were compared with experiments for both thermal cycling and hot shocks applied on both resistors R1 and R2, see Figure 22. Theory agrees with the fact that resistor R1 (the longest one) is the most vulnerable with respect to thermal cycling as observed in experiments. Once again, fatigue life calculated with the model are higher than the one observed in experiments as it does not take into account the presence of defects in the solder due to the soldering process.

![Figure 22 - Fatigue life for leadless components under thermal cycling.](image-url)
VI. Modal analysis

1. Preliminaries

In order to determine the board behavior with respect to shocks by means of equation (10), it is essential to know natural frequencies and modes shape. This can be done by simulations using any finite elements software, but one can also perform an experimental modal analysis.

Plate theory can describe quite well the behavior of a board without components. It is more complicated when components are soldered onto it. The mass of the added component tends to lower the board natural frequencies whereas the way of attaching the components to the board can increase its stiffness and thus increase its natural frequencies. Thus, both effects are present and it is impossible to predict without simulations which one will dominate. Moreover, most electronic boards developed by Schlumberger have stiffeners to increase their natural frequencies and reduce their vulnerability with respect to shocks. Modeling stiffeners and especially the contact between the board and the stiffeners is essential to calculate the natural frequencies.

In this section, the natural frequencies of a given board with no component and no stiffeners will be studied. Several ways of calculating the natural frequencies are compared. First plate theory will be used, and then modal analysis with a finite elements software (Abaqus), and finally an experimental modal analysis will be reviewed briefly.

2. Simulations

a) Board

The board which is used for this study is a rectangular board fixed by 18 screws along the two long edges of the board (Figure 23). Each area within a set of 4 screws is called a spacing.

Figure 23 - Board model.

b) Elements and shear-locking

When performing finite elements simulations with plates the phenomenon of shear-locking may appear. Finite elements calculations based upon the virtual work principle (also called the displacement method) may lead to a severe underestimation of the displacements, meaning that the structural response of the place is too stiff. This phenomenon is well known for simulations using 3D brick elements to model thin plates. In-plane and transverse shear-lockings exist and are strongly related. This work offers an opportunity to compare computed natural frequencies with results of experimental modal analysis to detect whether shear-locking is present or not.
**c) Boundary conditions and MESH**

To model the boundary conditions of the board (screws) as precise as possible one decided to lock the degrees of freedom of the nodes which are located on the inner surface of the screw hole. The mesh used for simulations with 3D brick elements and 3D tetrahedral elements are given in Figure 24 and Figure 25.

![Figure 24 - Mesh - 3D brick elements.](image1)

![Figure 25 - Mesh - 3D tetrahedral elements.](image2)

### 3. Experimental modal analysis

Experimental modal analysis is the only way to actually determine the natural frequencies of a board including components and stiffeners with complex boundary conditions. There exist several for doing it. Two of them used by Schlumberger will be described.

Both methods are based on the same principle. A point of the board is excited by an impact and the velocity of another point is recorded by optical means (LASER). Several tests are performed, changing the input point (where the impact is performed) but keeping the same output point (where the velocity is recorded by optics). A signal analysis allows calculation of the natural frequencies of the board. These two methods will be termed “Hammer” and “Shaker”.

**a) Hammer**

The input signal generated is close to a Dirac pulse, thus, all frequencies are excited. A Fourier transformation of the output signal permits the detection of peaks corresponding to the frequencies amplified by the board which correspond to the natural frequencies of the board. In practice, one looks at the ratio of the Fourier transformation between the output signal and the input signal. As the impact is not a perfect Dirac pulse, the Fourier transformation of the input signal is not constant but decreasing for high frequencies leading to an increase of the ratio observed which can contain peaks with no physical reality.

**b) Shaker**

With the shaker, the input signal is a harmonic oscillation generated by means of a signal generator, thus, only a single frequency at a time is excited on the board. By sweeping the input frequency and monitoring, analysis is performed. This method allows for improved precision in frequencies. If the transfer function between the output and input points is to be computed, this becomes more complicated than with the hammer method.
4. Results

a) Mode shapes

The mode shapes calculated with Abaqus are the same for all simulations performed and do not depend on the type of elements used. Only the values of the natural frequencies change with the conditions of simulations. As the board is divided into 8 spacings (space within a set of 4 screws) one can look at the mode shapes of a spacing which is closed to the ones of a rectangular plate. Thus the first three mode shapes for one spacing are given in Figure 28.

![Mode shapes](image)

**Figure 28 - Mode shapes.**

b) Natural frequencies

According to plate theory, the first natural frequency for a rectangular plate of thickness $t$ and width $W$, simply supported along the two long edges according to [2] is given by

$$f_{1,s} \approx \frac{\pi}{2W^2} \sqrt{\frac{Et^2}{12\rho}}$$

(35)

For a rectangular plate clamped along the two long edges, the frequency becomes

$$f_{1,c} \approx \frac{3.55}{W^2} \sqrt{\frac{Et^2}{12\rho}}$$

(36)

The Young’s modulus $E$ and the density $\rho$ of the board are calculated by knowledge of the board materials (dielectric and copper).

With the modeled board these formulas give:

$$f_{1,s} \approx 966 \text{ Hz} \text{ and } f_{1,c} \approx 2184 \text{ Hz}$$

(37)

The results from the simulations and experiments are presented in Figure 29 where one gives the value of the first three natural frequencies for spacing #4 (the one in the middle of the board). Due to high natural frequencies only the first mode of spacing #4 has been determined experimentally.

<table>
<thead>
<tr>
<th>METHOD</th>
<th>Finite elements simulation</th>
<th>Experimental modal analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3D tet. elements</td>
<td>3D brick elements</td>
</tr>
<tr>
<td>MODE 1</td>
<td>2153 Hz</td>
<td>2175 Hz</td>
</tr>
<tr>
<td></td>
<td>2836 Hz</td>
<td>2857 Hz</td>
</tr>
<tr>
<td>MODE 3</td>
<td>3521 Hz</td>
<td>3542 Hz</td>
</tr>
</tbody>
</table>

Figure 29 – Natural frequencies from simulations and experiments.
5. Conclusion

Estimating natural frequencies of electronic boards is essential to model their behavior with respect to shocks. However, such a task may be complex due to several parameters which are unknown but affect a lot the results. Apart from the mechanical properties of the board, depending on the methodology used to calculate the natural frequencies, results can be more or less accurate.

Calculating natural frequencies from plate theory may be a good approximation but boundary conditions are complex to model. On the board studied in this part, the first natural frequency calculated considering that the board is simply supported on the two long edges, is quite far from the results obtained with the other methodologies or considering that the board is clamped on the two long edges. Thus, modeling correctly boundary conditions is an important issue.

Using finite elements calculations may be a better way to take boundary conditions into account and get more accurate results. However, some computational artifacts, such as shear-locking, may lead to bad results. On the board studied in this part, calculations with 3D brick elements are slightly higher than the calculations with 3D tetrahedral elements for the first three modes. However, this difference is not high enough to talk about shear-locking. The recommendations of Abaqus documentation on the elements size for modeling plate were followed in order to avoid shear-locking in the simulations performed on this part.

Finally, one may think that the best way to calculate natural frequencies is to measure them experimentally. However, depending on the equipments and protocol used, results can be slightly different. On the board studied in this part, the first natural frequency appears to be around 2000 Hz according to the different methods used to calculate it. Measuring the natural frequencies with hammer, it has been highlighted that it was hard to stimulate the frequencies above 2000 Hz due to the board material. Thus, natural frequencies calculated with the hammer method may be higher than the real case whereas the shaker method allows to stimulate exactly the searched frequency. It is indeed observed that the first natural frequency measured with the hammer is slightly higher than the one measured with the shaker or calculated by finite elements.
Final conclusion

Assessing fatigue life for electronic components under hard loading conditions is a great challenge as mechanisms of failure involved are numerous and complex. Moreover, this is a combination of several mechanisms which most of the time leads to failure. Theoretical mechanical engineering brings some help to investigate the stress in the solder or in the leads under shocks or thermal cycling. Finite elements analysis gives more precise results even if both need an accurate fatigue model for materials used in electronics (especially solders) to predict the components fatigue life.

Concerning shocks, there is no criteria dealing with fatigue. The criterion used decides whether a component can resist a single shock or not which is a serious lack to predict rupture a component after repetitive shocks. However, repetitive shocks can be assimilated to vibrations for which the Basquin fatigue model can predict the fatigue life of the component. Both, shock criteria and Basquin model, are based on Steinberg equation which has not been adapted since the seventies when it was created. This equation was established semi-empirically for electronics boards made of materials which are not used today. Moreover, this equation does not model well the dynamic behavior of boards under shocks or vibrations and fatigue life calculated with this model are most of the time infinite, which is not the case in reality.

Regarding fatigue models under thermal cycling, the Engelmaier model is used to predict a component fatigue life. This model is based on the calculation of the plastic strain range experienced by the solder over one thermal cycle. The way of relating the plastic strain range to the fatigue life in the Engelmaier model depends on the coefficients used. These coefficients are proper of the solder and are determined experimentally. For specific solders, the lack of data is a great issue to predict fatigue life under thermal cycling. Results obtained with the Engelmaier model are always above the ones obtained experimentally as other phenomena (not modeled in the Engelmaier model) make the solder weaker during thermal cycling leading to failure. However, the model gives a good approximation of the order of magnitude of the number of cycles after which a component will fail. Some other basic fatigue models used in other industries (not electronics) are not based on plastic strain range but on creep energy. It would be very interesting to investigate whether these models can be transposed to the electronics industry.

Finally, the biggest challenge for all companies dealing with electronics failure is to find an accurate fatigue model combining both thermal cycling with shocks and vibrations and this field of research is very rich with plenty of possibilities which would be very useful for the industry.
**Bibliography**


