

## Soldered joints on leaded components : development of a design tool to predict failure during temperature cycle tests

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# **SOLDERED JOINTS ON LEADED COMPONENTS: DEVELOPMENT OF A DESIGN TOOL TO PREDICT FAILURE DURING TEMPERATURE CYCLE TESTS**

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**Abstract:** The soldered joints inside television sets are often the cause of failure during normal use. For this reason the mechanical behaviour of soldered joints was analysed. This analysis contains three new developments: Material model for solder (containing elastic, plastic and creep properties); Mechanical model describing the behaviour of a soldered joint in combination with a leaded component on a printed board; Design tool to predict the number of cycles to failure of a leaded component during a temperature cycle test. Comparison to practical temperature cycle tests showed that a reasonably accurate prediction of the number of cycles to failure can be expected.

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## **1. INTRODUCTION**

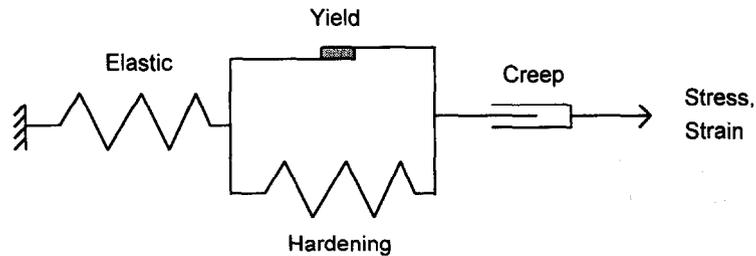
The soldered joints inside television sets are often the cause of failure during normal use. For this reason the mechanical behaviour of soldered joints was analysed. This analysis contains three new developments:

1. Material model for solder (containing elastic, plastic and creep properties);
2. Mechanical model describing the behaviour of a soldered joint in combination with a leaded component on a printed board;
3. Design tool to predict the number of cycles to failure of a leaded component during a temperature cycle test.

## **2. MATERIAL MODEL SOLDER**

The material behaviour of the solder alloy Sn60Pb40 is known for small strains (elastic behaviour). For large or plastic strains this material behaviour is very difficult to measure. Since the melting temperature of this solder is low (183 °C), the temperature and time dependence can not be neglected. This results in a different elasticity modulus and yield stress for different temperatures, and in the occurrence of creep and relaxation. The material parameters in this report were collected from ITRI [1] and de Kluizenaar [2].

The stress-strain relation of a combined elastic / plastic / creep behaviour can be described with the following model of two springs, a friction element and a damper (which are all non-linear):



**Figure 1** Symbolic material model solder

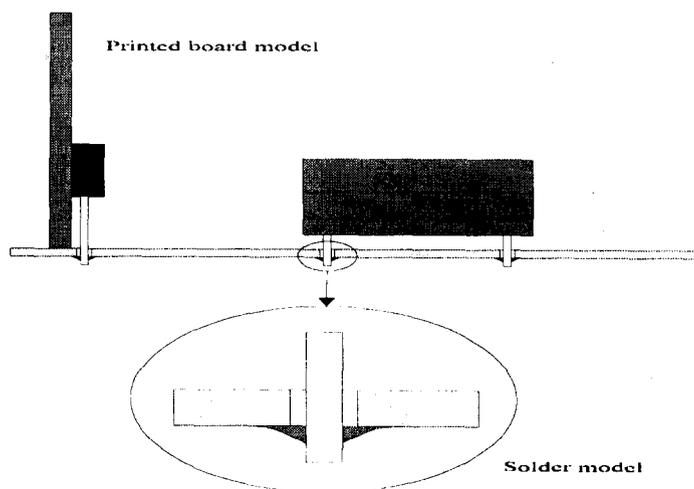
Fatigue failure can be predicted with the Coffin-Manson relation, in which the number of cycles to failure  $N$  and the incremental permanent strain per cycle  $\Delta\epsilon$  are coupled:

$$N = \frac{C}{\Delta\epsilon^2} \quad (1)$$

The material parameter  $C$  is taken to be a constant, according to de Kluizenaar [2] the value for solder Sn60Pb40 is:  $C = 0.15$ . The permanent strain per cycle can be caused by both plastic and creep deformation, so in our case we must sum both components. These components must both be true strains (i.e. equivalent values).

### 3. MECHANICAL MODEL SOLDERED JOINT ON COMPONENT

An example of two leaded components on a printed board is given below:



**Figure 2** Soldered joints on leaded components

The main assumption to describe the deformation of solder in this model is the limitation to shear stress and shear strain only:

$$\sigma_{rz}(r) = \frac{F}{A(r)} \quad (2)$$

$$\varepsilon_{rz} = \frac{1}{2} \cdot \frac{\partial u}{\partial r} \quad \text{so} \quad u = \int_r 2\varepsilon_{rz}(r) \cdot dr \quad (3)$$

With:  $\sigma_{rz}$ : shear stress within solder, F: force on wire, A: area solder,;  
and  $\varepsilon_{rz}$ : shear strain within solder, u: displacement, r: radial position within solder.

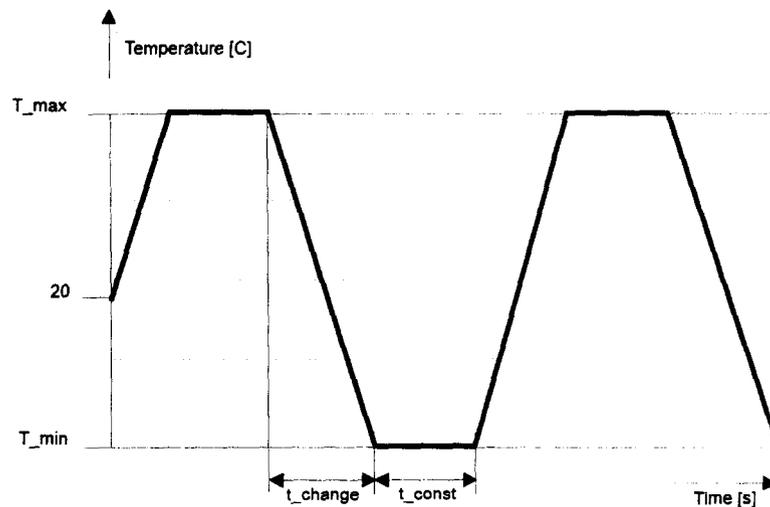
Using these equations, the mechanical behaviour of a soldered joint during the temperature cycle test can be described. For this purpose, a large number of time steps are performed, at which the equilibrium of forces and moments is determined. These forces and moments cause deformations, which can be elastic, plastic or creep deformation.

Note that the equilibrium equations to be solved are not linear due to the complicated material behaviour of solder (elastic, plastic and creep behaviour), which is also dependent on the current temperature.

#### 4. NUMERICAL PREDICTION

To predict the number of cycles to failure on practical leaded components, a numerical calculation must be performed, using a number of parameters:

- Geometry soldered joint (diameter wire, diameter hole, height solder at different positions);
- Characteristics component (stiffness at wire, thermal expansion coefficients);
- Environment conditions (temperature - time during the temperature cycle test).



**Figure 3** Temperature - time definition

A total of 3 temperature-cycles are calculated, after which the results of the third cycle are taken to predict the number of cycle to failure.

## 5. VERIFICATION OF RESULTS

The results of the numerical calculations were verified on two levels:

- Finite Element Method (FEM) calculations were performed to verify the stress and strain sub-results in the predictions;
- Practical temperature cycle tests were performed to verify the predictions of the final number of cycles to failure.

### 5.1 FEM verification

For this purpose two separate models were used:

- 2-dimensional FEM model to perform multiple variations;
- 3-dimensional FEM model for final verification.

The main results of the 2-dimensional FEM model are the plastic strain and the creep strain after one temperature cycle. These strains are also calculated by the Solder model. Comparison of these results indicates the calculation accuracy of the Solder model. This comparison was performed for several parameter variations.

**Table 1** Comparison 2-dimensional FEM model - Solder model

| Case                         | FEM model      |              | Solder model   |              |
|------------------------------|----------------|--------------|----------------|--------------|
|                              | Plastic strain | Creep strain | Plastic strain | Creep strain |
| Initial values               | 0.043          | 0.011        | 0.037          | 0.014        |
| Reduced temperature (80)     | 0.033          | 0.012        | 0.036          | 0.015        |
| Reduced solder height (0.3)  | 0.116          | 0.012        | 0.111          | 0.025        |
| Reduced wire length (7)      | 0.050          | 0.011        | 0.059          | 0.015        |
| Reduced displacement (0.001) | 0.008          | 0.007        | 0.002          | 0.001        |

This comparison indicates a reasonable calculation accuracy of the Solder model against the 2-dimensional FEM model.

Comparing the results from the 3-dimensional FEM model against the Solder model, the following remarks can be made:

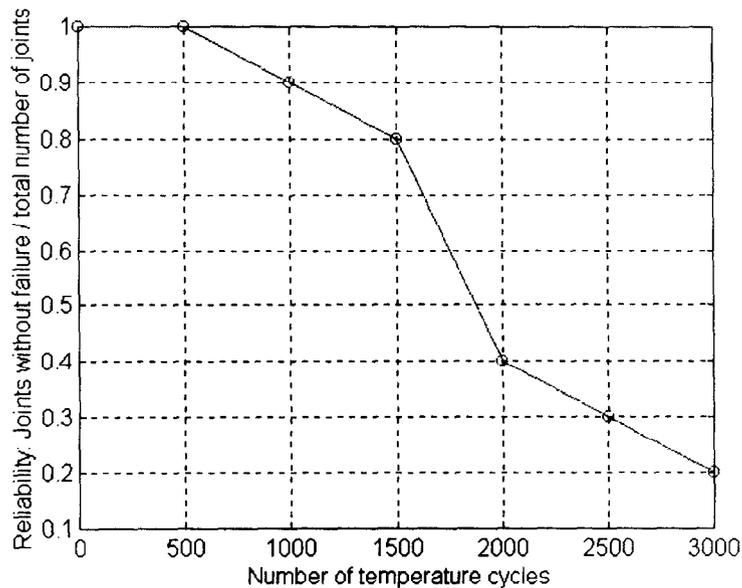
- The high stress values are almost equal, but the stress relaxation during cooling is faster in the FEM model.
- The final plastic strains show a small difference (FEM: 0.12, Solder: 0.11) and also a small difference in origin. In the FEM model, an equal amount of plastic strain is added due to cooling and heating. In the Solder model, the largest addition of plastic strain is caused by heating.
- The creep strains show a larger difference (FEM: 0.015, Solder: 0.025), which was also seen from the 2-dimensional FEM simulations.

From this comparison, the conclusion can be drawn that both models compare reasonably well.

## 5.2 Practical temperature cycle tests

To verify the final result of the Solder model (the predicted number of cycles to failure), existing temperature cycle tests on several printed boards were used. The results from these tests are taken from documentation by Philips - Television.

The main problems during practical use of a certain printed board were caused by fractured soldered joints on a Transformer. Therefore, these soldered joints were monitored closely during temperature cycle tests. The results of these tests are given below.



**Figure 4** Results temperature cycle test  
(reliability of soldered joints on Transformer)

This graph displays the reliability of the corner wire (pin 18) on the transformer. This reliability is defined as the number of soldered joints without failure divided by the total number of soldered joints on this pin. The visual ratings C, D and E (<math>180^\circ</math> crack, >math>180^\circ</math> crack, complete crack) are taken to be failures. These visual ratings were available for every 500 temperature cycles, for a total of 20 temperature cycle tests.

From this graph can be seen that a large part of all soldered joints fails between 1500 and 2000 cycles. The value of 2000 cycles will be used as a reference for predictions using the numerical models during this investigation.

The same procedure was applied to three other components: Flyback Capacitor, Connector and Transistor. From a separate board, more components were used: Mains Filter, LOT and Diode.

By using a simple formula to determine the thermal mismatch between component and printed board, the expected load on a soldered joint can be calculated in terms of a difference in displacement:

$$\Delta u = \frac{1}{2} \cdot a \cdot \Delta \alpha \cdot \Delta T \quad (4)$$

with  $\Delta u$ : displacement difference between component and printed board,  
 $a$ : Size of component (maximum distance between 2 soldered joints),  
 $\Delta \alpha$ : Difference in expansion coefficient component - printed board,  
 $\Delta T$ : Change in temperature.

This procedure was followed to predict the number of cycles to failure for the previously mentioned components. This prediction can be compared to the actual results during the temperature cycle tests.

**Table 2** Comparison of results temperature cycle test vs. predictions using the Solder model

|                   | Temp. cycle test                   | Prediction |
|-------------------|------------------------------------|------------|
| Transformer       | approx. 2000<br>cycles to failure  | 1000       |
| Flyback Capacitor | no failures<br>after 3000 cycles   | 8000       |
| Connector         | less then 500<br>cycles to failure | 100        |
| Power Transistor  | no failures<br>after 3000 cycles   | 11000      |
| Mains Filter      | approx. 1400<br>cycles to failure  | 1000       |
| LOT (flexible)    | approx. 3000<br>cycles to failure  | 4000       |
| LOT (original)    | approx. 1400<br>cycles to failure  | 900        |
| Diode             | no failures<br>after 3000 cycles   | 16000      |

This comparison shows that the predicted number of cycles to failures is an underestimation of reality (worst -case prediction). Differences up to 50 % may occur, but the correct components are indicated to have a low or high number of cycles to failure (i.e. 'good' and 'bad' components can be identified).

This result is found because the analytical formula of displacement assumes that no deformation (i.e. displacement or rotation) occurs inside the printed board or the component. This assumption underestimates reality: a small rotation of the printed board or the component will reduce the mechanical load on the soldered joint, and will thereby increase the number of cycles to failure.

Therefore, the underestimation of the number of cycles to failure (worst-case prediction) is entirely according to expectations.

## 6. DEVELOPMENT OF DESIGN TOOL

Based on the previous research, a design tool for Philips developers (responsible for the printed board layout) has been generated. This design tool will be used to compare alternative designs and prevent soldered joint fatigue failure in new designs.

This design tool is closely coupled to the CAD system ProENGINEER, because on this platform the (mechanical) printed board layout is developed. The graphical user interface (GUI) of the CAD system is used for the design tool also. An example is given below:

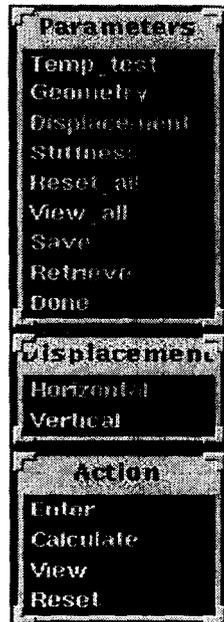


Figure 5 Design tool interface example

## 7. CONCLUSIONS

Prediction of soldered joint fatigue failure by using numerical calculation, was shown to be possible. These predictions were verified using FEM calculations and comparisons against practical temperature cycle tests.

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