Thermo-mechanical behaviour of solder joint in electronic assemblies under use and test conditions; Impact on reliability

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Solder joints -eutectic Tin-Lead alloy- between electronic components and printed circuit board are considered as a weak point of electronic assemblies: they are submitted to thermal mismatch due to differences between electronic materials expansion properties and thermal variations (environment and functional). This paper presents the solder joint behaviour during thermal variations in reliability tests and in service for two classical electronic components: microprocessor and dynamic memory. The influence of accelerated thermal cycles parameters (thermal range, ramp and hold times) is investigated in order to choose those which generate behaviours similar to the real ones. The microstructure damage evolution (Pb-phases migration and modification) such as the mechanical inputs involved in solder are studied respectively in experiments and with non-linear finite element simulation (which takes into account to solder properties: creep and time independent plasticity). This allows solder joint fatigue life prediction based on accelerated laboratory tests or on numerical results with a modified Coffin-Manson law.

1. INTRODUCTION

In electronic assemblies, components are attached to the printed circuit board with solder joints made of tin-lead alloys. Actually Surface Mount Technology (components are mounted on the board) is widely used in electronic industry (Figure 1), but the high integration degree and the small volumes of the card require small solder joints which are also the weak point of the assemblies. So the long-term reliability of surface mount solder joints is actually one of the main problem.

![Figure 1. Cross section of half Surface Mounted Components: (a), (b) leaded and (c) leadless components.](image-url)

When electronic assemblies are powered up, environmental and self heating can lead to high operating temperatures: for most solder alloys, such as Pb/Sn based solders, the
operating temperature can be as high as 0.5 to 0.8 TMelting of the alloy. As temperature changes from turning power on and off, the primary long term failure mode of surface mount assemblies is Low Cycle Fatigue, brought about by thermally and mechanically induced cyclic strains. The fatigue damage results from cyclic mechanical strains induced by the mismatch of the thermal expansion between the dissimilar components connected together by the solder. This thermal expansion mismatch is caused both by temperature ranges and by mismatch of the coefficient of thermal expansion and generate slow but unavoidable stresses in solder joints. So, thermo-mechanical fatigue cracking in solder joints has been identified as a major failure mode in electronic packages (Figure 2).

![Figure 2. Scanning Electron Microscopy (SEM) of crack in J-lead solder joint after 414 cycles between -20 and +100°C. (x 200).](image)

The effects of thermal cycles on solder joints thermo-mechanical behaviour are studied experimentally in accelerated qualification tests and numerically with a non-linear finite element method which takes into account the real properties of the solder (creep, time independent plasticity). The different thermal cycle parameters (thermal range, hold time at extreme temperatures, ramp rate...) are investigated in order to know the most damaging conditions for the solder. Fatigue life prediction are then calculated using experimental and numerical results.

2. THERMAL EXPERIMENTS

2.1. Test vehicles

Two types of surface mounted leaded components have been used : a microprocessor package -a Plastic Quad Flat Package (PQFP) with Gull-wing leads (Figure 1.a)- and a dynamic memory package -a Small Outline package with J-lead (SOJ) (Figure 1.b)-. The connection between lead and board are made with an eutectic Pb-Sn alloy : 37Pb-63Sn (% in weight). These components are connected to the board in order to allow an electrical measurement of solder joint continuity [1]. Thermal cycles have been applied to test the assemblies in accelerated conditions. The classical thermal profile is schematised on figure 3. Different thermal cycles parameters have been studied on qualification tests : thermal ranges (-20/+100°C and -40/+125°C), hold times at extreme temperature (0, 15, 30 and 60 min).
2.2. Results

In all cases the Gull-wing component solder joints are more damaged than the J-one. This is due to the lead shape which is less stiff in the Gull-wing case, so solicitation amplitude is greater and solder deformations too. The hold time effect is important too: the longer the hold time at extreme temperatures, the more damaging the solder joint. The thermal cycling effects on microstructure evolution has been studied too. It is independent of lead shape. Figure 4 shows the external damage of solder and lead: the thermal fatigue steps appear with the solder joint damage: the initial state show solder with smooth aspect; ageing generates crazing surfaces with small cavities development, then cracks, and rupture at the end of life. Tin present on the lead before assembly is submitted to ageing too and some oxidation phenomenon seems to be at the root of damage observed figure 4.b to 4.d.
Figure 5 shows the solder microstructural evolution during thermal cycles. It can be seen that tin-lead size and distribution evolve with ageing. Grain diameter increases with thermal cycles; the grain shape is modified too: the equiaxed initial microstructure becomes elongated and coarser particularly along the interfaces with the lead or the pad. These areas coincide with the crack initiation (Figure 2). These coarsened areas come from the thermal variations. Stresses are induced in the solder where plastic deformations are initiated; these deformations generate dislocations, then solder recrystallization so that lead and tin domains are enlarged [2]; the structure is fragilised and rupture will follow.

Figure 5. SEM Cross-sections in J-lead solder joint during thermal cycles x 400 (a) Initial state, (b) after 500 thermal cycles, (c) after 2000 cycles, (d) after 2500 cycles. Lighter areas: Pb-rich phase, darker areas: Sn-rich phase.
3. NUMERICAL SIMULATION

In order to better understand the solder mechanical behaviour during thermal cycles, a numerical simulation has been used to study test and use conditions. A two-dimensional finite element analysis has been applied to analyse the thermo-mechanical behaviour of surface mounted solder joint during thermal cycling and to determine the main parameters of the thermal cycle. A realistic model which takes into account the real properties of the solder, has been used to simulate the elasto-visco-plastic behaviour of J-lead and Gull-wing solder joints. The non-linear numerical analysis is carried out using CAEDS (IDEAS) and ANSYS softwares. Time independent plasticity (bilinear kinematic hardening) and steady-state creep laws are used to simulate real solder behaviour [1]. Materials mechanical characteristics are summarised in table 1. All materials are considered as isotropic except the board which is treated as orthotropic. The effects of temperature range, hold and ramp times on solder stresses and strains are investigated.

Solder joint is submitted alternatively to tension and compression stresses due to thermal mismatch between the different materials. Shear stress and inelastic strains distribution in solder joints under test conditions are shown in figures 6 to 8. Critical areas observed experimentally coincide with stress and strain high levels. The interfaces with lead and pad generate creep and plasticity in the solder so irreversible damage appears and is accumulated. Gull-wing solder joint is generally submitted to higher stresses and strains levels than the J-lead solder joint for all accelerated thermal cycles. The Gull-wing lead shape and stiffness contribute to high deformations which are accumulated in the solder and cannot be dissipated due to the thin solder thickness (= 10 µm).

Figure 6. Shear stress distribution in solder joint at the beginning of Tmini hold time (a) for a J-lead, (b) for a Gull-wing lead. (-40/+125°C, 3 min ramp, 60 min hold time) ; Scale in 103 Pa.
Figure 7. Inelastic shear strain distribution for a J-lead solder joint at the end of Tmaxi hold time (-40/+125°C, 3 min ramp, 60 min hold time) ; (a) Plastic shear strain, (b) Creep shear strain.

Figure 8. Inelastic shear strain distribution for a Gull-wing solder joint at the end of Tmaxi hold time (-40/+125°C, 3 min ramp, 60 min hold time) ; (a) Plastic shear strain, (b) Creep shear strain.
The influence of accelerated thermal cycles parameters on solder solicitations are investigated and extrapolated for fatigue life prediction [4]. It can be seen for accelerated tests that:

- if the $\Delta T = T_{\text{maxi}} - T_{\text{mini}}$ increases, stress level increases too, and fatigue life decreases;
- if the ramp time increases (i.e. if the ramp rate decreases), the Von Mises stress level decreases, so the total deformation is reduced and on the opposite the fatigue life increases;
- if the hold time increases, more stress relaxation appear and the fatigue life is reduced.

Thus it is important to choose an appropriate thermal cycle to simulate the use conditions in an accelerated test. In particular, the dwell time influence is very important and an accelerated test must have 15 minutes minimum dwell period, otherwise the realistic solder behaviour (i.e. creep and stress relaxation do not appear enough to show the behaviour under use conditions) is not taken into account.

4. THERMAL FATIGUE LIFE PREDICTION

The numerical results of few cycles allow solder fatigue life prediction. A modified Coffin-Manson law has been used [5, 6]:

$$N_f = \frac{1}{2} \left( \frac{\Delta W}{W'f} \right)^{\frac{1}{c}}$$

where
- $N_f$: number of cycles at failure,
- $W'f$: ductility fatigue coefficient,
- $W'f = 1.38$ MPa for all leaded surface mounted components [7],
- $c$: ductility fatigue exponent,
- $c = -0.442 - 6.10^{-4} \cdot T_{\text{mean}} + 1.74 \cdot 10^{-2} \cdot \ln(1+360/\text{thold})$, thold in minutes, $T_{\text{mean}} = (T_{\text{maxi}} + T_{\text{mini}})/2$ in °C,
- $\Delta W$: viscoplastic strain energy accumulated in each cycle.

With this fatigue model, thermal cycle parameters can be taken into account in the fatigue exponent, such as the irreversible damage accumulated in the solder (in $\Delta W$). To determine $\Delta W$, the stress-strain hysteresis calculated with the finite element method is used: $\Delta W$ represents the area under the $\Delta \varepsilon_{xy}/\varepsilon_{in xy}$ curve (where $\varepsilon_{in xy} = \varepsilon_{cr xy} + \varepsilon_{pl xy}$).

An acceleration factor between test and use conditions links the results obtained in laboratory and in real environment [1]. Results issued from accelerated and use conditions simulations have been compared for the two lead shapes. The fatigue life prediction has been studied for two real environments: electronic assemblies destined to computer and to military service. Fatigue prediction are resumed in Table 2 for both components. Results correlate except for accelerated tests with ramp time too slow (20°C/min) or hold time too fast (< 10 min). The solder fatigue life can also be estimated [1] and with a security coefficient we can say that an electronic assembly can survive:

- in computer environment 25 years for a J-lead, 2 years for a gull-wing solder joint,
- in military environment 2 years for a J-lead, 2 months for a gull-wing solder joint.

For these environments, the solder fatigue life desired is 5 years; so problems can occur for some gull-wing components.
5. CONCLUSION

This paper presents thermomechanical behaviour of electronic assemblies during thermal cycling. The experimental approach describes the solder damage evolution and its microstructural modification with thermal cycles. Another approach uses the numerical computation which gives a tool to better understand the mechanical solicitations undergone by the solder and to choose adequately acceleration conditions in order to evaluate reliability in use environments: for example hold time at extreme temperatures must be at least 15 min (measured on solder) in order to simulate creep accumulation such as in service (where assemblies can stay as long as 12 hours at hold time). If the accelerated thermal cycles parameters are good chosen, fatigue life prediction can be evaluated with the accelerated results, or with numerical simulation. Monitoring the microstructure damage evolution is more accurate but destructive; the numerical simulation give good information without destructive solder observations.

REFERENCES