Stability of Electronic Components in Lead-Free Processing

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ABSTRACT

With the widening interest and need to implement a lead-free process there has been much discussion and speculation on the stability of electronic components. In this study a range of components were selected and their functional and physical stability during lead-free reflow conditions assessed. The surface mount components examined were various LEDs, polyester and electrolytic capacitors, crystal oscillators, polyamide connectors and BGAs.

The work has shown that only minor effects occur, with the majority of components remaining within specification. There are, however, concerns with capacitors.

Industry concerns about lead-free soldering with these component types are addressed in light of the results.

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1 INTRODUCTION

The introduction of lead-free soldering in the UK is now widely considered to be inevitable due to market as well as legislative forces. The higher temperatures needed to reflow lead-free solders (for example tin/silver/copper, eutectic 217°C) have implications for the electronic components.

In implementing a lead-free process the major concern, and initially the biggest impediment, was the availability of compliant components. There are two issues for components in being compatible with the lead-free process. One is the metal finish on the terminations, and the other is the integrity of the component at the elevated processing temperature.

The former issue of termination finish, clearly requires that this be lead-free, and potentially impacts on solderability and thus process yield. The second issue of component integrity is considered here. Component integrity comprises two features, one is the physical robustness of the component, and the second is the functionality. Which of these is the most important varies with component type. For a wide range of active devices with silicon die, it is the packaging that is critical, the die and leadframe easily withstanding the increase in process temperature. For a number of discrete components it is the structure of the device that is critical. For example the multi-layer structure of capacitors may be sensitive to alternative thermal profiles. In the electronics industry technology moves at a great pace, and the issue of components being compatible with a lead-free process is a moving target, and one of continual improvement. None the less concerns centred on component robustness remain throughout the industry.

Historically components have been designed to withstand traditional tin-lead soldering temperatures, and manufacturers have recommended limits for heating during reflow that would often be exceeded under lead-free reflow conditions.

In this work several components that are considered by members of the Soldering Science & Technology Club (SSTC) to be most susceptible or problematic if overheated during reflow, are exposed to harsh lead-free reflow conditions and their functional and physical stability are measured. These include light emitting diodes (LEDs), capacitors, crystals, connectors and a plastic ball grid array (PBGA).

Table 1 lists the electronic components included.

Table 1. Components Tested

Component	Variation	Figure
SMT 2x1.25mm LED	green	1
SMT 2x1.25mm LED	yellow	
SMT 2x1.25mm LED	red	
Sub-Min, Gull Wing Lead LED	red	2
Sub-Min, Gull Wing Lead LED	yellow	
Sub-Min, Gull Wing Lead LED	green	
Metallised, SMT,Polyester Capacitor	7.3mm, 63V/40V AC - 0.47 µF	3
1mm Pitch, Top Entry, SMT Header	2 way	4
Panasonic Capacitors VFC SM 105°C	6.3V 47uF	5
Panasonic Capacitors VFC SM 105°C	16V100uF	6
Panasonic Capacitors VFC SM 105°C	35V 4.7uF	7
Crystal SMT	14·7456 MHz	8
Crystal SMT	20 MHz	
Crystal SMT	18.432 MHz	
Ball Grid Array	PBGA256-1.27mm-27mmm-DC	9

1.1 Surface Mount LEDs

Two types of surface mount LEDs were tested - standard SMT and gull wing, all based on GaAsP/GaP technology and in each case three colours (green, yellow and red). There have been concerns about LED polymer casings softening at lead-free reflow temperatures and the optical performance being impaired.

Figure 1. Standard SM LED.

A recommended reflow profile is supplied by the SM LED manufacturer, and is shown in Figure 2.

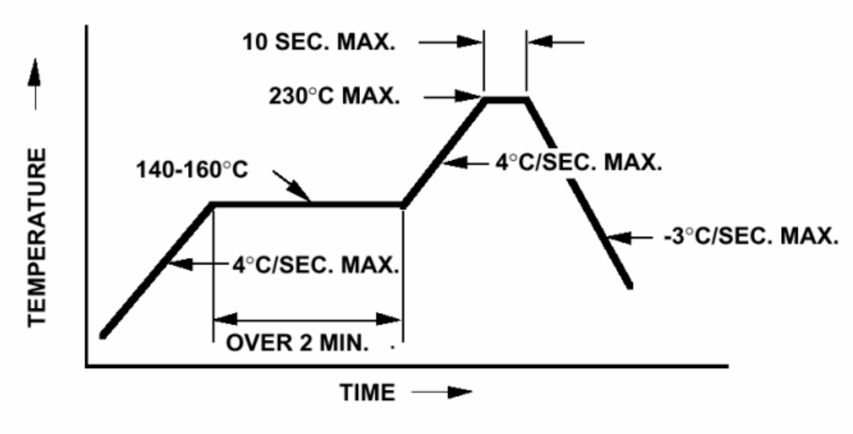

Figure 2. Manufacturer's recommended reflow profile for Standard SM LEDs

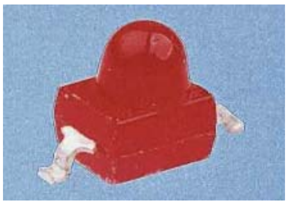

Figure 3. Gull Wing SM LED.

The manufacturer of the gull wing LEDs provides no guidelines for reflow soldering conditions.

1.2 Polyester Capacitors

These capacitors are surface mount devices manufactured with wound layers of polymer (polyethylene terephthalate, PET) foil coated with a vacuum deposited metal forming a coil. The ends of the coils are attached directly to the external component contacts at each end of the component so the entire outside edge of the wound conductive layer is in electrical contact. This wound construction leads to a vulnerability to a higher temperature profile and there are concerns about the physical stability of plastic capacitors.

The PET construction provides good volume efficiency and self-healing properties. Typical applications for PET capacitors are bypassing, coupling and filtering. The manufacturer recommends the following restrictions on the reflow soldering profile:

Preheat should be less than 150°C.
Over 180°C, 60 seconds maximum.
Peak temperature 215°C.

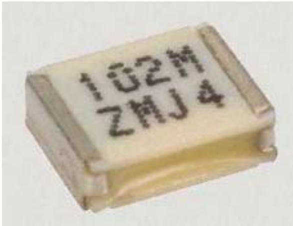

Figure 4. Polyester SM Capacitor.

1.3 Aluminium Electrolytic Capacitors

Higher values of capacitance are often achieved with the use of aluminium electrolytic capacitors. In this case an aluminium foil is wound with paper separating sheets into a coil, which is then filled with a liquid electrolyte, and encased in polymer and an aluminium casing. The expansion of the liquid electrolyte with temperature and the wound construction might be problematic under lead-free reflow, and reports of damage to these devices have been received by NPL.

Figure 5. Aluminium Electrolytic Capacitor.

The manufacturer states that after reflow soldering, once stabilized at +20°C, the capacitance shall be within ±10% of initial measured value.

1.4 SMT Header

This small header connector has a polymer casing, which must retain its physical dimensions in order for good mating to its corresponding plug. For this reason the higher temperature of lead-free soldering could be problematic if even small deformations in the polymer occur.

The contacts are phosphor bronze, tin-plated and the housing material is polyamide 66 rated to UL94V-0. There are no restrictions on reflow conditions from the manufacturer.

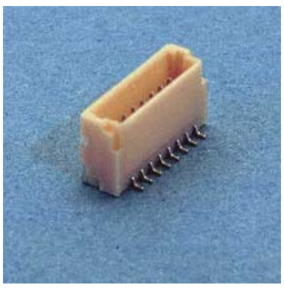

Figure 6. SMT Header Connector.

1.5 Crystal Oscillators

Quartz crystal resonators are widely used in electronics as highly stable and accurate frequency sources, but the oscillation frequency depends as much on the oscillator circuit as it does on the crystal. Resonators are passive, they do not oscillate without additional circuitry and a source of energy. A resonator, placed as a feedback element around an amplifier, makes an oscillator. The amplifier replaces energy lost in the resonator. The resonator controls the frequency of oscillation, and so stability of crystal devices is critical.

A quartz crystal resonator is simply a circular piece of quartz with electrodes plated on both sides, mounted inside an evacuated enclosure. Quartz is ideal for resonators because it is hard, dimensionally stable, non-conductive, and most importantly, piezoelectric.

Figure 7. SMT Crystal Oscillator.

The maximum manufacturer specified reflow conditions to maintain the +/-50ppm tolerance on resonant frequency for these crystals are:

Over 140°C Preheat, 100 seconds maximum
Over 200°C, 25 seconds maximum
Over 230°C, 5 seconds maximum

1.6 Ball Grid Array

A ball grid array device contains a silicon chip wire bonded to a laminate (normally BT type) with tracks leading out to underside pads. The chip and bonds are then encapsulated and the device is ‘bumped’ with solder to provide solder balls for surface mount connection. ‘Pop corning’ is a phenomenon associated with entrapped moisture when reflowing encapsulated devices e.g. BGA’s. During heating residual water vapour tries to escape from between the moulding and laminate and the bond can break allowing cracks to open up. The components used were ‘dummy’ components with no electrical functionality, but were identical in construction to a functional device, including the presence of the silicon die.

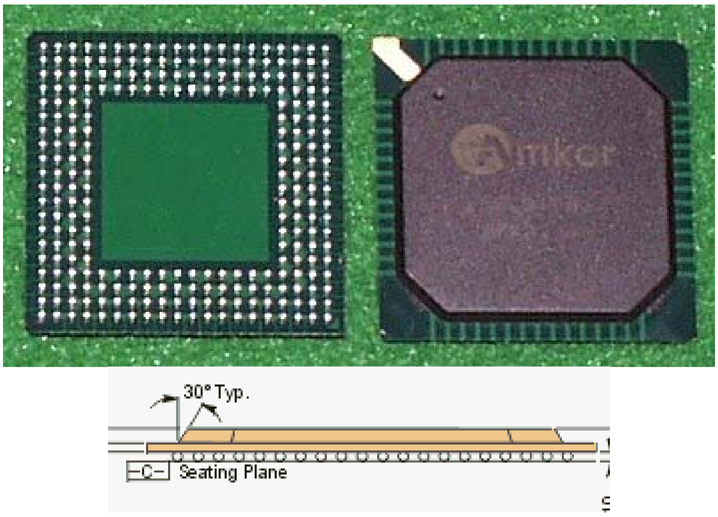

Figure 8. Plastic Ball Grid Array.

2 EXPERIMENTAL

2.1 Component Reflow

The components were heated using a Reddish Electronics SM2000CXE forced convection reflow oven. The oven has five zones, which were set as follows:

Table 2. Reflow Oven Settings for Lead-free Profile

Zone (Front and Rear)	Tin-Lead Profile Set Temperature	Lead-Free Profile Set Temperature
1	140°C	165°C
2	180°C	195°C
3	180°C	240°C
4	220°C	280°C
5	230°C	280°C

The temperature of the components during reflow was monitored using a DATAPAQ Reflow Tracker data acquisition system and typical profiles are shown in Figure 9. The thermocouples were K-type and were attached using thermally conductive adhesive[1].

No solder paste was applied to the board and the components were free standing. The components were subjected to 6 sequential reflow profiles with an additional 2 minute cooling period between each (i.e. from 300 to 420 seconds on the above plot).

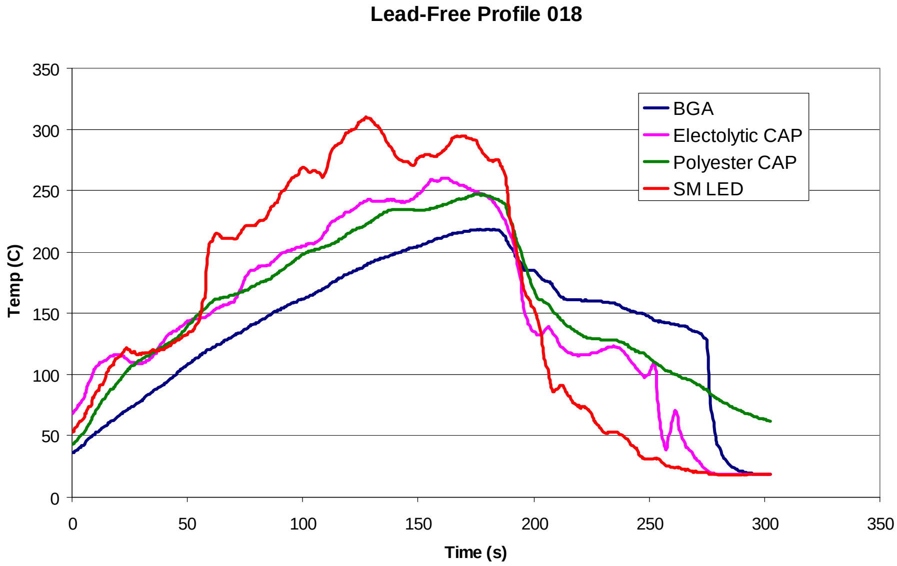

Figure 9. Temperature of Components in Lead-Free Profile.

2.2 Electrical Measurements

Measuring the threshold voltage and the presence of light assessed the LED devices' performance. The presence of visual emission and the threshold activation voltage were noted. In addition, the emission of certain LEDs was measured using a photometer mounted directly above the LED at 50, 55 and 80mm.

The equivalent parallel capacitance and dissipation factor (loss tangent) for each capacitor was determined using an Agilent 4263B LCR Meter. The driving frequency was 100Hz for electrolytic components and 100,KHz for the polyester capacitors.

No electrical measurements were made on the surface mount header.

The oscillator was connected to an impedance analyser, and the load impedance directly measured. There is a certain limitation to this measurement method, since the oscillator is not operating, the measurement fails to account for impedance shifts that occur during non-linear transistor operation. However, the measurement gives a good indication of crystal stability.

Three 14.7456 MHz quartz crystals oscillators commonly used in modems were measured on an HP impedance analyser. Gain and phase were measured to evaluate resonant frequency (Phase = 360°).

No electrical measurements were made on the dummy BGA devices.

2.3 Dimensional Measurements

The physical dimensions of the components were measured in all three axes before and after reflow, and any changes noted.

Measurements were made using a UKAS calibrated Mitutoyo Absolute Digimatic micrometer with 10µm precision.

For all components, the 'height' measured was the stand-off height of the component as mounted onto a board. Width and length were defined as the shorter and longer sides of the component.

2.4 Mass Change Measurements

The gull wing LEDs, polyester capacitors and electrolytic capacitors were also checked for weight change. Components were weighed on an AG 285 Mettler Toledo balance (0.1mg precision) before and after reflow.

2.5 BGA Popcorning

To promote delamination the BGA samples were subjected to 85°C/85%RH for 24 hours prior to immediate exposure to the reflow conditions. Also humidity aged components were placed directly onto a molten solder pot at 230°C as a worst case condition.

To study any possible 'pop corning' in the BGA samples microscopic examination of the perimeter of the components was performed. A search for contrasts in the laminate colouring, indicative of loss of adhesion between the BT substrate and the moulding compound was conducted.

3 RESULTS

3.1 Tin-Lead Profiled Components

For **all the components** which were passed through the tin-lead reflow profile there were only **negligible or no changes** in the dimensions and electrical performance, confirming past experience.

3.2 Lead-Free Profiled Components

3.2.1 Electrical Measurements

Table 3. Electrical Functionality Measurement results.

Component	Variation	Property	Before LF Reflow	After LF Reflow
SMT 2x1.25mm LED	Green	Threshold Voltage	1.812V	1.805V
SMT 2x1.25mm LED	Yellow	Threshold Voltage	1.77V	1.766V
SMT 2x1.25mm LED	Red	Threshold Voltage	1.62V	1.617V
Sub-Min, Gull Wing Lead LED	HE Red	Threshold Voltage	1.65V	1.646V
Sub-Min, Gull Wing Lead LED	Yellow	Threshold Voltage	1.753V	1.749V
Sub-Min, Gull Wing Lead LED	Green	Threshold Voltage	1.823V	1.815V
Metallised, SMT,Polyester Capacitor	7.3mm, 63V/40V AC - 0.47 µF	Capacitance	476.76pF	466.4µF
Panasonic Capacitors VFC SM 105°C	6.3V 47uF	Capacitance	45.96µF	42.75µF
Panasonic Capacitors VFC SM 105°C	16V100uF	Capacitance	104.74µF	94.23µF
Panasonic Capacitors VFC SM 105°C	35V 4.7uF	Capacitance	5.28µF	75.08µF
Metallised, SMT,Polyester Capacitor	7.3mm, 63V/40V AC - 0.47 µF	Loss Tangent	2.58	6.90
Panasonic Capacitors VFC SM 105°C	6.3V 47uF	Loss Tangent	0.0949	0.0849
Panasonic Capacitors VFC SM 105°C	16V100uF	Loss Tangent	0.0419	0.0919
Panasonic Capacitors VFC SM 105°C	35V 4.7uF	Loss Tangent	0.0399	0.0426
Crystal SMT	14·7456 MHz	Resonant Frequency	14766388.7Hz	14766571.6Hz
Crystal SMT	14·7456 MHz	Resonant Frequency	14767250.0Hz	14767263.8Hz
Crystal SMT	14·7456 MHz	Resonant Frequency	14769054.3Hz	14768994.4Hz

The electrical parameter, and the before and after reflow values are given in Table 3. The fractional changes in values are plotted in Figure 10. The figures are for single components, not average values.

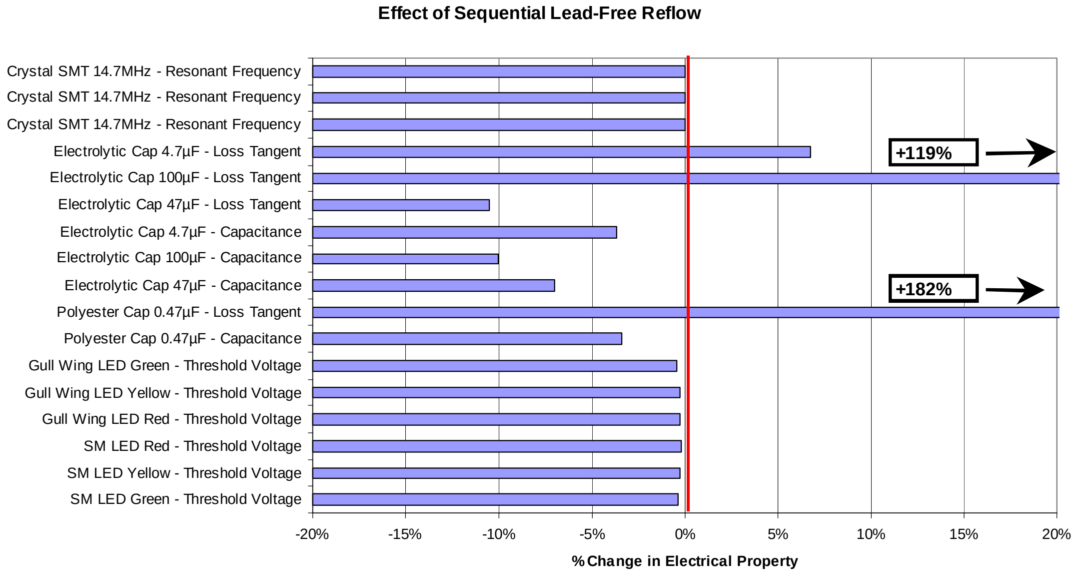

Figure 10. Effect of LF reflows on electrical functionality.

3.2.1.1 LEDs

The threshold voltage for light emission for all the LEDs proved to be unaffected by more than 0.5%. This suggests that the reflow temperatures are not affecting the basic function of the device. In the case of the red and green gull wing components, however, the polymer casing did look darker to the eye, and although the LED worked the light was somewhat obscured by the darkening of the plastic case.

This was quantified using a photometer, which produces a photon count. LEDs that had been passed through a lead-free and standard tin-lead profile were tested. The LEDs were held at 50, 55 and 80mm in front of the photometer, and the data are plotted in Figure 11.

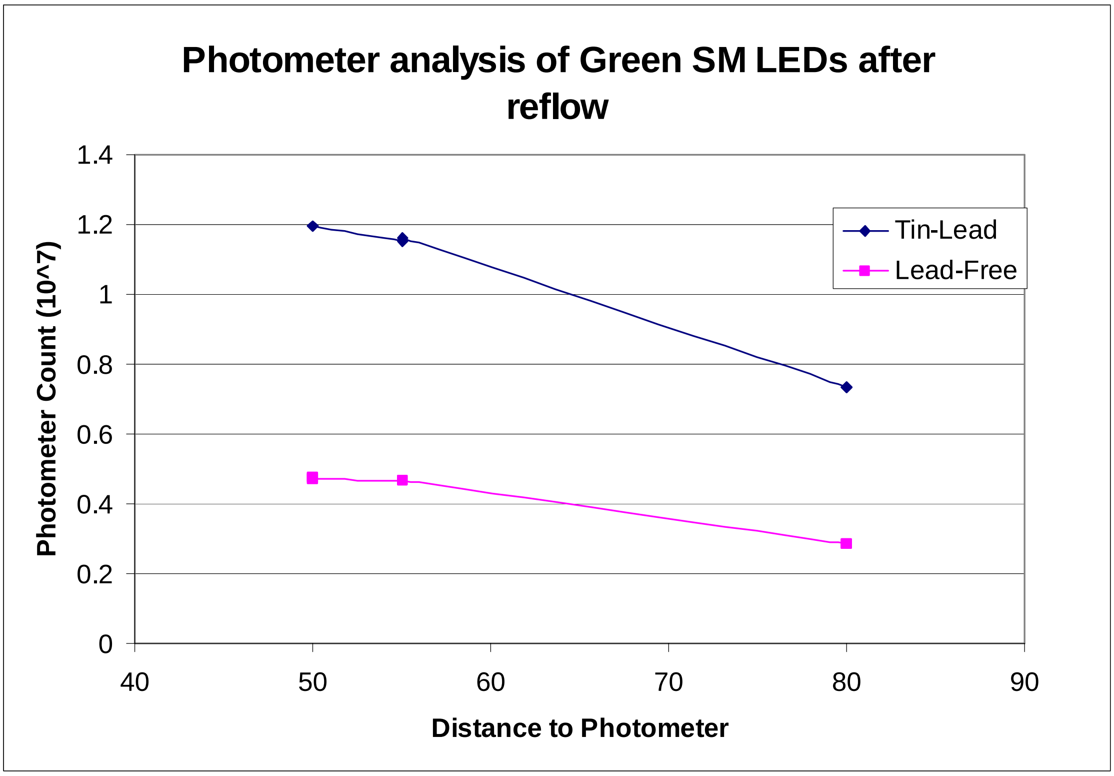

Figure 11. Reduction in LED Emission due to Darkening of Polymer Case.

The darkening of the LED case caused by lead-free reflow reduced the emission from the LED by about 60% relative to profiling under tin-lead conditions.

3.2.1.2 Polyester Capacitors

The polyester capacitors did prove to be susceptible to a higher temperature reflow profile. The capacitance did not change much, 3% over the frequency range of 100Hz to 100KHz, and remained within specification, but the loss tangent altered significantly. Figure 12 presents the loss tangent as a function of frequency, and this reveals that this exceeds the manufactures specification by 130%.

Polyester capacitors are designed for use in digital circuits at much higher frequencies than the electrolytic capacitors, and so the poor performance under these conditions is very relevant.

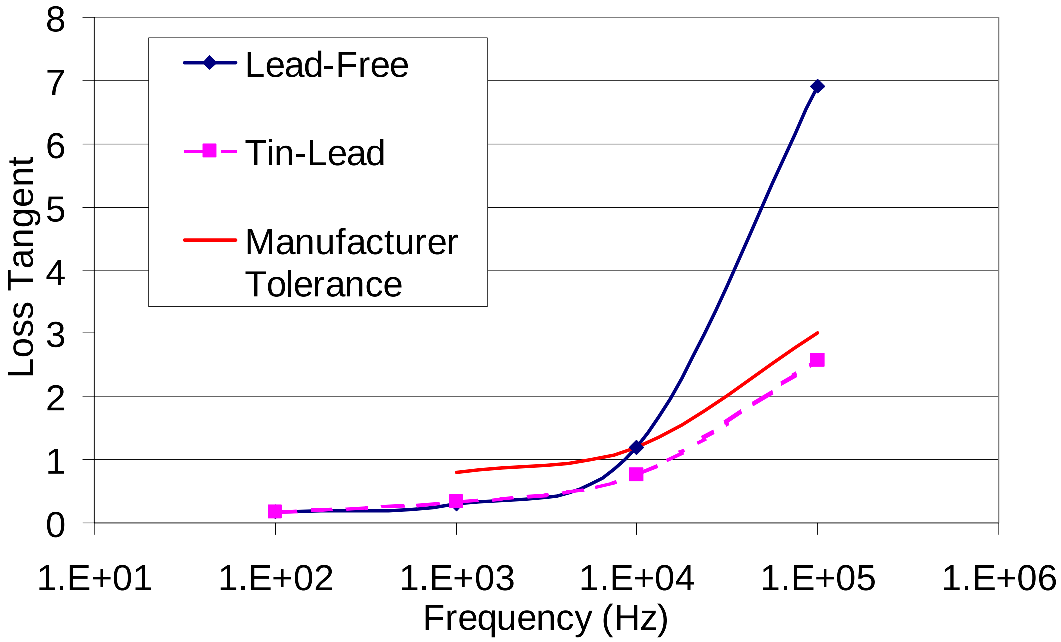

Figure 12. Effect of Reflow on Loss Tangent for Polyester Capacitor

3.2.1.3 Aluminium Electrolytic Capacitors

The capacitance of the electrolytic capacitors was reduced by between 4 and 11% by the 6 lead-free reflow processes. The loss tangent was significantly affected with a massive 119% change for the case of the highest value 100µF capacitor. The electrolytic capacitors are only specified to operate correctly up to relatively low frequencies so this measurement was at 100Hz only. The manufacturer of these components specifies no tolerance for loss-tangent.

3.2.1.4 Crystal Oscillators

The resonant frequency changed by only +/- 100 Hz (6 ppm) after reflow for the oscillators tested. The nominal stability is rated at 100ppm in the temperature range 0-60°C. Hence these devices appear impervious to multiple reflows.

3.2.2 Dimensional Stability Measurements

The dimensional values for the components before and after reflow are given in Table 4, and the percentage variation given in Figure 13. The figures are for single components, not average values.

		Before Reflow			After Reflow		
Component	**Variation**	**Width**	**Length**	**Height**	**Width**	**Length**	**Height**
SMT 2x1.25mm LED	green	1.24	1.08	2.05	1.23	1.09	2.04
SMT 2x1.25mm LED	yellow	1.18	1.08	2.01	1.2	1.08	2.01
SMT 2x1.25mm LED	red	1.18	1.07	2	1.2	1.06	1.99
Sub-Min, Gull Wing Lead LED	red	2.03	2.81	2.55	1.97	2.78	2.42
Sub-Min, Gull Wing Lead LED	yellow	1.98	2.81	2.44	1.98	2.75	2.5
Sub-Min, Gull Wing Lead LED	green	1.99	2.69	2.49	1.99	2.73	2.56
Metallised, SMT,Polyester Capacitor	7.3mm, 63V/40V AC - 0.47 µF	5.9	3.2	7.44	5.95	3.48	7.35
1mm Pitch, Top Entry, SMT Header	2 way	2.9	4.31	3.98	2.88	4.31	3.94
Panasonic Capacitors VFC SM 105°C	6.3V 47uF	5.3	5.36	5.3	5.28	5.48	5.28
Panasonic Capacitors VFC SM 105°C	16V100uF	8.34	6.42	8.33	8.28	7.6	8.28
Panasonic Capacitors VFC SM 105°C	35V 4.7uF	4.31	5.39	4.32	4.3	5.51	4.31
Ball Grid Array	PBGA256-1.27mm-27mmm-DC	27.03	2.1	27.13	27	2	27.01

Table 4. Dimensional Measurement Results (mm)

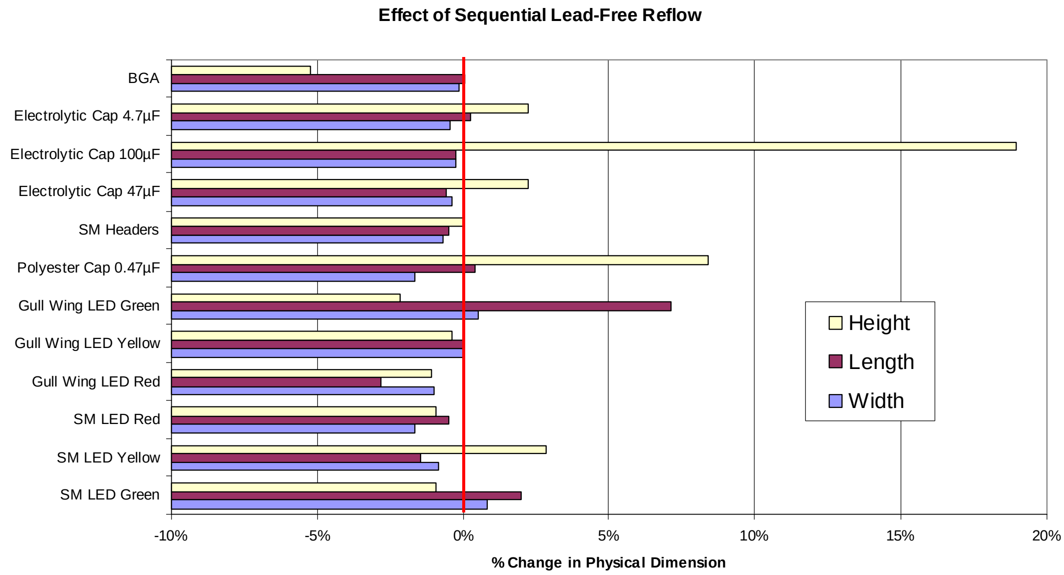

Figure 13. Effect of Sequential Reflows on Physical Dimensions

It is clear that the majority of the components tended to shrink as a result of lead-free profiling. However, for some components there was a marked increase in height, particularly for the capacitors. These are discussed in detail below.

3.2.2.4 LEDs

There was a change of typically 2-4% in the dimensions of the polymer LED devices.

To identify any breakdown or phase change in the packaging, differential scanning calorimetry (DSC) was performed on a gull wing LED device to look for changes in phase (breaking or formation of any chemical bonds). An example curve is shown in Figure 14.

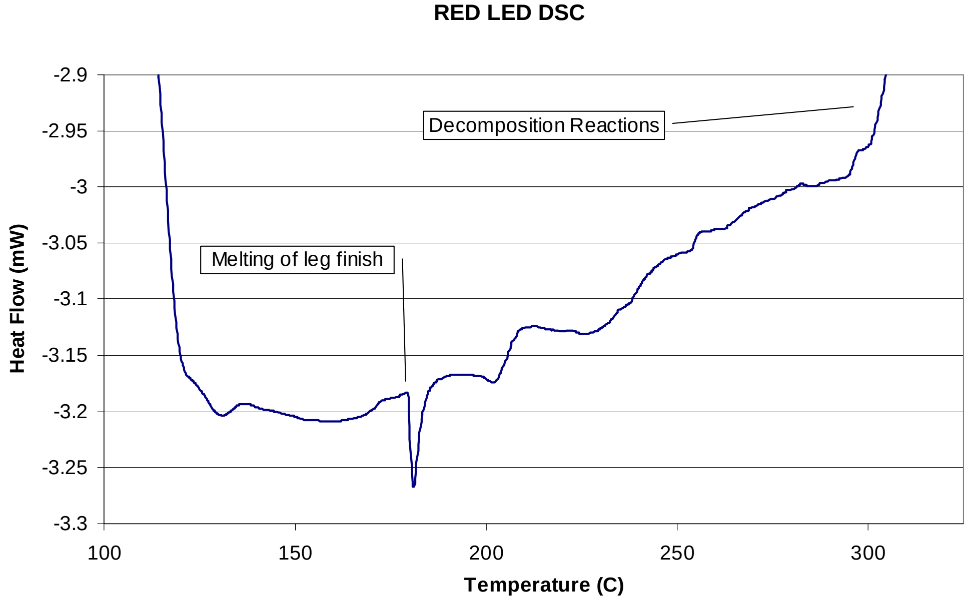

Figure 14. DSC for Gull Wing LED Component.

The DSC curve highlights any changes in phase as the component heats up. The melting of the solderable finish on the component legs is clearly seen at 180-185°C. The very small percentage mass of the whole component represented by this metallisation indicates the sensitivity of the technique. There is no clear indication of decomposition of the polymer casing under 290°C. Polymer decomposition reactions start at around 300°C and are characterised by energy released by the exothermic reaction, as opposed to the energy absorbed during a phase change. There is a small step around 210°C which may be significant in causing the dimensional changes and loss of emission.

3.2.2.5 BGAs

The overall height of the BGA device decreased due to the reflowing of the solder bumps which collapsed in their molten state, lowering the stand off to the laminate. This is to be expected. Otherwise the component was dimensionally stable through lead-free reflow.

No 'pop-corning' was observed on any of the BGA samples, even those humidity aged and placed directly onto molten solder. Clearly pop corning is a random event depending on component design and specific batches.

3.2.2.6 Surface Mount Header

The physical stability of the header proved excellent with changes being less than 1% in all axes.

3.2.2.7 Polyester Capacitors

The polyester capacitors exhibited expansion in height rather than in length or width. The behaviour is shown schematically in Figure 15.

Figure 15. Schematic of Polyester Capacitor Expansion.

The expansion of the capacitor can be clearly seen in the microscope image, Figure 16, where the top of the component has barrelled.

Figure 16. Deformation of Polyester Capacitor.

Cracks were also present on the ends of the component after exposure to lead-free reflow (Figure 17). The cracks appear to be between the end cap metallisation and the potting compound that forms the main body of the component.

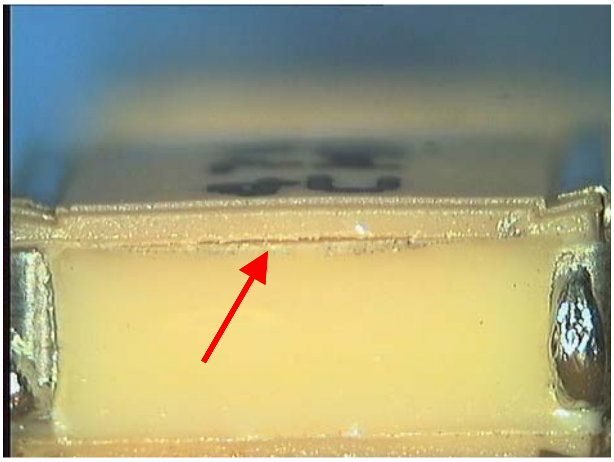

Figure 17. Cracks in the end of the Polyester Capacitor.

3.2.2.8 Electrolytic Capacitors

Whilst the width and length of these components were hardly affected by the reflow steps the height changed dramatically. This was due to expansion of the electrolyte in the casing causing a dome-like bulge at the top and bottom of the component. The bulge at the bottom was less noticeable due to the additional stability afforded by the plastic base. Figure 18 shows the 100µF electrolytic capacitor after lead-free profiling. The bulging of the top and bottom of the cylinder body can be clearly seen. In fact this deformation is even greater during peak reflow temperatures, but the casing contracts somewhat as the component cools. It has been reported that these components can pop[2].

Figure 18. 100µF Electrolytic Capacitor after LF Reflow

3.2.3 Mass Change Measurements

The mass change of a few sensitive components are given in Table 5, and the percentage change in mass is plotted in Figure 19. The figures are for single components, not average values.

Table 5. Mass Change Results (g).

Component	Variation	Mass Before Reflow	Mass After Reflow
Sub-Min, Gull Wing Lead LED	Red	0.0152	0.0151
Metallised, SMT,Polyester Capacitor	7.3mm, 63V/40V AC - 0.47 µF	0.2518	0.2494
Panasonic Capacitors VFC SM 105°C	16V100uF	0.522	0.5219

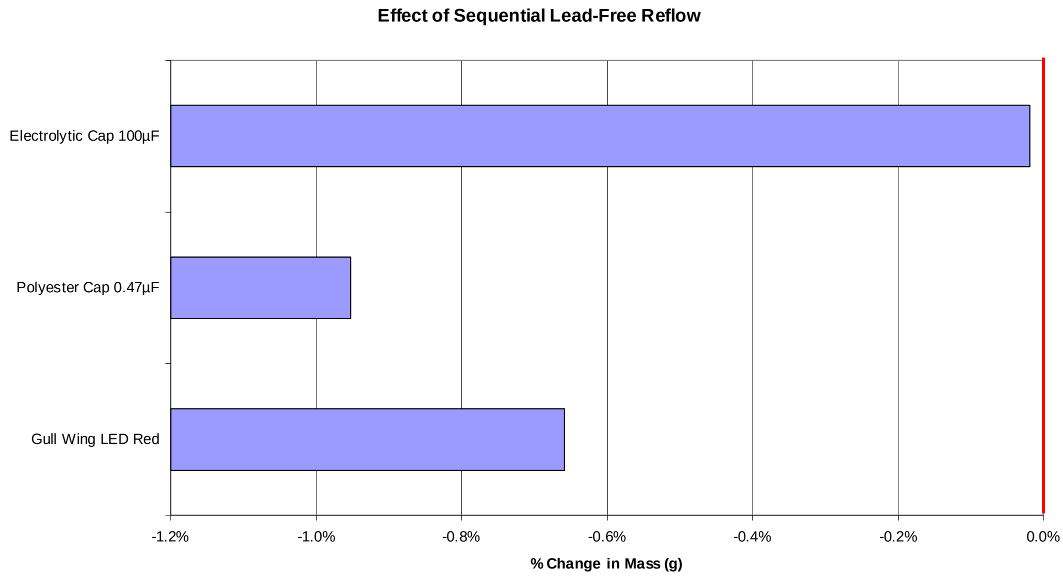

Figure 19. Mass Change from Lead-Free reflow.

In all cases mass was reduced with heating through sequential lead-free reflow profiles. Despite the large physical deformation of the electrolytic capacitor its mass change was very low. The LED lost about 0.65% by mass, which is consistent with a small amount of degradation in the polymer casing. The polyester capacitor exhibited the largest mass change of those components tested at nearly 1%.

4 DISCUSSION

4.1 Tin-Lead Profiled Components

As would be expected, the components which were passed through the tin-lead profile 6 times, were unaffected in terms of dimensions and electrical functionality. This provided a good reference point for comparison with the results for the lead-free profiled components.

4.2 LEDs

The functionality of the surface mount LEDs tested was not affected by the lead-free soldering conditions. For the red and green gull wing SM LEDs, however, discolouration of the polymer casing reduced the final emission of the device although the diode was still functioning properly.

The changes in dimension during heating suggest that the polymer casing was softened, but DSC shows that no major phase changes occurred in the material. Decomposition reaction began only at 300°C or higher.

4.3 Polyester Capacitors

The physical deformation of the polyester capacitors caused by the lead-free heating profiles was considerable. The low weight change during the process would suggest that the electrolyte, although building up pressure inside the component did not escape. The tolerance for capacitance quoted for these devices is +/-20% and this was not exceeded at any frequency between 100 and 100,000Hz for the lead-free process. The loss tangent for this component at the higher frequencies was well out of tolerance, and this is a potential problem for users.

4.4 Electrolytic Capacitors

The physical deformation of the electrolytic capacitors was significant, and is unlikely to be acceptable to a customer receiving electronic product on aesthetic grounds alone. The bulging of the base means that the legs of the component can be bent out of the plane of the board as the plastic base is pushed down. This may cause problems with soldering of the legs if they do not stay associated with pads.

The capacitance of all the electrolytic components was within the manufacturer’s tolerance after lead-free processing, but as with the polyester capacitor, the loss tangent was greatly affected.

4.5 Surface Mount Header

The dimensional stability of the SM Header proved to be excellent with a change of less than 1% in any axis. This magnitude of distortion is very unlikely to provide complications for the subsequent mating of a male connector.

4.6 Crystal Oscillator

Despite vastly exceeding the manufacturer’s temperature and time limits for these components, the resonant frequency of the components remained virtually unchanged, and well within the +/-50ppm tolerance specified. The stability of these quartz crystal oscillators gives no cause for concern with lead-free processing.

4.7 BGAs

The ball grid array components were included in this study due to widespread concerns about internal delamination (or pop-corning) of these devices. The industry spends considerable time and effort baking and sealing packages to ensure that moisture in the components is not problematic during reflow and it is reasonable to suggest that the higher ramp rates and temperatures of lead-free soldering will exacerbate the problem.

Despite this, no pop-corning was observed on any of the samples which were humidity soaked and rapidly heated in the reflow oven, or even in those directly floated onto a solder bath.

The design of a package and poor manufacturing are likely to be the main influences on its susceptibility to delamination. The BGA package samples used in this study clearly have a robust design and have been manufactured to high standards. Improvements in materials and construction of BGA packages, since their introduction in the 1990's, has improved delamination resistance.

5 CONCLUSIONS

Suppliers moving towards the manufacture of components that are compliant with lead-free soldering technologies, and indeed users of those technologies, now have to consider any possible consequential effects on the stability of those components caused by the higher processing temperatures involved. Hence this study has undertaken a comparative assessment of a range of components, thought to be sensitive to elevated thermal processing, before and after processing under worst-case lead-free soldering temperature conditions. The assessment was undertaken in terms of physical and functional stability, and the results were benchmarked against the performance of the components under traditional tin-lead soldering conditions.

The components studied were various LEDS, polyester and electrolytic capacitors, crystal oscillators, polyamide connectors, and BGAS. The salient findings were:

- The components were generally robust and compliant with lead-free processing, thus allaying some earlier concerns over component stability

- Within the limitations of this work, polyamide connectors, SM LEDS, quartz crystal oscillators and BGAs appeared compatible with lead-free processing. However, care must be taken not to darken LED casing materials due to overheating, which would reduce light emission levels.

- Some components did exhibit significant damage as a result of the lead-free processing and give cause for concern i.e. both the polyester and electrolytic capacitors, and this poor performance is attributed in part to their wound laminated construction. Although the capacitance remained within quoted tolerance levels, the loss tangent for the capacitors degraded to values well outside the tolerance levels

- Other types of capacitors (e.g. ceramic-based) perform well at the higher temperatures, although they cannot accommodate the same range of capacitance values.

- Although in this study a harsh lead-free soldering profile was applied 6 times to the components, in actual lead-free processes the temperature exposure is likely to be much less aggressive. However, other NPL studies (1) have shown that temperature differentials across boards can be as much as 50°C. For large electronic products with a mixture of large and small components, or for those using smaller reflow ovens, overheating of components may be more likely, and good temperature profiling will be critical

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7 REFERENCES

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