# REDUCED 2ND LEVEL SOLDER JOINT LIFE TIME OF LOW-CTE MOLD COMPOUND PACKAGES

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ABSTRACT

While the research community has spent a lot of effort into the search for a reliable lead-free solder alternative for SnPb, another change occurred below the radar but with a far greater threat for the package-to-board 2nd level solder interconnect reliability. This change is the transition towards low-CTE (coefficient of thermal expansion) mould compounds for basically all plastic packages (BGA, QFN, TSOP etc.) which happened in the period 2005-2010.
The work presented in this paper depicts the impact of the reduced CTE of mould materials through finite element modelling simulation and thermal cycling experiments. Reduction of the life time by up to 60% was found in comparison with packages using the conventional (higher CTE) mould compounds.
Finally, the paper will give recommendations on the minimum CTE needed to get sufficient life time.

## 1. INTRODUCTION

The use of these low-CTE mould materials was driven by the need to reduce the stress on the silicon chip, a lower moisture uptake and halogen-free "green" compounds.
This was realised by increasing the amount of $SiO_2$ particles in the epoxy matrix up to a filler content of 85%. The mould compound easily takes 50% of the total volume of the package (Figure *1*).
However, the reduction of the CTE from 12-15 ppm/°C for conventional mould materials to 7-9 ppm/°C for these low-CTE materials substantially increases the thermal expansion mismatch with the printed circuit board (typically 15-18 ppm/°C). As electronics is subjected to temperature cycling, the larger expansion/shrinkage mismatch between the board and component will increase the loading on the solder joint providing the electrical but also mechanical connection between package and board. The concern of the low-CTE mould compound packages has been first reported in 2011 [1]. Only few other references show some results on different mould compounds [2,3].

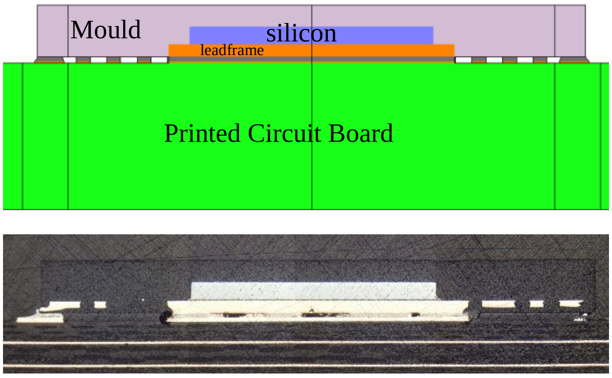


Figure 1: Schematic drawing (top) and cross-section (bottom) of QFN64 – 9x9mm package indicating that a major part of the package consists of the mould compound.

Additionally, these new low-CTE materials are up to a factor two more rigid than the conventional materials, creating also more mechanical stress in the interconnect and its surrounding. Figure 2 plots the elastic modulus as function of the CTE for commercially available mould compound materials. The graph clearly shows a correlation between the CTE and E-modulus.

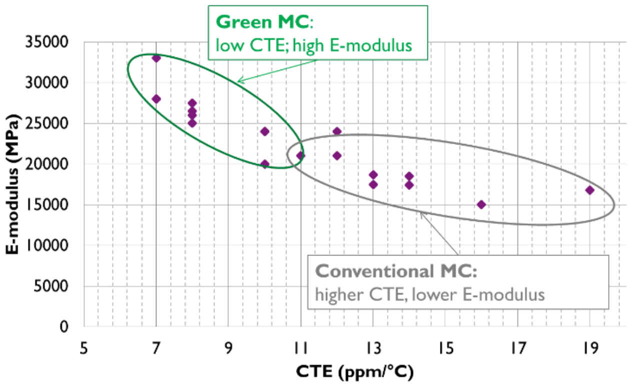


Figure 2: Correlation of the elastic modulus (stiffness) to the CTE of commercially available mould compounds. Values at room temperature (= below $T_g$) are shown.

Besides the impact on the solder joints, other phenomena were found that can be attributed to the low CTE compounds. One of them is higher risk of fatigue failures

of copper wire bonds which is also induced by the larger CTE mismatch between Cu (17.6 ppm/°C) and the low-CTE mould compounds [4]. Also more "head-in-pillow" process assembly issues are experienced which are related to the use of these new mould compound materials [5].
The objective of this work is to report on an experimental thermal test study to show the impact of low-CTE mould compounds on second level reliability.

## 2. EXPERIMENTAL SETUP

A run of thermal cycling testing has been performed on a selection of packages with two versions of mould compounds: one low-CTE (7 – 9 ppm/°C) representing the green mould compounds and one with a higher CTE (11-12 ppm/°C) representing the more conventional mould compounds. This benchmarking study allows us to generate concrete numbers for the impact on life time as a consequence of the introduction of the low-CTE mould compounds.

**Package description**
Based on earlier simulation work [1], two packages were selected because these results showed that the 2$^{nd}$ level reliability is very sensitive to the mould CTE.

Table 1: Description of test packages

| Name | Details | variations |
|---|---|---|
| PBGA228 | 228 I/O's<br>Pitch = 0.5 mm<br>12x12x1.0 mm$^3$ | • Mould material: 8.5 & 11 ppm/°C<br>• Solder ball: SnPb / SAC105/SAC305<br>• Solder paste: SnPb / SAC305 |
| QFN64 | 64 I/O's<br>Pitch = 0.5 mm<br>9x9x0.85 mm$^3$ | • Mould material: 7 & 12 ppm/°C<br>• Solder paste: SnPb / SAC305 |

In total, 36 samples per type were tested.

**Test conditions:**
The IPC-9701 TC1 accelerated test condition for solder joint evaluation was selected as the most appropriate test.

- 0 to 100°C thermal cycling (air-to-air)
- Total cycling time = 1 hour
    - ramp up time = 10 minutes
    - dwell-time = 20 minutes
- In-situ measurement for opens

**Printed circuit board:**
The boards are 8-layer boards with the 6 inner layers completely filled with copper in order to maximise the stiffness of the boards and obtain a CTE as close to that of Cu as possible. The total thickness is 2.4 mm.

## 3. EXPERIMENTAL RESULTS FOR PBGA228

The PBGA228 package is a full-array daisy chain BGA component of 12 mm by 12 mm with a ball pitch of 0.5 mm and a ball size of 0.3 mm.
The Weibull failure distributions for SnPb and SAC solder balls and two types of mould compounds are shown in Figure *3*.

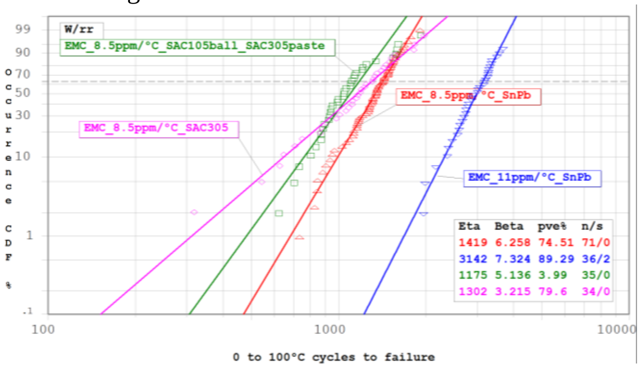


Figure 3: Weibull distribution for four different EMC /solder material combinations for the BGA228 package with 0.5 mm ball pitch.
(cycling test: 0 to 100°C)

Following determinations and conclusions can be made based on these results:

- For the SnPb solder versions, the characteristic life time (N63%) decreases from 3142 cycles to 1419 cycles when the CTE of the mould compound is reduced from 11 to 8.5 ppm/°C. This is more than a factor of 2.
- For the three BGA's with the same low-CTE mould compound but different solder combinations (SnPb, SAC105, SAC305), the characteristic life times are comparable. This supports the statement that the impact of the mould compound material is far greater than the solder material.

The latter observation is of very high relevancy for high reliability applications such as aerospace where the transition to lead-free soldering is not yet completed .

Failure analysis (Figure 4) on a SnPb soldered BGA with 8.5ppm/°C mould compound showed a heavily damaged solder joint especially at the corner/edge area indicative for a large mismatch.

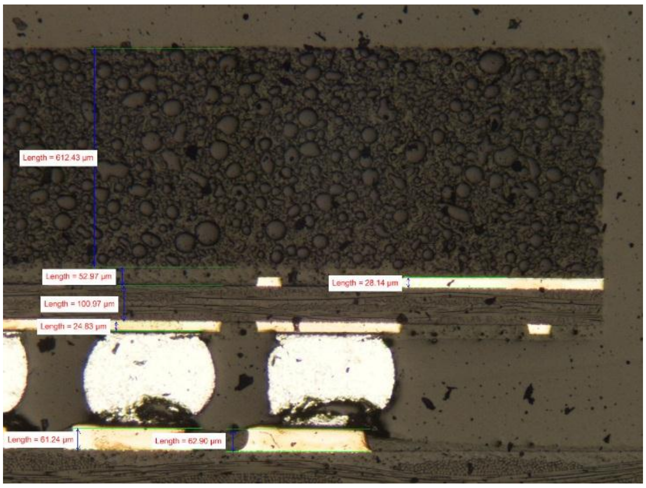


Figure 4: Cross-sections made on a SnPb PBGA with low-CTE mould compound

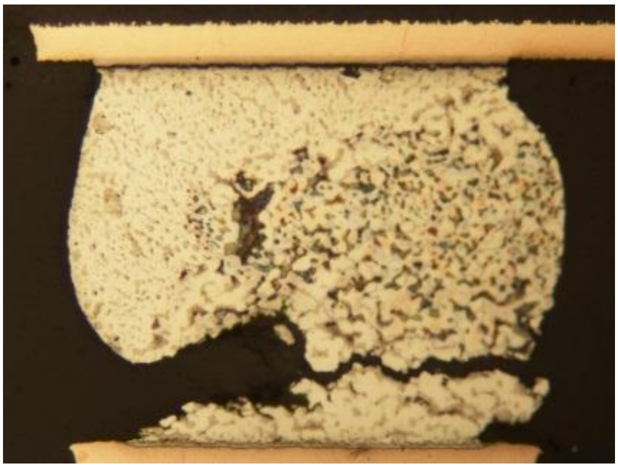

Figure 5: Detailed view of one failing SnPb solder ball joint

## 4. EXPERIMENTAL RESULTS FOR QFN64

A daisy chained 9x9 mm QFN with 0.5 mm pitch is soldered to the 2.4 mm thick PCB (Figure 6). The die size is 4x4x0.28 mm$^3$.

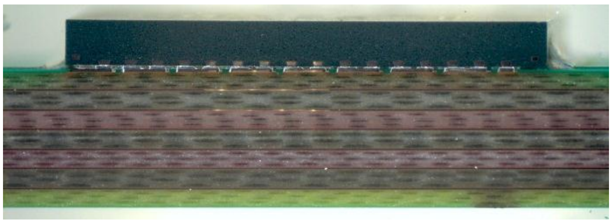

Figure 6: Side view of the QFN64 package (9x9 mm) assembled on a 2.4 mm thick PCB

The results of the thermal cycling tests are shown in Figure 7.

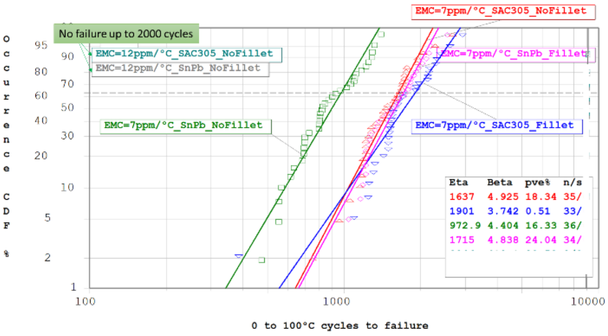


Figure 7: Weibull distribution of 6 tested QFN64 solder assemblies. The two QFN's with high CTE mould compound have not failed yet after 2000 cycles. (cycling test: 0 to 100°C)

Conclusions similar to the BGA228 could be derived from this graph:

- Up to 2000 temperature cycles, none of the QFN with high CTE failed while most of the low-CTE QFN did.
- Flank wetting allowing to have a solder fillet improves the solder joint life time, but the improvement is mainly seen for the SnPb soldered QFN's. At the moment the reason for this is unclear.

Failure analysis (Figure 8) showed that the corner joints fail first. This is expected as these joints see the highest absolute thermal expansion mismatch between component and board. For the packages soldered with SAC305, failure analysis is shown below.

### *QFN64: 7ppm/°C EMC – SAC305 solder – No fillet*

These QFN's failed in average after 1637 cycles. A fully cracked joint was found in one corner (left side on Figure 8) but also the other corner, damage is found in the solder joint (Figure 14).

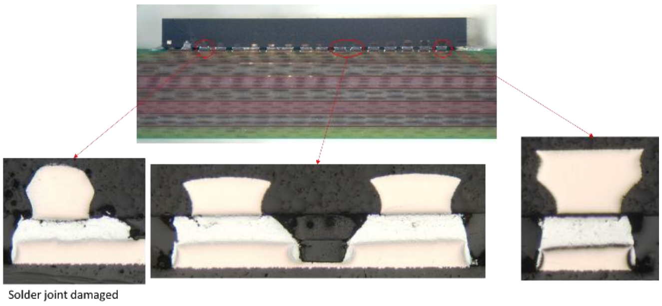


Figure 8: Cross-section of SAC305 soldered QFN64 package (9x9 mm) assembled on a 2.4 mm thick PCB after temperature cycling. (EMC = 7 ppm/°C)

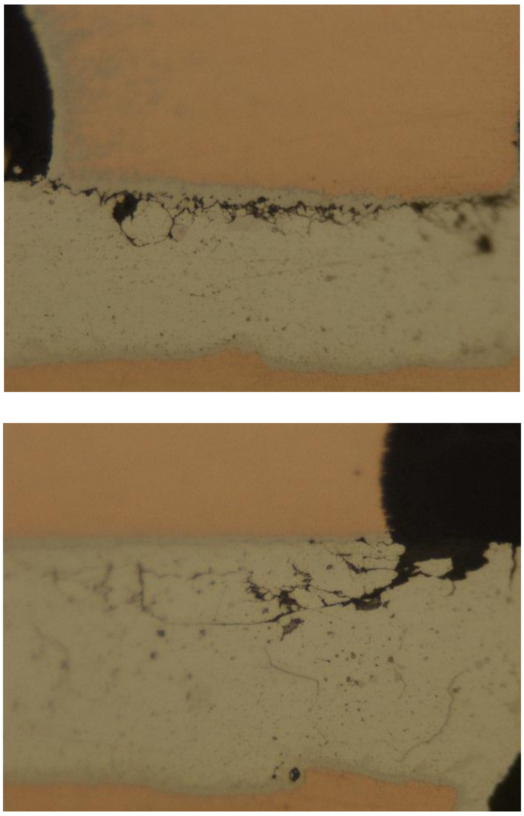

Figure 9: Detailed view of left and right corner joint for QFN's with 7 ppm/°C EMC and SAC305 solder joints without fillet (EMC = 7 ppm/°C)

***QFN64: 7ppm/°C EMC – SAC305 solder – With fillet***

These QFN's failed in average after 1901 cycles which is only 10% higher than without fillet. It is expected that fillet would positively benefit to the life time of the solder joint, but the explanation for the little difference with no fillet is the asymmetric soldering indicated in Figure 10. At the right side, the solder stand-off height is less than 20 µm and it is at this solder joint which fails first.

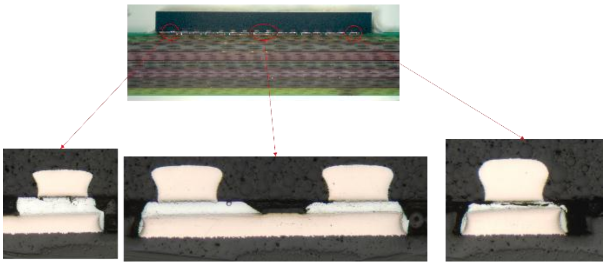

Figure 10: Cross-section of SAC305 soldered QFN64 package (9x9 mm) with solder fillet (EMC = 7 ppm/°C)

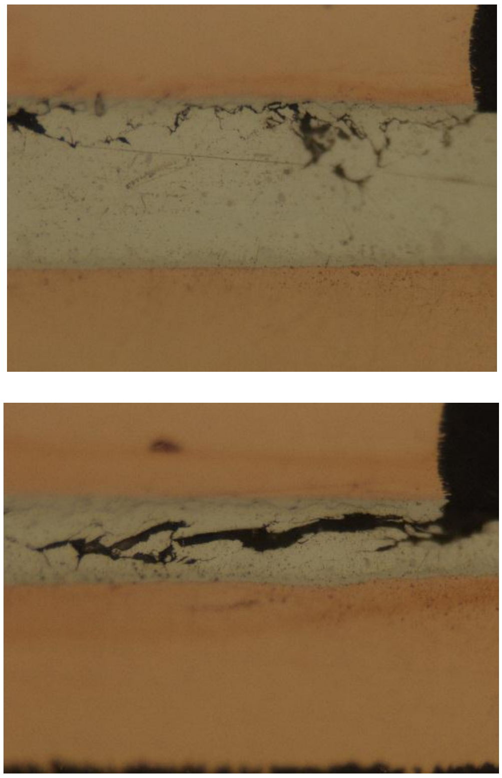

Figure 11: Detailed view on left and right corner joint of SAC305 soldered QFN64 package (9x9 mm) with solder fillet (EMC = 7 ppm/°C)

***QFN64: 12ppm/°C EMC – SAC305 solder – No fillet***

Any of these QFN's with high CTE of the mould compound failed up to 2000 cycles. Cross-sections depict that there is only little damage seen, even in the corner joints.

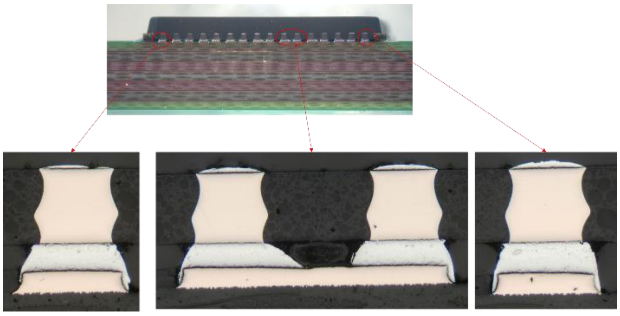

Figure 12: Cross-section of SAC305 soldered QFN64 package (9x9 mm) without solder fillet (EMC = 12 ppm/°C)

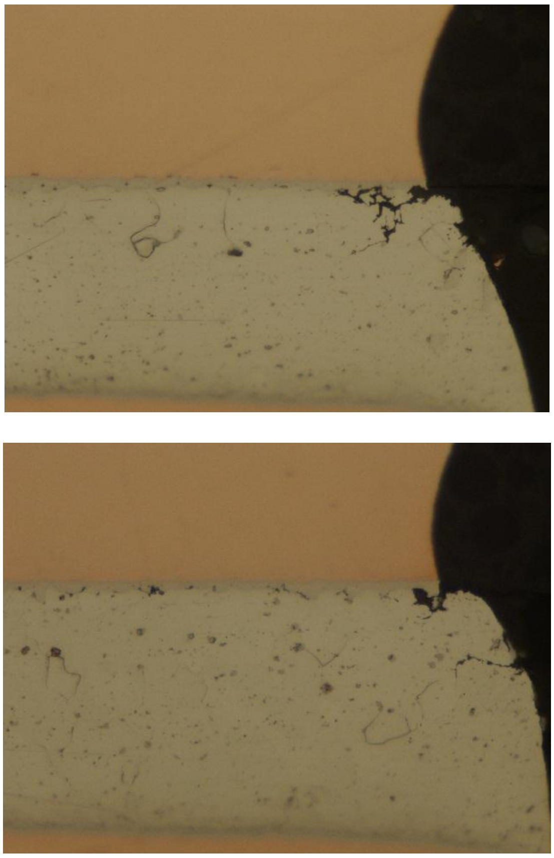

Figure 13: Detailed view on left and right corner joint of SAC305 soldered QFN64 package (9x9 mm) with solder fillet (EMC = 12 ppm/°C)

## 5. CORRELATION WITH FEM SIMULATIONS

Finite Element Modelling is a suitable technique for calculation of the induced stresses and strains . A unified visco-plastic Anand model is applied to the lead-free solder. The parameters of this material model is selected from reference work in literature [6].
Models have been created for the BGA228 and QFN64.

***BGA 228***

Figure 14 shows the FEM for this package.

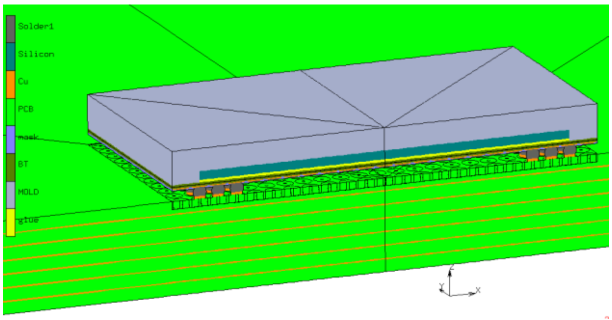


Figure 14: FEM of BGA228 package soldered to the PCB.

The output relevant for solder joint fatigue are the creep deformation in the solder joint happening during every temperature cycling. The highest creep strains are found in the corner joint at the PCB side Figure 15. This agrees well with the experiments where cracks were found at the corner joint near the PCB side (Figure 4).

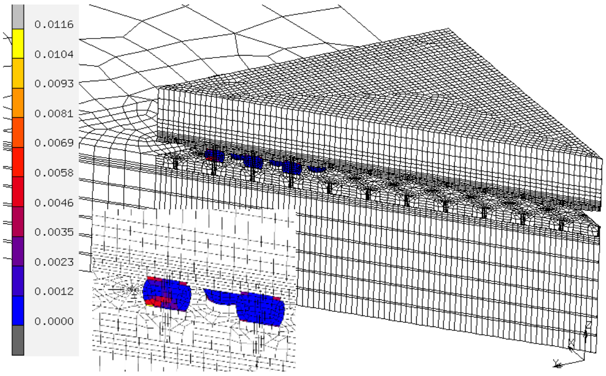


Figure 15: Inelastic strain distribution in SAC305 solder balls for BGA228 packages assembled to the 2.4 mm PCB (EMC = 8.5 ppm/°C)

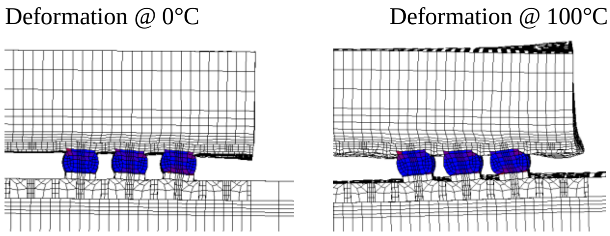


Figure 16: FEM simulation showing the mechanical cycling effect on the solder joint as a consequence of the CTE mismatch between component and board

Regarding the impact of the EMC, the simulations also predicts a factor of 2 reduction in life time due to the change from 11ppm/°C to 8.5 ppm/°C mould compounds.

***QFN64***

Figure 17 shows the FEM for this package.

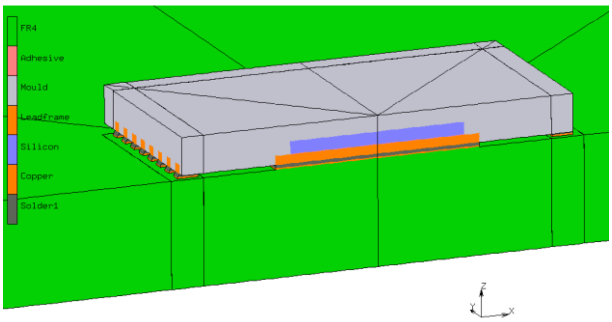


Figure 17: FEM of QFN64 soldered to the PCB

The simulated creep strain is shown in Figure *18*. The maximum is found in the corner and this also agrees with the experiments.

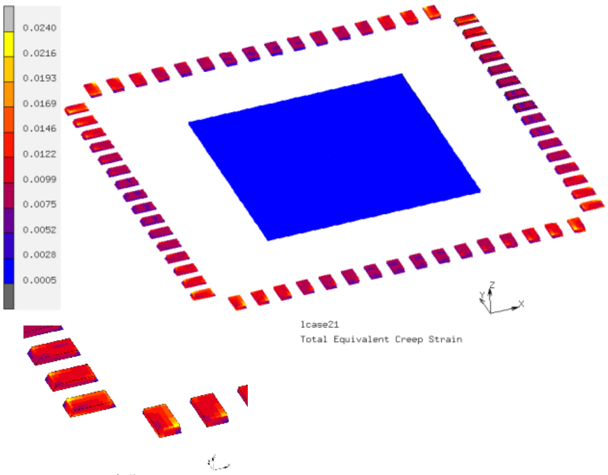


Figure 18: Inelastic strain distribution in SAC305 for QFN228 packages assembled to the 2.4 mm PCB (EMC = 7 ppm/°C)

## 6. FEM BASED PARAMETER STUDY

The objective of this parameter study is to relate the life time of the solder joints to the CTE of the mould compounds. As Figure *2* mentioned, the E-modulus is related to the CTE of the mould compound in a correlation curve (E * CTE = $C^{te}$). Therefore, five different mould compounds are defined with realistic properties:

*Table 2: Variation in mould compound properties for the FEM simulation based sensitivity study*

| | CTE | E-modulus | |
|---|---|---|---|
| **OM1** | 7 ppm/°C | 30000 MPa | Green MC |
| **OM2** | 8 ppm/°C | 26250 MPa | ⇕ |
| **OM3** | 10 ppm/°C | 21000 MPa | |
| **OM4** | 12 ppm/°C | 18000 MPa | |
| **OM5** | 14 ppm/°C | 15000 MPa | Conventional MC |

The results are shown Figure 19. The life time exponentially decreases with decreasing CTE of the mould compound. Only one experimental point could be added to the graph. The tests with 12 ppm/°C mould compounds have no failures up to 2000 cycles. A conservative extrapolation gives a characteristic life time of at least two times this number, so at least 4000 cycles. These latter tests will be continued.

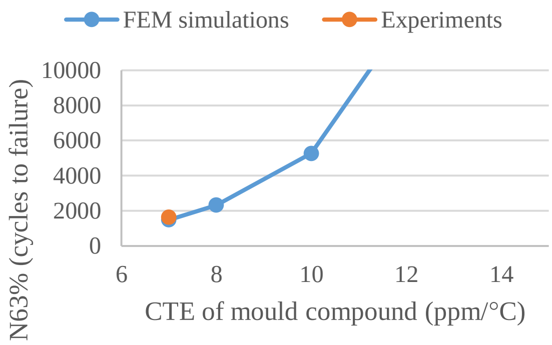


Figure 19: Sensitivity of the characteristic life of the QFN64 package as function of the CTE of the mould compound (the E-modulus is linked to the CTE through the table 2).

## 7. IMPACT OF BOARD STIFFNESS AND BOARD FIXATION

The issues become even worse when the PCB is prohibited to follow the warpage of the component. Figure *20* shows an extreme case (but not unrealistic!) where the board is not allowed to warp (out-of-plane displacement is zero). In that case, the life time really drops to very low numbers (554 cycles characteristic life for 7 ppm/°C).

This study highlights the risk for qualification of QFN's on rather flexible boards (< 1.6 mm) which can be a substantial overestimation for the real application case where the board is either much stiffer (> 1.6 mm; more and thicker copper layers) or even fixed to a frame not allowing any bending anymore.

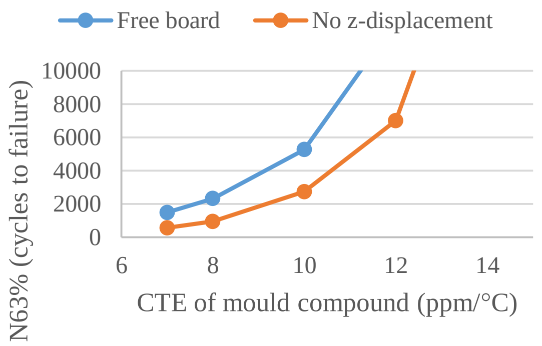


Figure 20: Impact of board support on life time of QFN assemblies.

## 8. CONCLUSIONS

Both experimental observation and FEM simulations reveal a clear negative impact of low CTE "green" mould compounds on the solder joint second level reliability of QFN and BGA packages. Life time reduction up to 60% are measured.

The impact highly depends on the stiffness and support of the printed circuit board. The less the board can bend, the higher the impact of the low-CTE will be. Qualification of packages on rather flexible (<1.6 mm) boards can be a substantial overestimation of the life time for your real product.

For high reliability applications and electronics operating under severe conditions, this mould compound change creates a major reliability concern and requires thorough evaluation. The impact on electronics reliability is considerably greater than that of a change in solder alloy but as yet did not get a similar level of attention.

## 9. ACKNOWLEDGMENTS

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## 10. REFERENCES

1. B. Vandevelde, M. Lofrano and G. Willems, Green mold compounds: impact on second level interconnect reliability. In: Electronics Packaging Technology Conference - EPTC. IEEE, 2011, 7-9 December 2011; Singapore, Singapore.
2. Tong Yan Tee, Hun Shen Ng, Zhaowei Zhong, and Jiang Zhou, Board-Level Solder Joint Reliability Analysis of Thermally Enhanced BGAs and LGAs, IEEE Transactions on Advanced Packaging, vol. 29, no. 2, May 2006.
3. A. Syed and W. Kang, Board level Assembly and reliability for QFN type packages, SMTA International 2003.
4. B. Vandevelde, G. Willems, Early fatigue failures in copper wire bonds inside packages with low CTE green mold compounds. In: 4th Electronics System Integration technologies Conference - ESTC. 17-20 September 2012, Amsterdam, The Netherlands.
5. B. Vandevelde, G. Willems, B. Allaert, Hidden Head-In-Pillow soldering failures, 15$^{th}$ Eurosime conference, 6-9 April 2014, Gent, Belgium.
6. K. Mysore, G. Subbarayan, V. Gupta, R. Zhang, "Constitutive and Aging behaviour of Sn3.0Ag0.5Cu Solder Alloy", IEEE Transactions on Electronic Packaging Manufacturing, v 32, n4, p221-232, Oct 2009.
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