

# Reliability of BGA Packages in an Automotive Environment

Roger Rörgren, Per-Erik Tegehall and Per Carlsson  
IVF - The Swedish Institute of Production Engineering Research  
Argongatan 30, SE-431 53 Mölndal, Sweden. <http://www.ivf.se>

## ABSTRACT

This paper addresses reliability aspects of great importance to any user of BGA packages. Results from reliability tests under harsh automotive-like environmental conditions are presented, involving a number of different BGA packages, including OMPACS, Super BGAs and Tape BGAs, as well as fine-pitch quad flatpacks serving as a reference. All packages were mounted to standard gold-plated FR-4 test boards, specifically designed for the tests. Parameters such as pad design, BGA substrate thickness, and use of underfill or conformal coating, were varied in order to study their influence on the reliability. Daisy Chain packages were used to check the electrical performance of the solder joints whereas micro-sectioning and the use of a dye penetrant were employed to study the joint quality. The environmental tests comprised temperature cycling from -40 to 100°C, with and without simultaneous exposure to vibration (8 G, 10-500 Hz) during the high temperature phase, as well as humidity cycling from 25 to 65 % RH.

The results show that non-soldermask defined (NSMD) pads on both board and package give superior performance for the PBGA361, compared to when solder mask defined (SMD) pads are used. The 1.27 mm pitch PBGA361 passed 5000 cycles and the PBGA256, as well as the QFP reference samples, passed 6000 cycles from -40 to 100 °C without failure. Cross-section analysis after 6000 thermal cycles, performed on 1.5 mm pitch PBGA225s, shows extensive cracking, which however could be avoided with the use of a suitable underfill. A dye penetrant was successfully employed as a complementary technique, giving added value when combined with cross-sectioning.

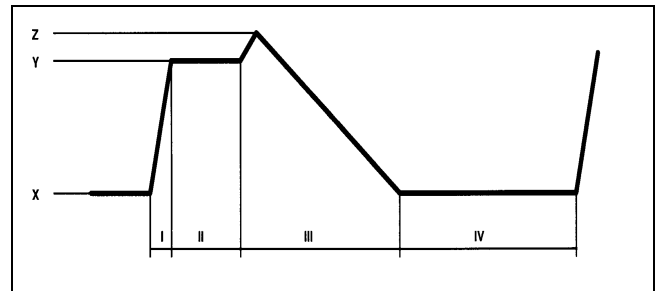
## INTRODUCTION

The present miniaturization trend towards higher-performance, smaller and lighter products has resulted in an increasing demand for smaller component packages and/or higher pin counts [1]. The properties of the Ball Grid Array (BGA) package, and especially its potentially higher assembly yields compared to fine-pitch quad flat packages (QFPs), make them attractive for other application areas with volume production such as automotive electronics [2,3]. For cost reasons, however,

only plastic BGAs will probably be an alternative for most automotive applications.

The leadless feature of the BGA package raises some doubts about the reliability in applications with large temperature variations and in harsh environments typical of automotive electronics. This paper addresses some of the reliability concerns encountered with the advent of the BGA in automotive electronics.

When evaluating the reliability of BGAs at board-level, it is the service environment and the performance requirements of BGAs at board-level that must be specified. The service environment for automotive electronics are often divided into three zones with quite different environments, namely under-the-hood, chassis and compartment. Furthermore, the service environment and the performance requirements are usually quite different between private cars and commercial vehicles. A schematic temperature cycle for a circuit assembly in a car is given in Figure 1. The peak z is caused when the cooling of the unit is shut down when the engine is turned off. The still warm engine will cause some heating of the unit. Typical seasonal values for a car is given in Table 1, below.



**Figure 1.** Schematic temperature profile for a circuit assembly located under-the-hood on a car (see Table 1).

**Table 1.** Typical seasonal values for a circuit assembly located under-the-hood on a car (see Figure 1).

Season	x (°C)	y (°C)	z (°C)	I (h)	II (h)	III (h)	IV (h)
Spring	+10	+50	+100	0.05	1.0	2.0	6-12
Summer	+20	+80	+100	0.05	1.0	2.0	6-12
Autumn	+10	+50	+100	0.05	1.0	2.0	6-12

Previous studies have shown that cracking of solder joints due to fatigue is the most likely failure mechanism [4]. Failures due to corrosion are not considered likely, provided sufficient environmental protection is used. However, to our knowledge, the effect on reliability from conditions in the service environment as e. g. temperature variations together with vibration exposure, is not yet well documented. The same holds for electrochemical migration due to flux residues and other contaminants that may cause failures. Moreover, the large variety of BGA packages with different properties will most likely have a significant impact on the board level reliability.

### TEST PROGRAM

Three environmental tests were invoked in order to evaluate how the service environment and various BGA package properties affect the reliability. In an attempt to simulate an automotive environment, temperature cycling with and without simultaneous vibration or humidity, was chosen for the primary environmental exposures.

#### Temperature cycling

Test boards were thermally cycled between -40 and +100°C with a temperature ramp of 10 °C/minute and a dwell time of 16 minutes at each temperature. The maximum number of thermal cycles used in the investigations was 6000 cycles for certain boards. In this test, the effect of the properties of the BGA package and the geometry of the solder joint was evaluated. The following properties of the BGA package were varied: size (169, 225 and 361 I/Os), pitch (1.27 and 1.5 mm) and substrate thickness (0.2, 0.4 and 0.6 mm). Some of the BGA packages had no chip in order to evaluate the impact of the chip on the fatigue of solder joints. The geometry of the solder joints was varied by using non-solder mask defined (NSMD) and solder mask defined (SMD) pads on both BGA packages and PCB and by varying the diameters of the pads on the PCB to adjust the stand-off. The influence of conformal coating and underfill on the resistance against fatigue was also evaluated. One conformal coating and three different underfills were used. In addition, other types of BGA packages, including Super BGAs and Tape BGAs, were included in the temperature cycling test, as well as QFPs with 0.4 and 0.65 mm pitch serving as a reference.

#### Vibration

Some test boards were additionally exposed to vibration during the high temperature phase of 250 thermal cycles. The samples were attached to the vibration fixture by means of 8 screws, see Figure 2, and subjected to random vibration for 20 h in each of the three perpendicular directions. The frequency range employed was 10 to 500

Hz and the acceleration level was 8 G (RMS). Some boards were exposed to vibration from the start of the thermal cycling test and others after 500, 1000 and 2000 thermal cycles had been performed. Temperature cycling was performed according to IEC 68-2-14, Nb, and vibration to IEC 68-2-35, Fda.

#### Humidity cycling

A cyclic humidity test was used to evaluate how flux residues and conformal coatings affect electro-chemical migration. Some boards were cleaned and some coated. In this test, cycling was performed between 25 and 65 °C at a nominal 93 % relative humidity. The duration of the test was one week (168 h) and measurements of the surface insulation resistance (SIR) were made *in situ* at specified intervals. This test was performed according to IPC TM-650 2.6.3.1 Class 2, *except* for the polarization and measurement voltages which both were 5 V dc (same polarity).

## EXPERIMENTAL PROCEDURES

### Sample preparation

Three different test boards were designed for use in the process and reliability evaluations. All boards were four-layer standard FR-4, measuring 145x185 mm, with a flash gold finish (0.1  $\mu\text{m}$  electroless Au over 5  $\mu\text{m}$  Ni). The first board holds 12 packages, see Figure 2, out of which four are 256 and 160-lead QFP reference packages with 0.4 and 0.65 mm pitch, respectively. The remaining eight BGAs were all 1.5 mm pitch PBGA225s (OMPAC), with 30 mil diameter 62Sn/36Pb/2Ag solder spheres, with some variations according to Table 2.

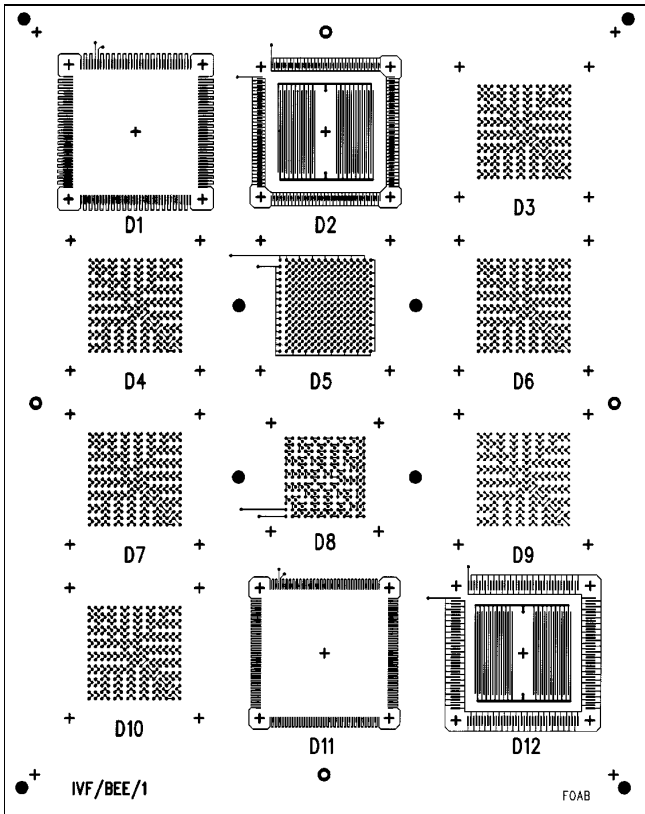


Figure 2. Layout of Test Board 1.

**Table 2.** BGA225 parameters varied using Test Board 1.

Pos.	No. of Pins	Die	BT thickn.	Board Pad	BGA Pad	Conf (*)
D3,6	225	Yes	0.2 mm	SMD	SMD	DC
D4	225	No	0.2 mm	SMD	SMD	DC
D5	225	No	0.2 mm	NSMD	SMD	SIR
D7,9	225	No	0.2 mm	NSMD	SMD	DC
D8	169	No	0.2 mm	SMD	SMD	DC
D10	225	Yes	0.6 mm	SMD	SMD	DC

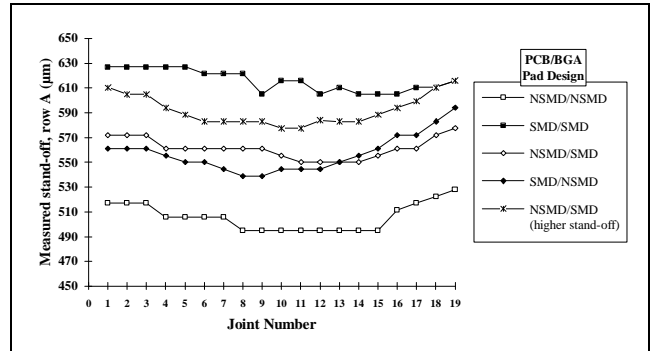
(\*) DC: Daisy Chain for electrical continuity monitoring  
SIR: For Surface Insulation Resistance measurement

Unfortunately, the BGAs used on the first board all had SMD pads, due to limited availability of NSMD BGA packages at that time. On the second test board (not depicted) only 361 pin OMPACS were used, but with all four combinations possible of SMD and NSMD pads of BGA and board, as well as one version with increased stand-off. The solderable lands were designed equal to give a symmetrical joint, except for the one combination with increased stand-off, for which the board pad was made smaller, see Table 3. The PBGA361s had 25 mil diameter 62Sn/36Pb/2Ag solder spheres arranged in a full 19x19 array on a 1.27 mm grid pitch. They also contained a square 13.5 mm silicon die with a thickness of 0.35 mm, glued onto a 0.2 mm thick BT substrate with either SMD or NSMD pads and a 0.8 mm thick overmould, giving a total package thickness of 1.16 mm (excl. solder spheres).

**Table 3.** Solderable pad area of board and BGA pads, and resulting stand-off for PBGA361 on Test Board 2.

Board Pad	Size (mm)	BGA Pad	Size (mm)	Stand-Off (mm)
NSMD	0.51	NSMD	0.51	0.49
SMD	0.56	SMD	0.56	0.59
SMD	0.51	NSMD	0.51	0.54
NSMD	0.56	SMD	0.56	0.55
NSMD	0.46	SMD	0.56	0.58

The resulting stand-off, as given in Table 3 above, is the average value of all joints from one centre row and one outer row, including 38 balls in total. An example of the actual variation of the joint height is shown in Figure 3 below, where measurements were made along an outer row. A slight bath-tub-like shape is observed, where corner joints exhibit a higher stand-off than balls in more central regions. It is also clear that the use of NSMD pads renders a lower stand-off since part of the solder is consumed when the pad edges are wetted. In this experiment, the higher stand-off intentionally accomplished using a smaller NSMD pad on the board (labelled Hi in Figure 3) falls just below that of the sample using SMD pads at both end, but they should still be comparable in this respect.



**Figure 3.** Joint height (Stand-Off) measured along an outer row of PBGA361s with various pad designs.

The third test board was designed to allow reliability comparisons between different types of BGA packages. The packages employed are described in Table 3. Please note that the OMPAC (PBGA256) used on this board was an improved version developed to give higher reliability than the PBGA225 and PBGA361. It has a depopulated matrix (4 rows), increased BT thickness of 0.4 mm and 16 additional 63Sn/37Pb thermal balls under the centre of the 10x10 mm die. Also note that the TBGAs have 10Sn/90Pb balls that do not melt during reflow and that the SBGAs have SMD pads.

**Table 4.** Components used with Test Board 3.

Comp.	No. of Pins	Pitch (mm)	Lead alloy	Board Pad	BGA Pad
PBGA	256	1.27	63/37	NSMD	NSMD
PQFP	160	0.65	Cu	N/A	N/A
PQFP	256	0.4	A42	N/A	N/A
TBGA	240	1.27	10/90	NSMD	N/A
SBGA	256	1.27	63/37	NSMD	SMD
SBGA	352	1.27	63/37	NSMD	SMD

The boards were all assembled using a standard fine-pitch RMA no-clean solder paste (62Sn/36Pb/2Ag) with a particle size range from 20 to 45 µm (IPC type 3), and reflowed in a nitrogen atmosphere. The solder paste was applied by stencil printing, using metal blade squeegees, at a speed of 10 mm/s. The thickness of the electroformed, additively built-up and nickel-plated stencil was 125 µm (5 mils). The diameter of the circular apertures was decreased by 10% in order to provide better gasketing between stencil and pad and thus reduce solder balling effects.

A selected number of test boards of the first type were additionally cleaned, underfilled or coated in order to study the influence on reliability from these parameters and their combinations. Three underfill materials were used, with different CTEs: 10, 23 and 45 ppm/°C, respectively. Prior to coating or underfilling, the samples were cleaned using

a commercially available liquid glycol-ether based cleaning agent, except for the control group which was left uncleaned.

Underfill was applied both on cleaned and uncleaned boards by repeatedly dispensing underfill on the test board along two edges of the BGA. The boards were kept on a hot plate at 70 °C which lowered the underfill viscosity sufficiently to allow the capillary forces to completely fill the volume under the BGA in a few minutes. The vacuum deposited conformal coating, which was applied on cleaned boards at room temperature, serves as a moisture barrier and is believed to add both mechanical strength and environmental protection to the joints.

Packages not used for SIR measurements were Daisy Chain configured, allowing for monitoring of the electrical continuity of the solder joints being connected in one long chain. In order to resemble real applications as much as possible, a great number of dummy via holes were drilled between the BGA pads, see Figure 2, which may cause the local CTE under the BGAs to differ substantially from that of circuit boards with a less dense via population. Since all the vias were connected to a pair of BGA pads, it also made it possible to manually locate any open circuit to a specific pair of joints by probing the pairs. For the odd-numbered BGAs (225 and 361), this meant that one ball could not be included in the Daisy Chain. Moreover, the Daisy Chains were accomplished on the top side of the board as not to allow any via failures to influence the Daisy Chain resistance.

A 128-channel high-speed event detector was used for monitoring the Daisy Chain resistance *in situ* the temperature cycling chamber (no vibration applied). The event detector can detect ultra-short spikes or open-circuits, in this case in the Daisy Chain, provided the spikes are at least 1 μs long. An open circuit in this case was defined as a total Daisy Chain resistance above 100 ohms, i.e. about 100 times the measured resistance of the BGA Daisy Chains prior to environmental stress. The poll time was 2 minutes and the measuring cycle 10 hours. A complete solder failure thus gives rise to 300 events. Unfortunately, due to human error, only test boards 2 and 3 could be monitored in this way throughout the temperature cycling test.

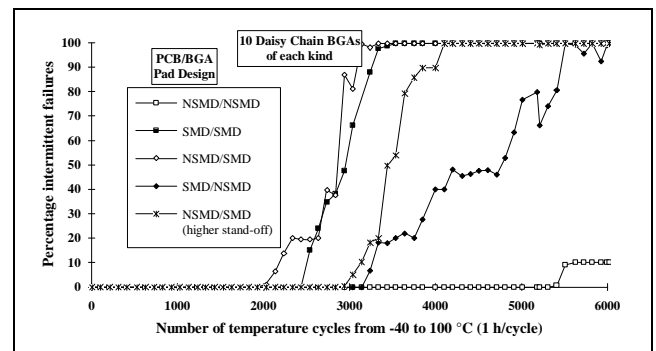
Cross-sectioning, using conventional diamond saw techniques, was performed on packages from Test Board 1, covering all material and geometry variations discussed above. In particular, the BGA225 in Pos. D3 (SMD/SMD) was studied extensively and sectioned both through an outer row and through row number 6, which is located under the die perimeter. Thus, both two package corner balls and two die corner balls were sectioned.

As an alternative to cross-sectioning, a dye penetrant analysis, as described in [5], was made on samples from different test boards, after having been subjected to temperature cycling for 1000, 1500, 2000 and 6000 cycles, respectively. A steel red layout fluid was flushed under the mounted BGAs repeatedly to penetrate the joint and possible cracks, decorating any fracture surfaces. Following the dye application, performed under vacuum, the samples were baked at 100 °C for up to one hour to dry the ink. A steel hook was then glued on top of the packages with a high-strength epoxy, and a weight of 10 kg was attached to the hook, applying a vertical pull force. With time, sometimes for several hours, and a little help from elevating the temperature to approximately 85 °C, all BGAs could be removed in a consistent way. Samples subjected to less than 6000 cycles were in fact put back in the cycling cabinet after having been flushed with ink at the selected cycle numbers, so that the continued cycling would help removing the devices through further propagation of possible cracks. Thus, all samples experienced 6000 thermal cycles but the dye only penetrated and decorated fractures present at the cycle numbers given above.

## RESULTS AND DISCUSSION

### Electrical Measurements

Results from the measurements of intermittent failures during temperature cycling of the 1.27 mm pitch PBGA361s on Test Board 2, as recorded by the event detector, are shown in Figure 4 below.

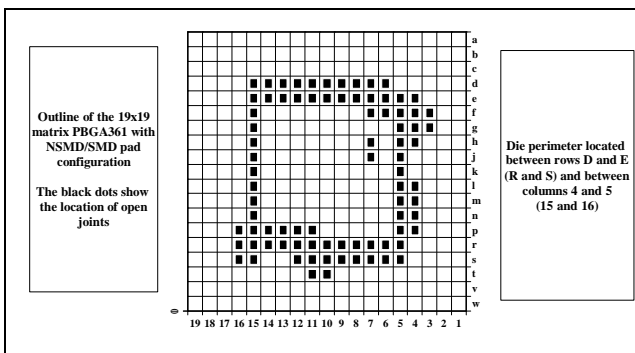


**Figure 4.** Pad design influence on reliability of 1.27 mm pitch PBGA361 during 6000 h of temperature cycling.

Ten identical Daisy Chain samples were used for every board/BGA pad combination, so a *complete* failure for one package will show up as a 10 % increase in the diagram. Please note however, that the number of intermittent failures for a given sample usually grows gradually from zero to 100 %, permitting intermediate values. After 6000 cycles, all 10 samples of each combination had failed, showing open circuits, except for the NSMD/NSMD combination for which only one out of the ten samples had failed.

As evident from Figure 4, the most important factor for achieving high reliability is to have an NSMD pad on the BGA package substrate. The use of NSMD pads on *both* the board and the BGA package did not yield any intermittent failures up to 5500 cycles (1 hour per cycle), while switching to SMD pads on the board caused failures to start at approximately 3000 cycles. However, if NSMD BGA packages are not available, it is not a good idea to use NSMD pads only on the board, as this combination (NSMD/SMD) gives an even shorter life than SMD pads on both sides. The reason for the lower reliability with the NSMD/SMD combination is assumed to be a stress concentration to a weaker point at the package-ball interface. The stand-off is approximately the same in the two cases NSMD/SMD and SMD/NSMD (see Table 3) and therefore cannot explain the different failure behaviour. However, it is clear from the diagram that an increased stand-off for the NSMD/SMD combination actually delays the onset of intermittent failures to a value slightly better than SMD/SMD.

The location of the open joints in the PBGA361 Daisy Chain packages, mounted to Test Board 2, was found by manually probing the packages that had shown intermittent failures during temperature cycling, mainly packages with SMD pad designs. The result is depicted in Figure 5 below, which with remarkable consistency shows that electrical integrity is lost predominantly in joints near the die edge. Each black dot in Figure 5 denotes an open circuit in *either or both* of the two joints forming that particular pair of joints. Thus, the actual number of open joints produced during the temperature cycling exposure of the PBGA361s lies between half and all of those marked black.



**Figure 5.** Location of open joints in the Daisy Chain circuit of a PBGA361 with NSMD/SMD pad design.

The occurrence of intermittent failures under temperature cycling conditions was also measured using Test Board 3, to which different types of BGA packages had been mounted. 16 test boards were hooked up to the event detector described above. No failures were observed for neither the PBGA256 nor the QFP reference samples during the 6000 cycle long test. A few intermittent

failures were detected for the SBGAs and the TBGA, as given in Table 5. Six out of the 16 test boards had also been exposed to vibration during the high-temperature phase of 250 thermal cycles (three boards from cycle 1032 to 1282, and three more from 2037 to 2287). This, however, did not seem to have any effect on the devices, i.e. the failures either occurred before vibration exposure (SBGA) or within the control group not subjected to vibration (TBGA).

**Table 5.** Intermittent failure registration using Test Board 3 during temperature cycling from -40 to 100 °C.

Device Type	No. of Pins	No. of Devices Tested	No. of Cycles to First Failure	No. of Failed Devices at 6000 cycles
PBGA	256	32	-	0
QFP	160	16	-	0
QFP	256	16	-	0
SBGA	256	32	527	5
SBGA	352	15	383	4
TBGA	240	31	3478	15

For the two SBGA types, the first failures occurred rather early in the test, and developed slowly to a final failure rate of 15 % and 10 % , respectively, at the end of the 6000 cycle test. The TBGAs, on the other hand, exhibited the first failure at a much later stage, around 3500 cycles, but failed massively between 5000 and 6000 cycles when 13 out of the 15 final failures appeared. It should be noted, however, that in the present work the cause of the failures above has not yet been identified, and therefore may be both package specific and/or assembly related.

Preliminary results from the measurements of the surface insulation resistance (SIR) of Test Board 1 show no unusual or unexpected values. A slightly lower value was recorded for the PBGA225 (Pos. D5), as compared to the QFP reference samples, most likely due the larger area under the BGAs being exposed to humidity and thereby increasing the leakage currents, registered as lower SIR in the measurements. Further work is planned to continue the evaluation of the SIR test.

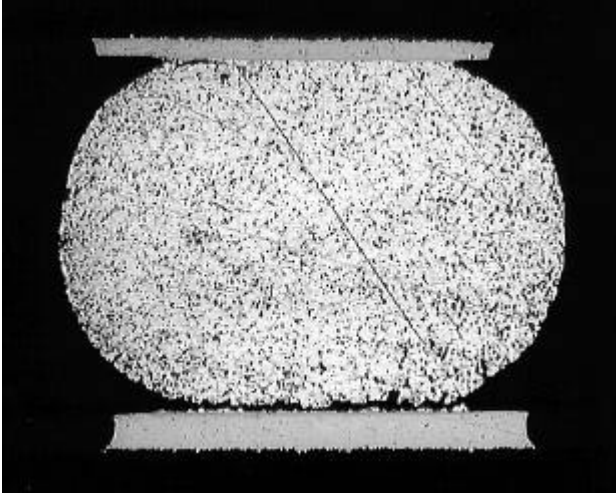
### Cross-sectioning

Micrographs of cross-sections from the 1.5 mm pitch PBGA225 (pos. D3) from Test Board 1 are shown in the following Figures 6 through 12. All samples have been thermally cycled for 6000 hours between -40 and 100 °C and the figures show joints with SMD pads on both board and package. The different parameters in the cross-section study include:

- the effect of additional vibration exposure
- the impact of using underfill (3 different CTEs)
- the influence of cleaning before underfilling

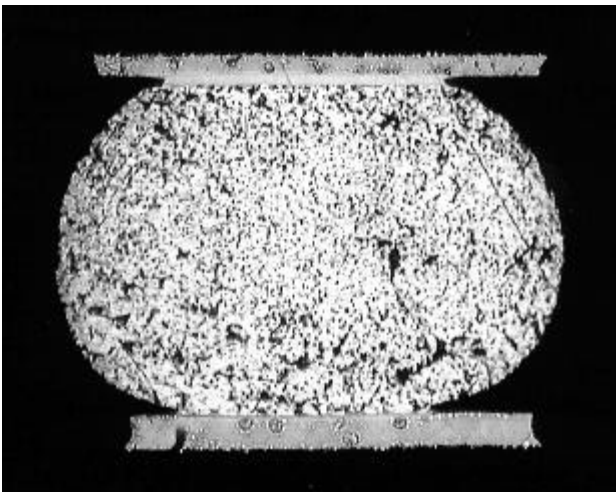
- location of sectioned balls (corner, die or centre).

The first two micrographs show joints from samples that were cleaned, cycled 6000 times without vibration and cut through balls directly under the die perimeter. The difference is the use of an underfill with a CTE of 23 ppm/°C.



**Figure 6.** PBGA225 centre ball under die perimeter, cleaned, after 6000 thermal cycles *without* underfill.

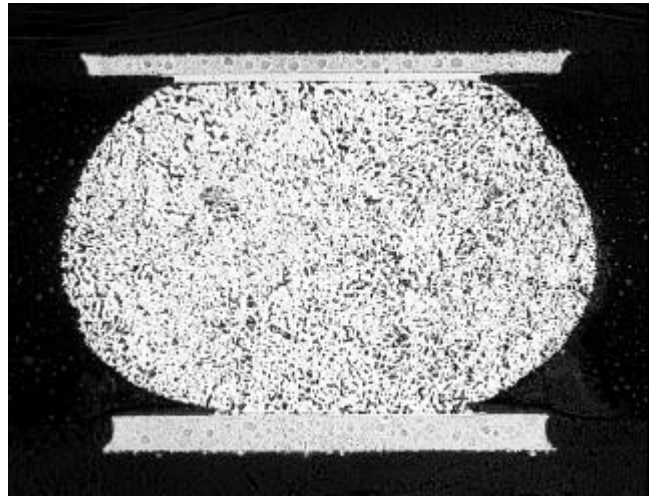
As evident from Figures 6 and 7, there is without the underfill a total separation of the ball from the board pad since a crack has propagated all the way. No significant effect of ball location could be observed (not shown here).



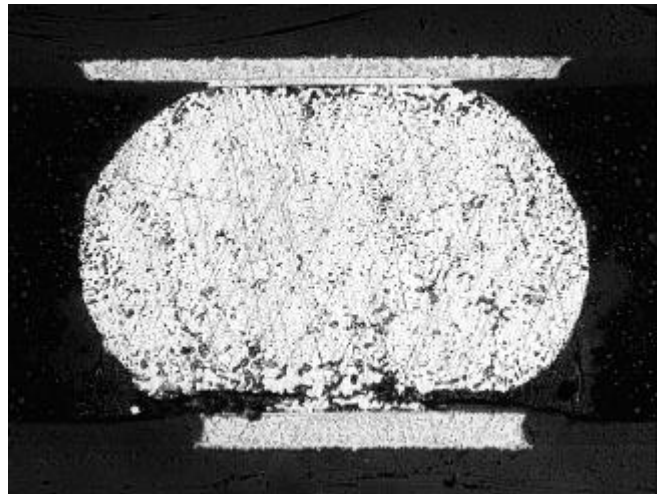
**Figure 7.** PBGA225 centre ball under die perimeter, cleaned, after 6000 cycles *with* underfill (CTE=23 ppm).

The result from using an underfill on a *cleaned* board, as in the previous figure, was of course very good, indicating its presence to be utterly benign. However, when uncleaned boards were used, i.e. with no-clean flux residues present, the result was a little different. Figures 8 through 10 show a joint from the same ball location,

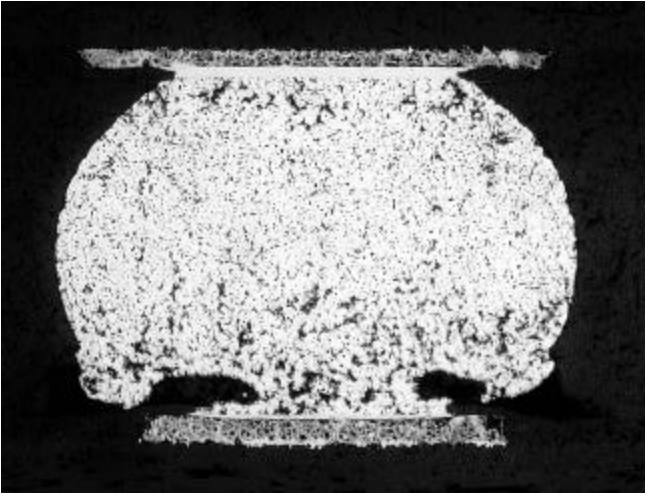
uncleaned but cycled as above, with three different underfill CTEs: 10, 23 and 45 ppm/°C. In this case, only the joint with 10 ppm underfill is left intact. The flux residues seem to have disturbed the 23 ppm underfill that had a positive effect on cleaned boards.



**Figure 8.** PBGA225 centre ball under die perimeter, uncleaned, after 6000 cycles, with underfill 10 ppm/°C.



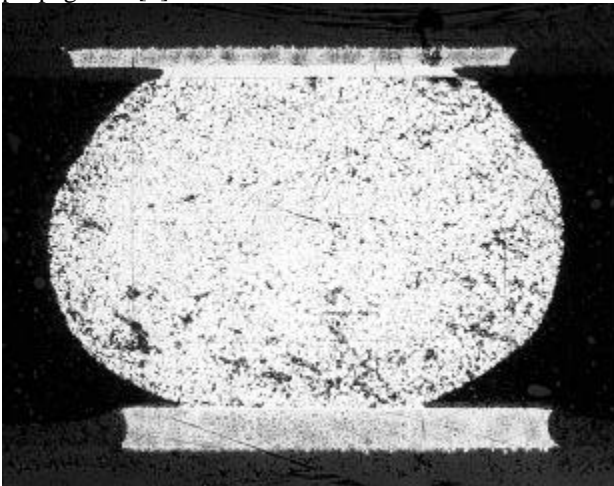
**Figure 9.** PBGA225 centre ball under die perimeter, uncleaned, after 6000 cycles with underfill 23 ppm/°C.



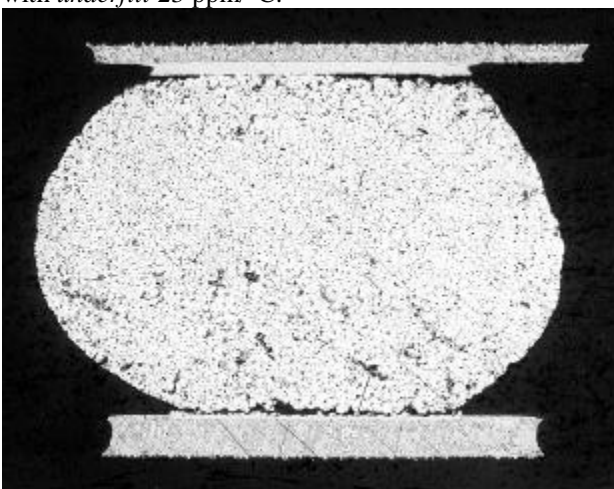
**Figure 10.** PBGA225 centre ball under die perimeter, uncleaned, after 6000 cycles with underfill  $45 \text{ ppm}/^{\circ}\text{C}$ .

Even worse appears the joint with the 45 ppm underfill, Figure 10, almost intuitively implying an expansion problem with this high CTE compared to that of solder (23 ppm/°C). A lower CTE, e.g. 10 ppm as in Figure 8, does not seem to cause any problems.

Figures 11 and 12 below show a cut through a ball in the centre of an outer row, with and without the 23 ppm underfill applied after cleaning. In this case, the temperature cycling included 250 cycles (from cycle number 500 to 750) with vibration applied during the high-temperature dwell. As with temperature cycling without vibration, the underfill seems to have inhibited crack propagation. Without the underfill, the damage looks worse than without vibration applied, with conspicuous cracks at both the ball/board and the ball/package interfaces. This is in agreement with other studies under identical conditions, showing that vibration has little effect on crack initiation but contributes to crack propagation [6].



**Figure 11.** PBGA225, cleaned, cut through outer row centre ball, after 6000 cycles incl. 250 with vibration and with *underfill* 23 ppm/°C.



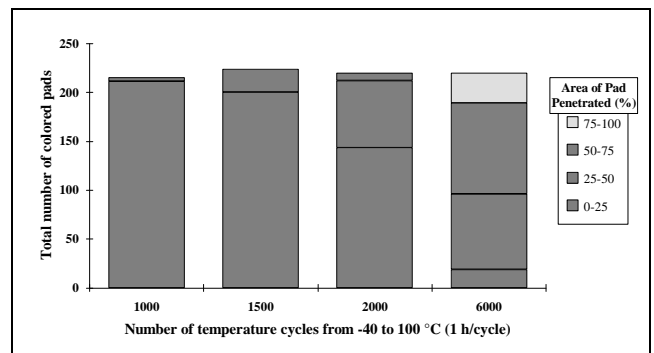
**Figure 12.** PBGA225, cleaned, cut through outer row

centre ball, after 6000 cycles incl. 250 with vibration but *without underfill*.

In most of the above samples exhibiting cracks, the crack occurrence seems concentrated to the ball/board interface. However, in higher magnification and in accordance with other studies [7], smaller cracks were also found near the package substrate. The soldermask protrusion into the joint was somewhat smaller at the ball/package interface, which may explain the relative occurrence of cracks at the different interfaces. The dye penetrant analysis described below, also confirmed the crack occurrence nearer to the package substrate.

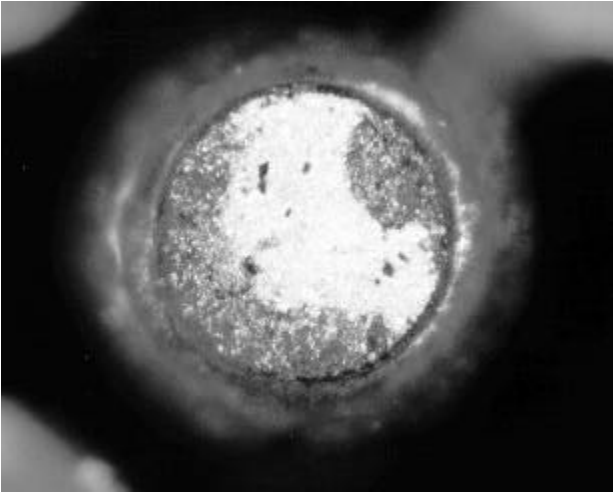
### Dye penetrant analysis

The dye penetrant analysis was performed on Test Board 1, with samples that had been subjected to 1000, 1500, 2000 and 6000 temperature cycles. Figure 13 below shows the number of balls of the BGA225 (Pos. D3) that was found with red dye coloured fracture sites upon removal of the device.



**Figure 13.** Dye penetrant analysis of the PBGA225, with SMD/SMD pad configuration, after temperature cycling.

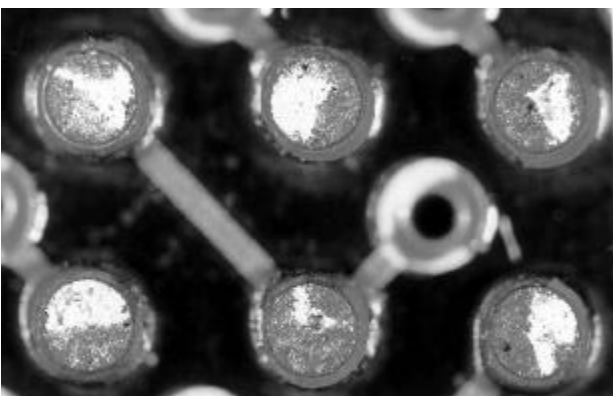
The bars are divided in portions corresponding to the area proportion that was decorated by the penetrant fluid. After 1000 thermal cycles, most of the 225 joints of the sample exhibited an area penetrated by the liquid below 25 %, and only a few balls more than 25 %. The relative occurrence of these smaller cracks decreased as the number of thermal cycles increased, causing larger cracks and a greater penetrated area of the balls. After 6000 cycles, more than 10 % of the joints were totally coloured, indicating that electrical contact was lost.



**Figure 14.** A PBGA225 joint fracture at the ball/package interface, decorated using dye penetrant after 6000 cycles from -40 to 100 °C. The SMD pad diameter is 0.6 mm.

The dye penetrant analysis also showed that the weakest spot in the joint was the ball/package interface, as virtually all joints were broken here when the devices were removed. Upon examination of the fracture sites, it was found that the cracks near the package almost all followed the package pad surface very smoothly and resulted in a near interfacial separation, see Figure 14 above.

Near the board pad, fractures were generally more coarse, with the solder protruding upwards in the centre of the joint. The relative occurrence of cracks near the board pad also increased with number of cycles, indicating that cracks had propagated faster closer to the board. It is also very interesting to note that adjacent joints exhibit very dissimilar fracture patterns. As seen in Figure 15, the coloured area of the fracture sites seem to have originated from different sides, indicating an anisotropic crack propagation behaviour.



**Figure 15.** PBGA225 joint fractures at the ball/package interface, decorated using dye penetrant after 6000 thermal cycles from -40 to 100 °C. Note lower left ball.

Figure 15 also explains how traditional cross-sectioning techniques may fail to reveal cracks, as e.g. if the sample is

cut parallel to a crack propagation front (as in the lower left ball).

## CONCLUSIONS

In the present study, a selection of test methods for assessing the reliability of BGA packages in automotive electronics has been made. BGA packages of different types as well as with different design features have been included.

Temperature cycling from -40 to 100 °C for 6000 cycles (1 hour per cycle) revealed the importance of the pad design for the 1.27 mm pitch PBGA361, a crucial factor which has to be considered both at package and board level. It was clearly demonstrated that the use of non-soldermask defined (NSMD) pads on both board and package was superior to any other combination of NSMD and SMD pads. Intermittent failures showed up after 2000 to 3000 thermal cycles from -40 to 100 °C using any other combination than the NSMD/NSMD and they all eventually failed after 6000 cycles, whereas the NSMD/NSMD combination only exhibited a ten percent failure rate at the end of the test, first appearing at 5500 cycles. Bearing in mind no underfill was used in this experiment, it might be possible to extend the life time of these packages, should it be required.

The location of the PBGA361 failures after 6000 thermal cycles was found, with remarkable consistency, in joints near the die perimeter. This effect is most likely enhanced by the fact that this PBGA361 package was built using a thin (0.2 mm) BT substrate which is then to a greater extent affected by the lower TCE (~3 ppm/°C) of the silicon die. Also, both the new PBGA256, designed for high reliability, as well as the QFP reference samples, all passed the 6000 hour temperature cycling test without any sign of failure. In this context, the electrical measurements were not clear or conclusive in determining the effect of an additional vibration exposure or, preliminary, of a humid cyclic exposure.

The cross-section analysis after 6000 temperature cycles from -40 to 100 °C, performed on the 1.5 mm pitch PBGA225 with SMD pads, showed extensive cracking, unless the joints were encapsulated using an underfill. An underfill coefficient of thermal expansion (CTE) lower or similar to that of solder (approximately 23 ppm/°C) seems to be required to achieve such an improvement. However, flux residues were found to interfere with the benign effect of the underfill, leaving a recommendation to thoroughly clean all boards prior to underfill application. The addition of an underfill to the joint interface also seems to have inhibited crack propagation otherwise encountered after

exposure to temperature cycling and vibration. The cross-sectioning of the 1.5 mm pitch PBGA225 did not show any significant difference between solder joints located directly under the die, or under the die or package corner. Moreover, it was demonstrated that a dye penetrant analysis can provide information complementary to that of traditional cross-sectioning. The advantage of the dye penetrant approach is not only that it may be less time and labour consuming, but also that it provides a two-dimensional overview of all fracture sites of the package joints at the same time. Under certain circumstances, cross-sectioning may fail to locate cracks that easily would show up using a dye penetrant technique.

#### ACKNOWLEDGEMENTS

This work has been financed by the Swedish National Board for Industrial and Technical Development (NUTEK) within the Electronic Packaging Research Program. The following participating companies are gratefully acknowledged for enthusiastic support and technical advice: Berifors Production AB, Combitech Electronics AB, IM - The Swedish Institute for Metals Research, Mikroelektronik Konsult AB, Saab Automobile AB, Scania CV AB, and Volvo Car Corp. The authors are greatly indebted to Andrew Mawer, Motorola, for invaluable assistance and fruitful discussions.

#### REFERENCES

- [1] R. J. Chronoes, D. Mallik, S. D. Prough, *Packaging alternatives for high lead count, fine pitch, surface mount technology*, IEEE Transactions on Components, Hybrids and Manufacturing Technology, June 1993
- [2] R. Rörgren, P. Carlsson, J. Liu, *A comparative study of ball grid array and ultra fine-pitch QFP technologies using solder paste stencil printing*, Proceedings Surface Mount International, San Jose, CA, September, 1995
- [3] P. Mescher, G. Phelan, *A practical comparison of surface mount assembly for ball grid array components*, Proceedings Surface Mount International, San Jose, CA, September, 1994
- [4] P. Carlsson, R. Rörgren, P.-E. Tegehall, *Tailoring of a Test Programme for Evaluating the Reliability of Plastic Ball Grid Array Packages in Automotive Environments*, Proceedings Semicon/Europe '96, Geneva, Switzerland, March, 1996
- [5] A. J. Mawer, S. C. Bolton, E. Mammo, *Plastic BGA solder joint reliability considerations*, Proceedings Surface Mount International, San Jose, CA, September, 1994

[6] M. Nylén, B. Hutchinson, U. Gustavsson, *Microstructural degradation of solder*, Proceedings Micro Materials '97, Berlin, Germany, April, 1997

[7] A. I. Attarwala, R. Stierman, *Failure mode analysis of a 540 pin plastic ball grid array*, Proceedings Surface Mount International, San Jose, CA, September, 1994

#### BIOGRAPHIES



Roger Rörgren received the Master's Degree in Engineering Physics in 1986 and the Licentiate Degree in Optoelectronics in 1990, both from Chalmers University of Technology in Göteborg. In 1991 he joined IVF to work in the Electronics Packaging group. His work has included reliability issues and manufacturability using both electrically conductive adhesives and solder paste technologies for fine-pitch applications. Currently he is working with production processes involving BGA and related topics.



Dr Per-Erik Tegehall received his PhD in Inorganic Chemistry from Chalmers University of Technology, Göteborg, in 1990. He has worked for two and a half year at Ericsson Radar Electronics AB with inorganic surface treatments and corrosion problems of electronics. Since 1990, he is project manager at IVF in projects concerning cleaning of electronics, conformal coatings and reliability testing of electronics.



Dr. Per Carlsson graduated in Physical Chemistry 1986 at Göteborg University. After one year as post Doc at Hokkaido University, he joined the Swedish Institute for Production Engineering Research in 1990. His present field of work includes packaging and production of electronics with special emphasis on reliability, such as

cleanliness, electrochemical migration, crack formation in solder joints, formation of solder balls, solderability, silicone contamination and evaluation of printed circuit boards. Material issues have played a central part in this work.