

BOARD LEVEL RELIABILITY TESTING OF HIGH-REL MICROPROCESSORS ASSOCIATED TO ROHS PACKAGING SOLUTIONS

Olivier Gaillard, Benoît Dervaux*

e2v semiconductors - Grenoble (France)

Avenue de Rochepleine - BP123 - 38521 St-Egrève Cedex, France

olivier.gaillard@e2v.com – benoit.dervaux@e2v.com

Abstract

With over twenty five years of experience in manufacturing high-reliability products, e2v semiconductors has reached worldwide renowned recognition for supplying microprocessors for severe environment applications. By achieving the requirements of today's highest level of reliability, e2v keeps offering products dedicated to serve High-Rel applications such as avionics, military and space. In 2008, e2v semiconductors has conducted a board level reliability study involving HITCE™ ceramic material associated to lead-free solder joints under harsh environmental conditions. This paper describes in details the reliability testing conditions and results for the HITCE Ceramic Ball Grid Array technology when soldered on FR4 printed circuit boards and submitted to temperature cycles between -40°C and +125°C.

Keywords: Board Level Reliability, Solder Joint Quality, Temperature Cycle Test, Polymer-core Solder Balls, Flip Chip, HITCE, CBGA.

1. INTRODUCTION

Since the advent of the RoHS directive, component manufacturers have been working on the conversion of their leaded components to equivalent lead-free solutions. This conversion has led to strong efforts from the whole microelectronics industry and particularly when high reliability was required. As a key actor of the military, aerospace and industrial markets, e2v has been actively working to qualify robust lead-free interconnect technologies and to keep manufacturing high reliability components while preserving environment.

In order to go further in this lead-free transition, e2v has been conducting a board level reliability study on its high-reliability microprocessors product family. This product family is based on Kyocera HITCE (High Thermal Coefficient of Expansion) Flip Chip Ceramic Ball Grid Array (FC-CBGA) packages with a 1.27mm solder sphere pitch. Three different BGA configurations have been tested comparing leaded to unleaded solutions.

This paper gives a precise description of the board level reliability study conducted by e2v, detailing step by step the different procedures leading to the final results. The purpose of this study, the test vehicles, the assembly conditions, the temperature cycle conditions, and the results of this study including Weibull plots are fully detailed. Mechanical analyses have been carried out using high power light microscopy (HPLM) on cross-sections, scanning electron microscopy (SEM) and energy dispersive X-Ray (EDX) equipments. Preliminary observations are presented in the result section of the document.

2. BOARD LEVEL RELIABILITY STUDY

Board level reliability, also known as second level reliability (SLR) is the reliability of solder joints usually presented in terms of solder joint life. The solder joint of interest is the connection between the mother board and the substrate.

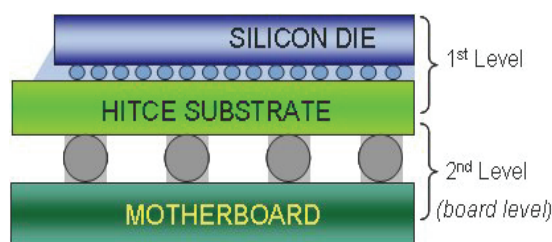


Fig 1: Schematics of Flip Chip CBGA

The Board Reliability is mainly affected by mismatch of thermal expansion coefficients and Young's modulus between components, substrates, solder itself and the materials to which it is bonded. TCE mismatch can generate cracks and failures in time.

2.1. Purpose

The purpose of this study is to determine the ability of e2v's HITCE Power Architecture™ microprocessors components to sustain extremely low and extremely high temperatures, as well as their ability to withstand cyclical exposures to these temperature extremes when surface mounted onto FR4 printed circuit boards. This study has been conducted in accordance with the IPC-9701 standard [1], which is one of the major standards [2,3] that define temperature cycle testing methods and conditions.

* IMAPS Member

Our target when starting this study was to withstand a minimum of 1000 cycles in the range of -40°C to +125°C and this for each tested configuration.

2.2. Test Vehicle

The HITCE 360-ball FC-CBGA package footprint as been retained as the ideal candidate to represent the HITCE Flip-Chip BGA family associated to a ball pitch of 1.27mm. A specific HITCE daisy-chain package has been designed, manufactured, surface mounted on board and subjected to temperature cycles. The daisy-chain has been designed to realize a single continuous monitoring for each package. A mechanical die has been flip-chip mounted onto the substrate.

Several Power Architecture microprocessor products from e2v (PC755, PC7410, PC7447A and PC7448) are sharing this common 360-ball package footprint in HITCE ceramic. This material is a low temperature co-fired ceramic (LTCC) material patented by Kyocera. HITCE is an exceptional material with low resistance metallization (copper conductors) and a low dielectric constant making it ideal for high speed applications. Construction is based on a laminate design associated to stacked via configuration allowing multiple layers, extreme design flexibility and high routing density.

HITCE ceramic material has been developed to have a coefficient of thermal expansion very close to that of the printed circuit boards (PCBs), in order to achieve high reliability at board assembly level [4]. The plating on the substrate lands is electroless nickel and immersion gold. HITCE ceramic material can be easily identified by its green color.

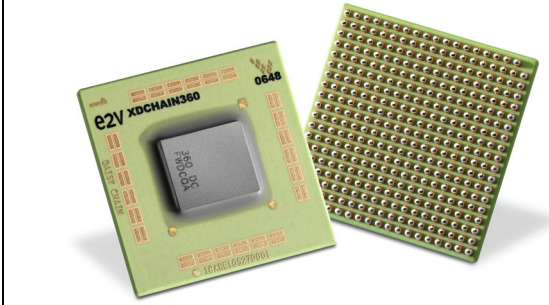
Table 1: Properties of HITCE™ material

	CERAMIC		ORGANIC
	AL ₂ O ₃	HITCE	FR4
THERMAL			
CTE (ppm/°C) (Room Temp ~ 400°C)	7.1	12.3	12~18
Thermal Conductivity (W/m/°K)	14	2.0	0.2
ELECTRICAL			
Dielectric Constant (1MHz)	9.8	5.3	4.3
Dielectric Constant (10GHz)	-	5.2	4.2
MECHANICAL			
Flexural Strength (MPa)	400	170	430
Young's Modulus of Elasticity (GPa)	310	74	-
CONDUCTOR MATERIAL	W, Mo	Cu	Cu

The default condition of the IPC-9701 mandates the use of a daisy-chain with a bumped mechanical die to assure the full characterization of the interconnection during temperature cycling. Actually, all the components of the interconnection do participate to board reliability.

A mechanical die has thus been placed on the daisy-chain making it the exact replica of a fully functional product.

Table 2: FC-CBGA 360 HITCE Daisy Chain Characteristics

	
Function	Daisy Chain
Body Size	25x25mm
Substrate Thickness	1.2mm
Ball Count	360
Ball Pitch	1.27mm
Die Dimensions (mm)	11 x 9 x 0.750

The HITCE ceramic patented by Kyocera has an alumina coating at the land side. This very thin alumina layer does prevent copper lands from delaminating while defining the BGA pads opening:

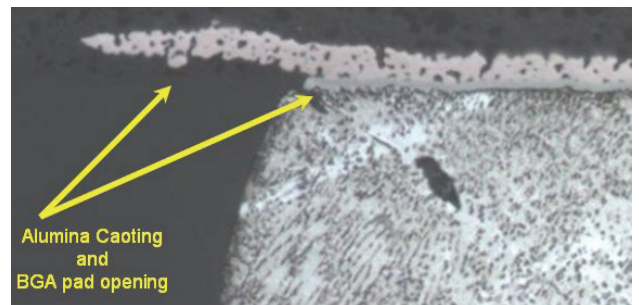


Fig 2: HPLM photograph of alumina coating

2.3. Balling Configurations

Three different configurations consisting in three different solder sphere solutions have been tested:

- HITCE Daisy-Chain + High-Lead Balls
- HITCE Daisy-Chain + SAC 305 Balls
- HITCE Daisy-Chain + Polymer-core Balls

These various configurations are detailed in §2.4. As per IPC-9701 recommendation, 32 daisy-chains have been tested per configuration. Extra daisy-chains have been placed in the chamber for mechanical analysis purposes.

2.4. Balling solutions

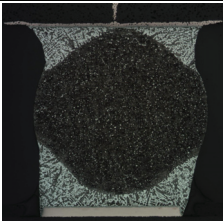
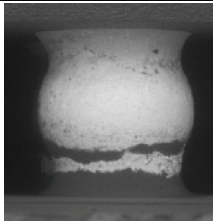
For years, high-lead spheres have been associated to HITCE material to improve the board level reliability of e2v's high-rel microprocessors. This leaded solution is the most widely used on current ceramic packages, offering a fixed stand-off and a better reliability than eutectic solder balls. To carry on developing extended reliability products in an environmental-friendly world, e2v has been working on preparing its lead-free product deployment since the industry consortium first announcements. Two lead-free solutions have been

identified and qualified, and are now available in the e2v's portfolio. The three available balling solutions retained by e2v are detailed hereafter.

2.4.1 High-Lead Solution: Pb90Sn10 Spheres

The typical high-lead solder ball composition is a lead/tin alloy with 90 percent lead and 10 percent tin. Those solder spheres, which have a high melting temperature, prevent standoff collapse at surface mounting stage and contribute to board reliability improvement.

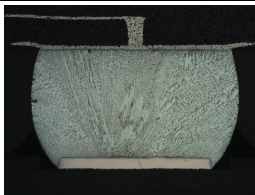
Table 3: High-Lead Balls at T0 cycle

Composition	Pb90Sn10		
Diameter	890 μ m		
Stand-off	950 μ m (Typical)		
BGA Pitch	1.27mm		
			
HPLM	SEM		
Ball shear – 10 samples – 10 balls sheared per sample			
Configuration	Specification	Measurement	Cpk
Pb90Sn10	1kg	1.65kg	1.42

2.4.2 First Lead-Free Solution: SAC 305 Balls

The first lead-free solder ball solution qualified by e2v is based on a tin, silver and copper lead-free solder alloy.

Table 4: SAC 305 Balls at T0 cycle

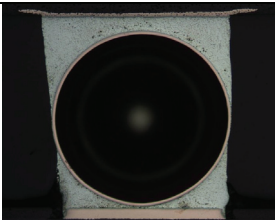
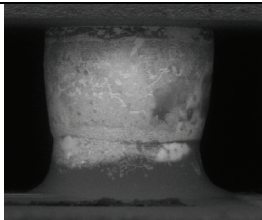
Composition	SAC 305 (Sn/Ag3.0%/Cu0.5%)		
Diameter	760 um		
Stand-off	480 um (Typical)		
BGA Pitch	1.27mm		
			
HPLM	SEM		
Ball shear – 10 samples – 10 balls sheared per sample			
Configuration	Specification	Measurement	Cpk
SAC 305	1kg	2.70kg	1.50

2.4.3 Second Lead-Free Solution: Polymer-core Balls

The second lead-free solder ball solution qualified by e2v is of particular interest since it combines lead-free material with the advantages of the controlled standoff BGA configuration [6]. This solution utilizes a novel interconnection based on a polymer-core ball. The polymer-core balls brand-named „Micropearl SOL” have been developed and optimized by the Sekisui Chemical Company. Polymer-core balls consist of a polymer-core ball covered with a thin conductive copper layer and a tin silver coating (finishing). Polymer-core balls are made of a compliant plastic core with a Young's Modulus smaller than that of metal. This particularity helps relaxing

thermal stress during temperature excursions and polymer-core balls do definitely act as a stress buffer. Polymer-core balls are available in a wide range of diameters and can be implemented without major process change. It has thus been possible to get polymer-core balls having the same appearance as high-lead balls, and manufacture equivalent stand-off BGAs.

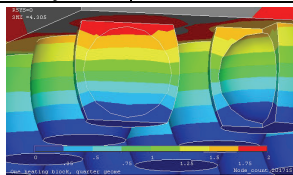
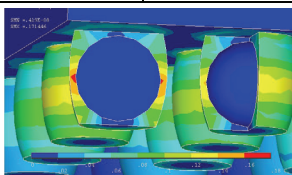
Table 5: Polymer-core Balls at T0 cycle

Composition		Divinyl Benzene Core Copper Layer Tin 96.5% Silver 3.5% Overplating	
Diameter		890 μm	
	Polymer core diameter 790 μm Copper Layer Thickness 20 μm Tin Silver Layer Thickness 30 μm		
Stand-off		950 μm (Typical)	
BGA Pitch		1.27mm	
			
HPLM		SEM	
Ball shear – 10 samples – 10 balls sheared per sample			
Configuration	Specification	Measurement	Cpk
Polymer-core	1kg	2.44kg	1.75

Electrical and thermal comparisons of the three balling solutions have been made. Electrical performances of the polymer-core balls are quite equivalent to conventional balling solutions. The thermal analysis performed using the ANSYS 9.0 finite element software have shown that the use of polymer-core balls leads to thermal resistance from die junction to bottom of balls slightly higher than conventional balling solutions and equivalent to column interposers. The thin copper layer around polymer-core balls helps the thermal flux to flow around the polymer ball of low thermal conductivity. A comparison of Sn63Pb37 balls, SAC 305 balls, Solder Column Interposers (SCI – Pb90Sn10) and Polymer Balls has been made (Assumptions: no convection – no radiation):

Table 6: Thermal Simulations Results

Balling Solution	Stand-Off	Land Diameter	Rth Junction to bottom of balls
Sn63Pb37	650 μ m	650 μ m	3.92°C/Watt
Pb90Sn10	950 μ m	860 μ m	3.87°C/Watt
SAC 305	480 μ m	860 μ m	3.40°C/Watt
SCI	2,1 mm	860 μ m	4.55°C/Watt
Polymer	950 μ m	860 μ m	4.44°C/Watt

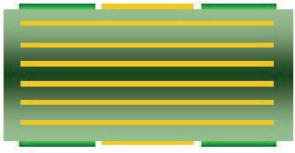
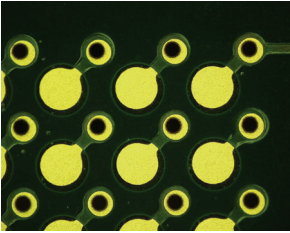



Isothermal Lines

Thermal Flux

2.5. Printed Circuit Board

Table 7: PCB Specification

Material Reference	ISOLA IS420
Glass Transition Temperature (Tg)	170°C
Coefficient of Thermal Expansion (CTE)	Fill direction 15/12 ppm/°K Warp direction 12/5 ppm/°K Vertical 40/200 ppm/°K
Layer Count	8
PCB Class	6
Thickness	1.60mm (Nominal)
 ----- Foil ----- 1X1080 1X2116 ----- 0.2 8/8 ----- 2X2116 ----- 0.2 8/8 ----- 2X2116 ----- 0.2 8/8 ----- 1X2116 1X1080 ----- Foil -----	
 NSMD Configuration Non Solder Mask Defined	

The success of a board reliability study is highly dependant on the selected PCB technology. e2v has been carefully specifying the PCBs, in order to make sure that potential temperature-cycling failures would not be

induced by the PCB technology. For this study we have used high reliability PCBs commonly used by avionics manufacturers. The glass transition temperature (Tg) of the PCB material is 170°C. The maximum temperature for thermal cycling was 125°C, which is below the glass transition temperature of the PCB material. Indeed, the move to a lead-free solder has led to higher reflow temperatures and, as a consequence, the PCB and all the other components must withstand higher process temperatures. With eutectic solders, boards did already exceed their Tg at reflow stage. The need for a higher Tg was directed by the temperature differential between Tg and lead-free reflow peak temperature similar to the one between lower Tg and eutectic reflow peak temperature.

2.6. Assembly Conditions

The two assemblies have been handled by a major assembly contractor and performed using a class 3 qualified assembly line (as per IPC-A-610 standard). Laser cut stencils with 850um aperture and 200um thickness have been used to screen-print the solder paste on PCBs. The solder paste volume was of 7000 cubic mils per land for both eutectic and lead-free assemblies.

The solder pastes and the corresponding reflow profiles qualified by the assembly subcontractor have been applied. The reflow has been performed using a 10-zone convection oven working under nitrogen atmosphere to emphasize wettability. The reflow profiles have been optimized with a dedicated board:

- Peak temp for the leaded reflow profile: 219°C
- Peak temp for the lead-free reflow profile: 239°C

In order to reduce the risk of assembly issue, a non aggressive baking of the PCBs has been performed prior to assembly. This procedure aimed at removing volatiles and remaining moisture has been performed in a dedicated oven (Baking conditions: 16 hours @110°C).

3. TEST VEHICLE SUMMARY

Table 8: Test Vehicle Parameters – Assembly Conditions

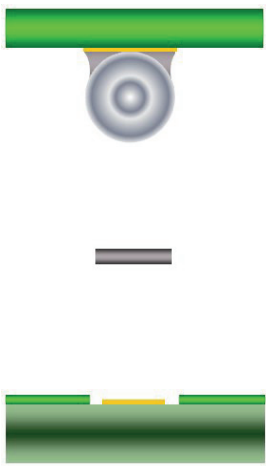
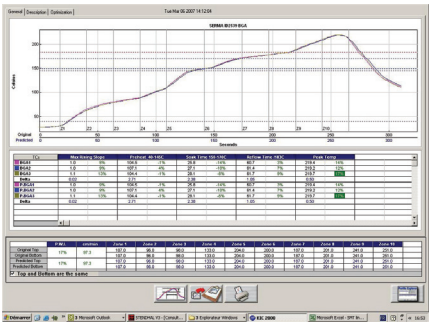
		Pb90Sn10 Balls	SAC 305 Balls	Polymer Balls
	Substrate material	HITCE™ ceramics	HITCE™ ceramics	HITCE™ ceramics
	Solder paste at substrate	Sn63Pb37	SAC 305	SAC 305
	Solder ball diameter (um)	890	760	890
	Solder paste at PCB	Sn63Pb37 INDIUM SMQ92H	SAC 305 ALPHA OM338-T	SAC 305 ALPHA OM338-T
	Solder paste volume (mils ³)	7000 +/-15%	7000 +/-15%	7000 +/-15%
	PCB land diameter (um)	750	750	750
	Solder mask opening diameter (um)	850	850	850

Table 9: Assembly Conditions – Reflow profile

Stencil aperture (um)	850
Stencil thickness (um)	200
Solder paste thickness (um)	200 (typical)
Convection oven	BTU PARAGON 150 / 10 Zones N2 controlled atmosphere – Conveyor speed 103 cm/mn
 Eutectic reflow profile - Peak Temp: 219°C	 Lead-free reflow profile - Peak Temp: 239°C

4. TEMPERATURE CYCLES

4.1. Temperature Cycling Equipment

The preferred recommendation of the IPC-9701 is to use a single zone chamber in which boards are vertically oriented and are parallel to the air flow. Another recommendation is to have a ramp rate below or equal to 20°C/minute to avoid thermal shock. Those recommendations have been fulfilled by using a CLIMAT Excal 7728HE equipment.

Table 10: Temperature Cycles Equipment Spec.

 CLIMAT Excal 7728HE	Chamber Capability Temperature range: -90°C / +180°C Max Ramp rate 20°C per min
	9 Boards 96 Components Continuous Thermal and Electrical Monitoring

The above picture shows the 9 boards vertically oriented in the chamber and parallel to the air flow coming from the back of the chamber. Extra boards with mechanical samples dedicated to mechanical analyses have been placed in the chamber.

4.2. Continuous Temperature Monitoring

Table 11: Thermal Monitoring Equipments Spec.

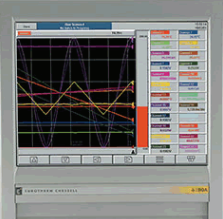
 Eurotherm Chessel 6100A	Equipment Capability High and Low Temperature Monitoring 12 Universal Inputs Secure Digital Media
--	--

In this study, 12 thermal probes have been used (4 boards with 3 thermal probes on each: center and perimeter) for board temperature measurements. The 12 temperatures have been monitored using a Eurotherm Chessel 6100A Equipment. One reading has been performed every 30 seconds.

4.3. Continuous Daisy Chain Electrical Monitoring

The IPC-9701 mandates to continuously monitor the daisy-chain resistances of the tested components. This is the most stringent recommendation of the IPC-9701, but also the only way to capture the failure point. This recommendation has been filled using two Eurotherm Chessel 6180A (2x48 channels) data logger equipments. One reading of each component resistance has been performed every 30 seconds.

Table 12: Electrical Monitoring Equipments Spec.

 Eurotherm Chessel 6180A	Equipment Capability High and Low Temperature Electrical Monitoring 48 Universal Inputs Secure Digital Media
---	---

4.4. Failure Criteria

The IPC-9701 defines a failure as a maximum of 20% nominal resistance increase within a maximum of five consecutive reading scans. It is particularly difficult to identify this 20% increase considering that the resistance is a function of temperature and will thus vary according to temperature fluctuations.

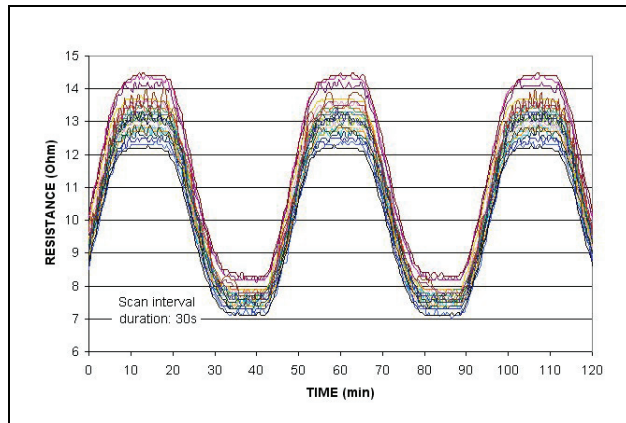


Fig 3: Continuous Resistance Monitoring

This particularity has led to spending a lot of time on post processing to control data and identify failures. Fortunately, the components did exhibit very constant behavior in time, and failure could be identified without any doubt.

4.5. Temperature Cycling Profile

A temperature cycle profile has been defined according to the IPC-9701. Both upper and lower dwell times have been set to 10 minutes. A ramp rate of 14°C/minute has been achieved leading to a total cycle time duration of 46 minutes. The average of thermocouples on PCBs has been used for the ramp rates calculation.

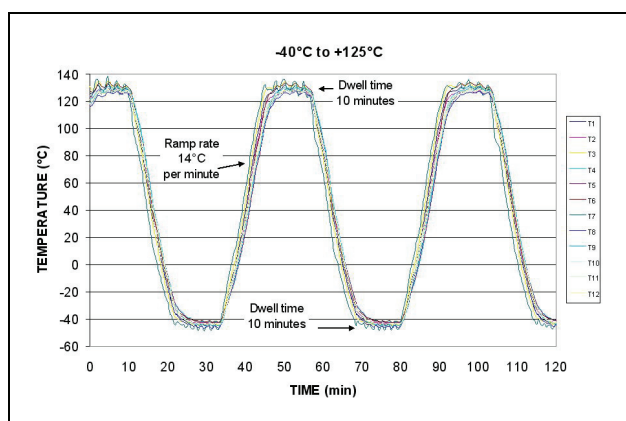


Fig 4: Temperature Cycling Profile

5. RESULTS

5.1. Weibull Probability Analysis

The main target when starting this study was to evaluate high-lead and lead-free solder joint reliability and prove that they could withstand at least 1000 temperature

cycles in the range of -40°C to +125°C without exhibiting any failure. All the three configurations did surpass this goal. However, polymer balls did behave much better than both high-lead and SAC 305 balls leading us to review our initial qualification plan and extend the total number of cycles from 3000 to 6000. All the accumulated failures have been plotted in Weibull format.

5.1.1 High-Lead Balls Test Results

The first high-lead ball failure occurred after 1896 cycles and the last one after 2928 cycles. It should be kept in mind that high-lead balls have been used for years and shall be considered as a reference in this study [5]. The high-lead solder spheres do not melt during reflow. The two solder joints depend solely on the bonding of eutectic Sn63Pb37 between the substrate lands and the high-lead balls, and between the PCB and the high-lead balls.

5.1.2 SAC 305 Balls Test Results

The first SAC 305 ball failure occurred after 1896 cycles (same cycle as first high-lead ball failure) and the last one after 5298 cycles. It is to be noticed that the second failure occurred after 2724 cycles. This gap of 828 cycles between the first and the second failure led us to investigate the possibility of an early failure. Unfortunately, it has not been possible to conclude any results on this particular point after failure analysis. Thus, the first failure occurrence has been taken into account to build the Weibull plot.

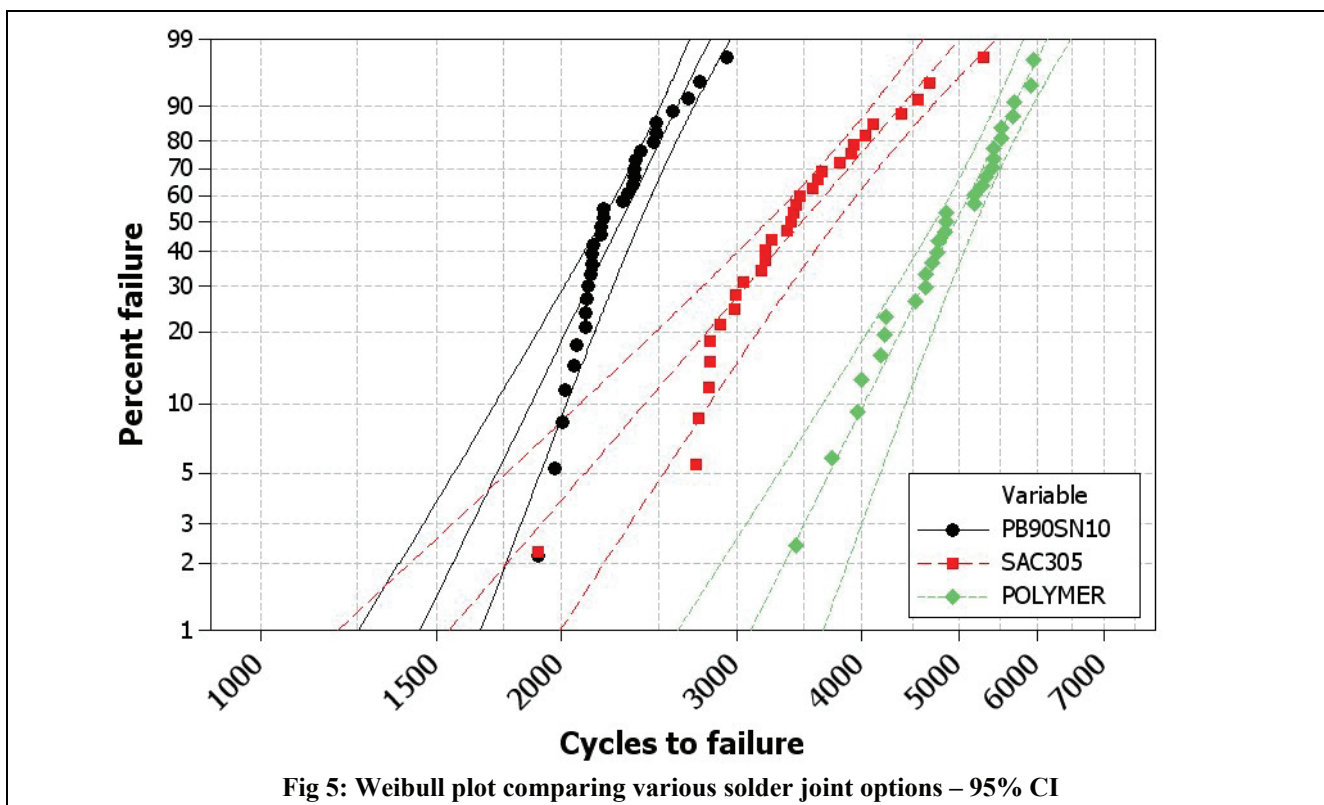
5.1.3 Polymer-core Balls Test Results

The first polymer-core ball failure occurred after 3433 cycles. At that time, all high-lead balled daisy-chains had already failed for more than 500 cycles. The last polymer-core ball failure has been observed after 5941 cycles. After 6000 cycles, 3 daisy-chains balled with polymer-core balls were still working. We can thus conclude that polymer-core balls demonstrate an excellent reliability compared to conventional high-lead solder balls.

The polymer-core solder balls are definitely a good alternative to solid solder balls such as high-lead balls to achieve good board level reliability.

The use of polymer-core solder-balls does not require any specific assembly improvement at both component manufacturing and surface mounting stages. The low weight of the polymer-core balls does even positively contribute to the self-centering behavior during ball attachment process.

5.1.4 Weibull Probability Plot



5.2. Mechanical Analysis

A total of 21 mechanical samples have been placed in the chamber and have been submitted to the temperature cycles as well but without electrical monitoring. The samples have been taken out of the chamber after 500, 1000, 1500, 2000, 2500 and 3000 cycles. Failure analysis has been performed afterwards. T0 samples have also been retained to control the quality of surface mounting assembly. The comparison of SEM external views and HPLM cross-section views have permitted to conclude that no cracking was present at T0 (See cross-section views in subsection 2.4). High power light microscopy analysis shows good solder wetting and apparently good solder joint formation throughout the process. Failure analyses performed at the end of the temperature cycle tests show very classical failure modes for the three evaluated configurations. Crack initiation begins in the solder at the interface between package and balls, and the interface between balls and PCB. Both regions are submitted to high stress.

All the analyses have been performed on outer rows of solder attachments. Those regions are known to be of particular high failure risk.

5.2.1 High-Lead Balls Analysis

After 3000 temperature cycles, the comparison of external and cross-section views of the high-lead solder joints shows that the solder joint has cracked along the

entire length of the substrate interface and has become misplaced with respect to its pad.

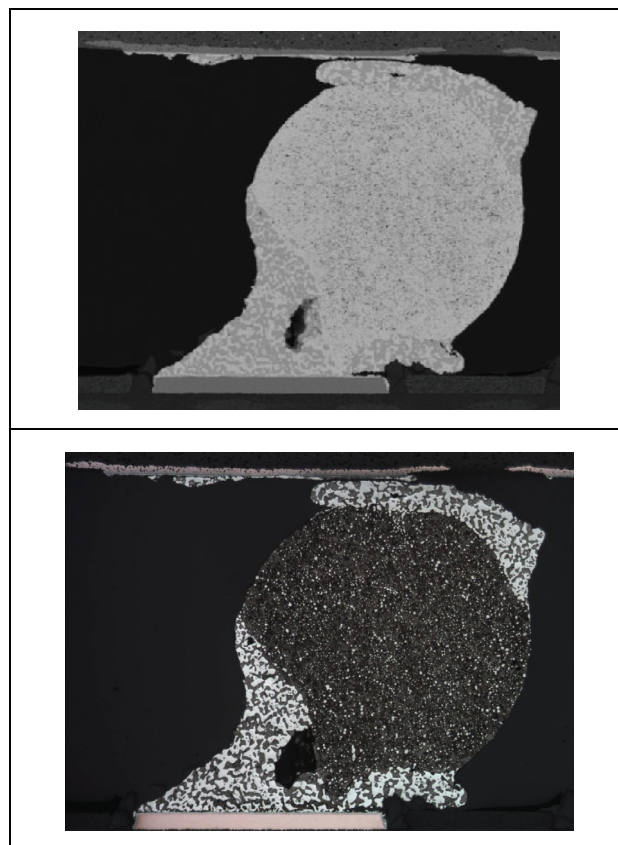


Fig 6: Pb90Sn10 Balls SEM and HPLM views

SEM inspection has shown that intermetallics (IMC) layers are thicker than the IMC's in their original condition.

5.2.2 SAC 305 Balls Analysis

After 6000 temperature cycles, the comparison between external and cross-section views of the SAC 305 solder joints shows that severe cracking is present through the solder adjacent to the substrate interface and partial cracking is present through the solder adjacent to the PCB interface.

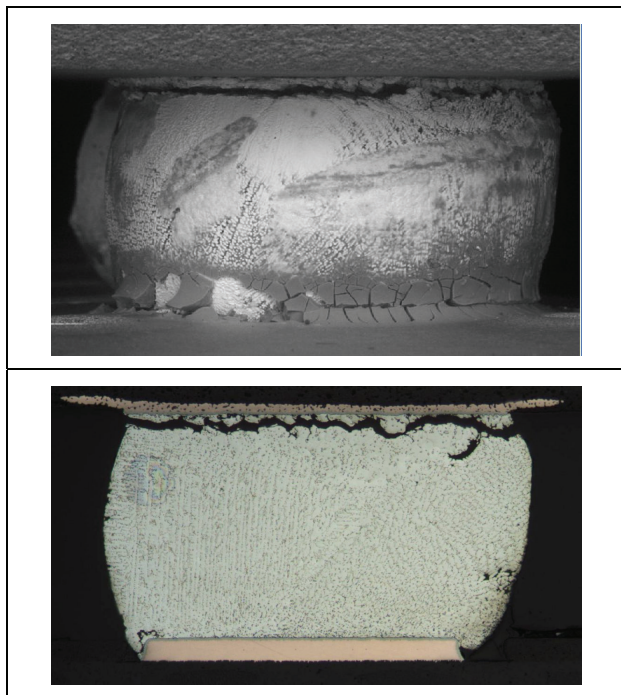


Fig 7: SAC 305 Balls SEM and HPLM views

5.2.3 Polymer-core Balls Analysis

After 6000 temperature cycles, the polymer core looks particularly unaffected by the test. The polymer core is not damaged and do still exhibit a perfectly round shape. The stand-off of the interconnection is very close to the initial one.

The path of the crack through the top of the solder ball as well as intermetallic compounds dispersed through the joint and at the interface between solder and substrate surfaces can be clearly seen in the cross-section view.

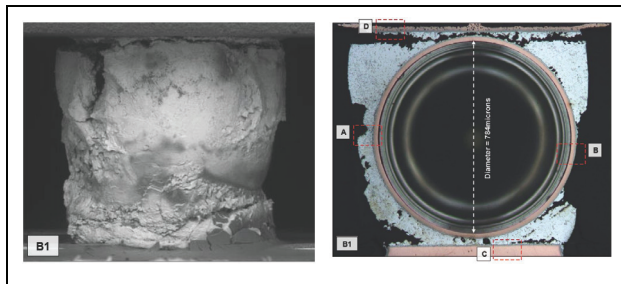


Fig 8: Polymer-core Balls SEM and HPLM views

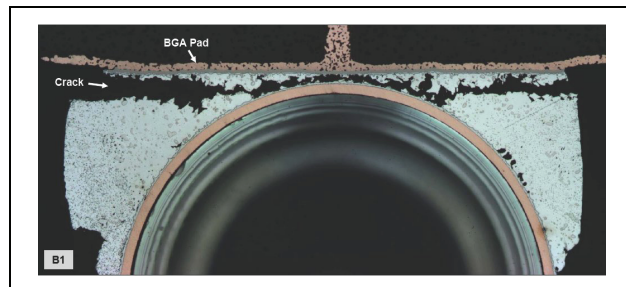


Fig 9: Polymer-core Balls HPLM Cross-Section

We can conclude that extensive solder deformation and fracturing occurred within the bulk solder, and that it only very seldomly reaches intermetallics interfaces. No abnormal weakness was found.

6. CONCLUSIONS

A board reliability study in the range of -40°C to $+125^{\circ}\text{C}$ has been conducted by e2v on the HITCE Flip chip BGA family with a pitch of 1.27mm. Three different balling solutions have been tested. All those configurations can be easily assembled onto PCB using classical ways of mounting.

High-Lead balls and SAC 305 balls do exhibit very good board reliability with a first nominal failure after 1500 Cycles. Polymer-core balls demonstrate excellent board reliability, twice better than high-lead solder balls, with a nominal break point at 3000 Cycles.

The next step for e2v will be to perform the same study for its HITCE PowerPC family associated to a ball pitch of 1mm.

References

- [1] IPC-9701 "Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments", January 2002.
- [2] JEDEC JESD22-A104C "Temperature Cycling", May 2005.
- [3] MIL-STD-883G METHOD 1010.8 "Temperature Cycling", June 2004.
- [4] Kazutaka Maeda and others, "The Application of HITCE Ceramic Material for LGA-Type Chip Scale Package" Proceeding of the 2000 Electronic Components and Technology Conference.
- [5] Rocky Shih and others, "Reliability of HITCE Ceramic Ball Grid Array Package", Proceeding of IMAPS 2005, Philadelphia.

Journal Article

- [6] Werner Engelmaier, "Achieving solder joint reliability in a lead-free world", part1 & part2, Global SMT & Packaging, August 2007.

-----00000-----