As originally published in the IPC APEX EXPO Conference Proceedings.

Control of the Underfill of Surface Mount Assemblies by Non-Destructive Techniques

Julien Perraud
Shaïma Enouz-Vedrenne, Jean-Claude Clement
Thales Research and Technology
Palaiseau, France

Arnaud Grivon
Thales Global Services
Meudon La Forêt, France.

Abstract
Underfilling is a long-standing process issued from the micro-electronics that can enhance the robustness and the reliability of first or second-level interconnects for a variety of electronic applications. Its usage is currently spreading across the industry fueled by the decreasing reliability margins induced by the miniaturization and interconnect pitch reduction.

While material and processing aspects keep pace with the fast technology evolutions, the control of the quality and the integrity of under filled assemblies remains challenging in some cases, especially when considering non-destructive inspection techniques and board-level underfilling. In particular, Scanning Acoustic Microscopy (SAM) which is routinely used for the control of under filled flip-chips turns out to be almost ineffective for usual BGA devices due to the presence of the component PCB substrate.

This paper will address the control of surface mount under filled assemblies, focusing on applicable inspection techniques and possible options to overcome their limitations.

Introduction
The vast majority of electronic applications and devices are following a pervasive trend towards increased miniaturization and system integration. Resulting in always denser PCBA (Printed Circuit Board Assembly) with finer pitch components, tighter component spacings and higher solder joint densities. Current high-end designs typically feature closely spaced BGA components with pitches down to 0.4mm which raises growing reliability concerns and drives the need of ruggedization, especially for harsh environment applications.

For BGA assemblies, dispensing a resin under the BGA (underfilling) is an approach that is rapidly gaining momentum for varied applications to enhance the mechanical or thermo-mechanical reliability at the board level. The underfilling technique is not new: it was originally introduced some decades ago to improve the reliability of flip-chips on ceramic or organic substrates by reducing stress on the chip-to-substrate bump interconnects due to the CTE mismatch between the laminate and the silicon die. Its usage then became broader with the growth of FC-PBGA devices and extended to several other volume applications. As an example, most BGA/LGA modules and PoP BGA assemblies in smartphones are underfilled to improve the drop shock resistance. The 3D packaging and heterogeneous integration trends also rely on SiP (System-in-Package) modules with several dies or WLP (Wafer Level Packages) that need to be underfilled.

While several material and process variants such as capillary underfills, reflow encapsulants or edge/corner bonding can accommodate the various ruggedization needs, limited options are available for the control of underfilled assemblies. This concern is outlined in the reference IPC J-STD-030A industry standard that addresses board-level underfills.

Process validation and control however remain key as the integrity of the resin deposits has a direct incidence on the underfill efficiency. Ruggedization performances or reliability can be altered in case of poor adhesion or voids within the underfill resin.

The present paper will review the capabilities and limitations of several inspection techniques that can be used at the qualification or production stages to control the quality and integrity of underfilled assemblies. Considered inspection methods are visual, X-ray and SAM, focused on BGA component assemblies.

Visual inspection

BGA underfilling is a post-assembly process that consists of dispensing a low viscosity fluid resin under the BGA component. The underfill resin is deposited close to the BGA edges, flows by capillary action and fills the space between the BGA and the PCB, thus encapsulating the BGA solder joints. The application process can be achieved by different methods and dispense patterns. It is typically done by needle dispensing or non-contact jetting in several passes with board pre-heating to enhance the resin flow. The dispensing operation is followed by a thermal curing step. After processing, the underfilled BGA has resin fillets around the four sides and under the whole BGA area. An overview of an underfilled BGA device is given in the picture below.

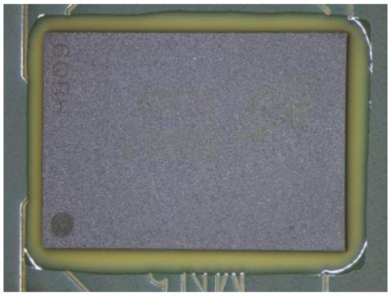


Figure 1 - Global view of an underfilled BGA

As it can be understood from the above picture, the visual inspection of an underfilled BGA is very limited and only permits to control the resin fillets and overflow on surrounding components. Possible defects under the BGA device such as underfill voids or cracks cannot be checked by this inspection method. Destructive horizontal cross-sectioning is needed to expose and control the array of BGA solder balls encapsulated by the underfill material.

To overcome these limitations, X-ray and SAM non-destructive techniques have been studied in an effort to optimize them for the control of underfilled BGA assemblies.

X-ray

Amongst others techniques, imaging using X-ray sources is a non-destructive technique for controlling the quality and integrity of assemblies. Conventional X-ray absorption imaging consists of illuminating the investigated object with X-rays and in measuring the two-dimensional profile of the intensity transmitted by the object with a detector placed close behind the object. At a given X-ray photon energy, the absorption depends on both the density and the elemental composition of the features within the object. Features with high density differences produce in general high X-ray absorption contrast. Therefore, such a technique is nowadays widely used for many industrial processes related to the control and failure analysis of surface mount assemblies and electronic packaging [1]. Beside, another advantage of such a technique is its possibility to perform X-ray Computed Tomography (CT) which consists of putting between the X-ray source and the detector, a rotating stage that rotates the sample through 360° in equally spaced angles. Based on a collection of 2D X-ray images captured around a single axis of rotation, a computed tomography (CT) algorithm reconstructs an accurate 3D volume dataset that represents the internal structure of the sample [2]. Viewed as slices in any orientation or as a 3D scene, the inner part is visualized and permits to explore all the details of the sample. In a number of cases, it is possible to draw a failure conclusion based on 3D X-ray CT without the need of destructive, physical cross sectioning [3,4]. This might be a real advantage for the analysis of the underfill on PCBA which is between the component and the board.

Despite recent advances in X-ray imaging systems and digital image processing, absorption contrast to distinguish different types of elements of similar densities remains challenging. For many materials at high X-ray energies, the X-ray attenuation length can be very long, resulting in little X-ray absorption and therefore poor imaging contrast. In the case of underfill, the resin has a very low density compared to boards and components. Moreover, voids in the underfill do not have enough density variation for an easy detection.

Another limit of X-ray CT is the so called beam hardening artifact which is caused by the polychromatic nature of the X-ray source and the energy dependent characteristics of the object. The presence of a dense object (e.g. metal, solder) within the field of view of a CT can create severe artifacts in the reconstructed images in particular dark shading between solder balls in a BGA component as illustrated in Figures 2 and 3.

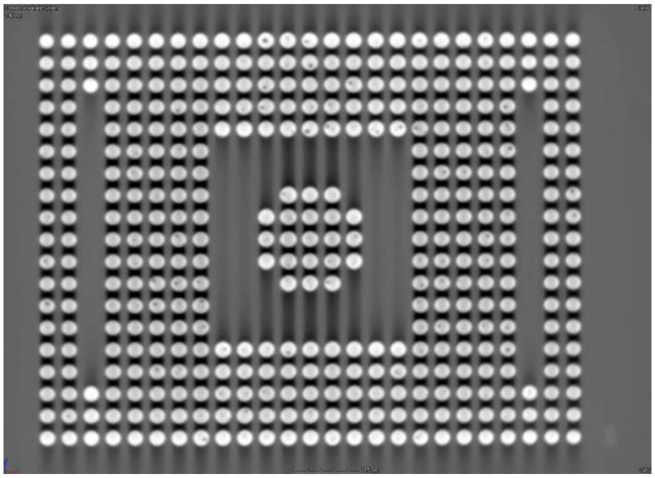


Figure 2 - X-ray virtual cross-section view of a BGA component

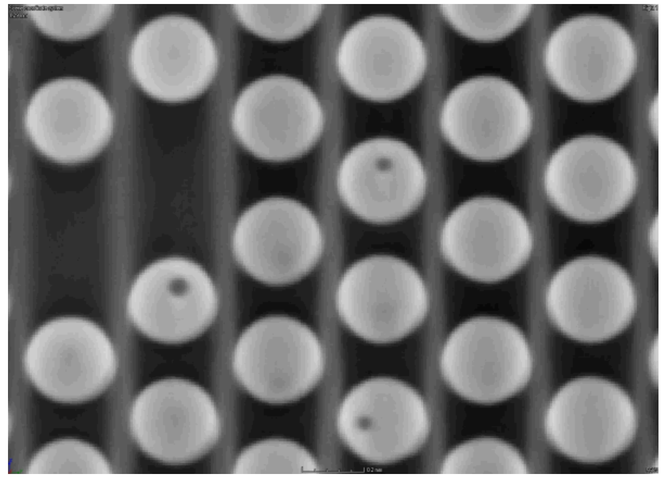


Figure 3 - Dark streaks connecting the dense objects in the image are visible.

In this paper, the X-ray CT has been performed with production equipment that uses a microfocus X-ray source with variable acceleration voltage up to 160kV. High-resolution imaging is achieved using a production flat panel detector of 1024 x1024 pixels matrix with a pixel pitch of 127µm². With such equipment it is possible to produce in less than 30 minutes, a 3D volume with a voxel resolution of up to 6µm with a field of view of roughly 6 x 6 mm². The observation of voids within the underfill in BGA components was not possible due to the intrinsic resolution of the equipment and artifacts that occurs during the acquisition.

Scanning Acoustic Microscopy

The acoustic analysis relies on ultrasound waves to detect defects linked to the presence of air such as porosity, voids, cracks or delaminations. It is routinely used to evaluate the package integrity at different interfaces of electronic components. Two main modes are commonly used for components analysis: C-scan and Through-scan modes.

In C-scan mode, a transducer produces an acoustic wave that propagates through the DI water (coupling element) and is reflected by all the interfaces. The reflected wave is captured by the same transducer that works alternatively in emission and reception. The image is obtained by scanning the entire sample line by line. In Through scan mode, a second transducer is placed below the sample and computes the acoustic waves transmitted through the samples.

For many years, SAM has been proven as an efficient method for the analysis of bumps, bump connection and underfills of flip chip components. Defects such as delaminations and voids are readily detected by this technique. The morphology and the depth location of the defects are also useful information that can be obtained through the use of SAM [5].

The final achievable resolution however is dependent on various parameters: some relate to the transducer design (acoustic frequency, aperture) and others to the sample under investigation (acoustic attenuation of the material and depth) [6]. To increase the resolution, the acoustic frequency has to be increased resulting in a decrease of the penetration depth. This becomes increasingly needed for flip-chips when the bump diameter and the pitch reduce.

SAM could easily be applied on underfilled WLP components on the board. It is possible to control voids, lack of underfill or delaminations with high accuracy. The main difference will be the larger size of the balls compared to bumps and by the way the thickness of the underfill. Thus, to control all the underfill thickness and interfaces, one way is to lower the frequency for increasing the penetration depth.

For the BGA/LGA component, the presence of multiple layers in the laminate substrate and multiple interfaces make the underfill characterization by direct C-scan mode inappropriate. Indeed, BGA/LGA packages include a PCB reinforced substrate made of numerous glass fibers layers that diffract the acoustic waves in every direction. This induces a rapid attenuation of the acoustic waves which prevents from getting any clear echo by direct reflection.

SAM in through scan mode could be one possible solution, especially taking advantage of the recent progresses in transducer design like the use of directly focused transducers without lenses. Such transducers enable the scan of a full-size PCB assembly and the control of the resin of underfilled BGA/LGA assemblies [7]. However, only a low resolution can be achieved in such mode and only large delaminations with X-Y sizes in the range of 1mm can be detected.

On the illustration below, underfilled assemblies from a smartphone mainboard were analyzed in through scan mode. Large voids in the resin under an underfilled LGA component could be detected using this technique and were confirmed by a destructive cross-section.

SAM analysis was performed using a fast scanning production acoustic microscope equipped with several transducers covering a frequency range from 20 MHz up to 150 MHz. The focal length of the transducers also differed from 5.9 mm @ 150 MHz up to 25 mm @ 20 MHz.

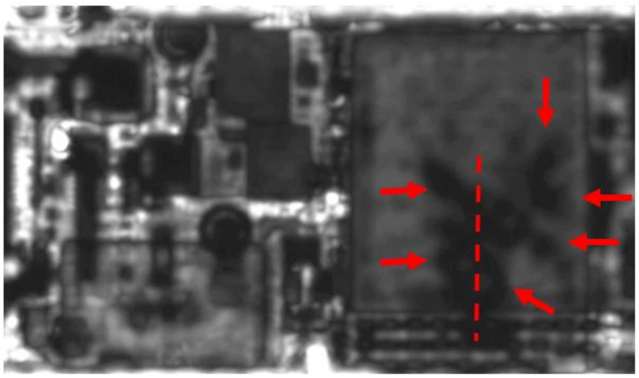


Figure 4 - Through-scan mode of an underfilled board. Voids in the underfill under an LGA assembly (red arrows).

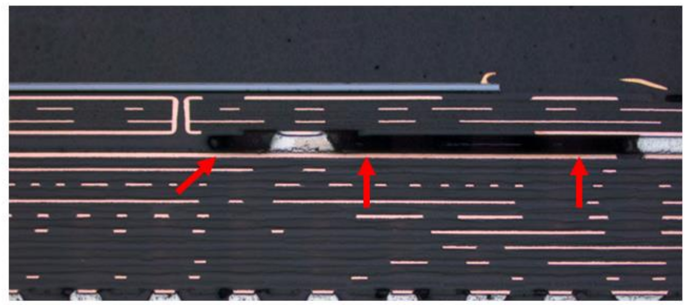


Figure 5 - Cross-section on the underfilled LGA assembly. Voids in the underfill (red arrows).

QFN packages are typically not appropriate or compatible with underfilling due to their low stand-off and specific design which includes a large central pad.

With a dedicated experiment where QFN components were underfilled on a PCB test vehicle board, C-scan turned out to be efficient in detecting voids within the underfill resin. By reducing the frequency, it was possible to go through all the molding compound thickness and directly image the underfill. In through-scan mode, underfilled QFN could also be inspected but at a lower resolution. As illustrated, the two pictures hereafter show the compared results of underfilled QFN with a high level of underfill voids analyzed at 30 MHz in both C-scan and through-scan modes.

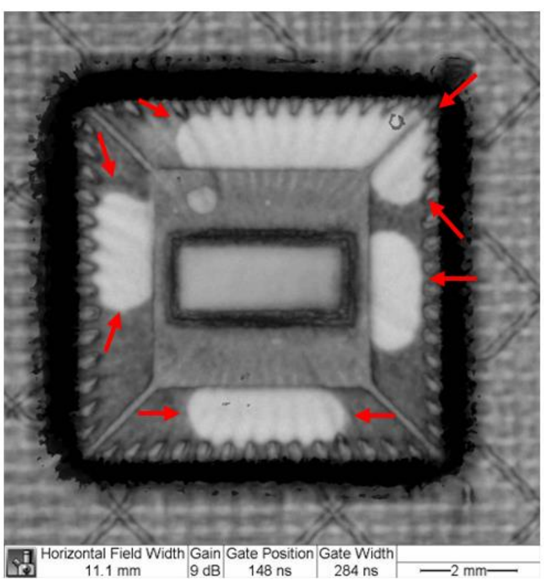


Figure 6 - C-scan mode of an underfilled QFN assembly. Large voids in the underfill (red arrows).

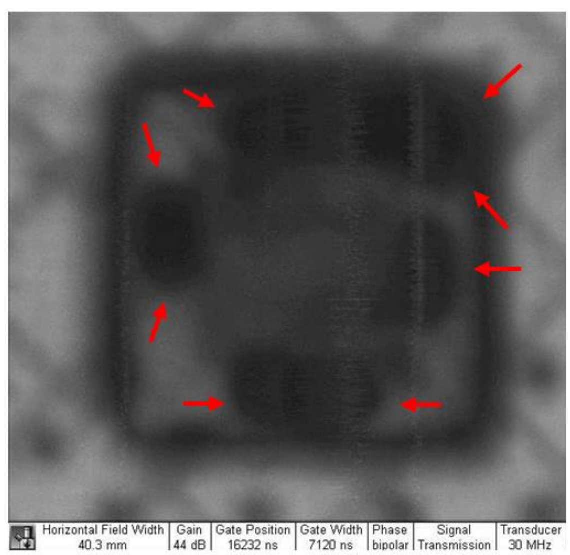
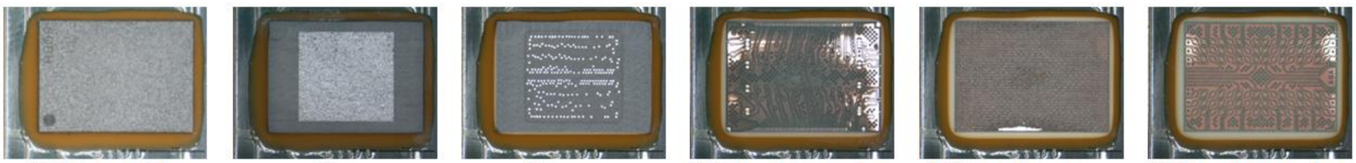


Figure 7 - Through-scan mode of an underfilled QFN assembly. Large voids in the underfill (red arrows).

By contrast, C-scan was expectedly found not to be capable for the control of underfilled BGA components on the same test vehicle board. Through scan can only give a first level of inspection, to detect the presence of large voids in the underfill. Further analysis requires destructive or partially destructive sample preparation techniques like conventional planar cross-sectioning which permits to inspect the complete area under the component and observe defects like buried voids. However, this technique has limitations. First, it is very time consuming. It does also require more than one cross-section axis to fully control the entire underfill volume, as well as both component/underfill and underfill/board interfaces. As we will see, this method could become much more efficient if used in combination with SAM.

Planar cross-sectioning was performed on different types of underfilled BGA but the conventional mechanical polishing was replaced by a high precision micro-polishing performed on a production preparation machine [8]. This kind of micro-polishing is typically dedicated to component decapsulation and dies backside analyses. The sample is mounted on a specially designed moving table that oscillates in the X and Y directions. A z-axis controlled rotating tool ensures a precise and reproducible grinding down to a specified thickness as well as a scratch-free mirror polish finishing. With this tool, it is possible to control the thinning and stop just before the component/underfill interface prior to SAM analysis.



BGA top side | Die | Bumps | BGA substrate 1st Cu layer (top) | BGA substrate - dielectric | BGA substrate last Cu layer (ball side)

Figure 8 - Progressive planar cross-section of an underfilled BGA assembly with the high precision micro-polishing machine

C-scans were performed directly on the last copper layer of the BGA substrate (ball side) at a 150 MHz frequency. The whole BGA area and both component/underfill and underfill/board interfaces could be analyzed with a lateral resolution around 50 µm. With such high resolution, small voids can be detected including in the most difficult areas between the BGA solder joints. The technique enabled to evidence different kinds of underfill voids like local voids at the base of BGA solder joints or larger voids bridging the gap between two adjacent joints (see figures 9 and 10).

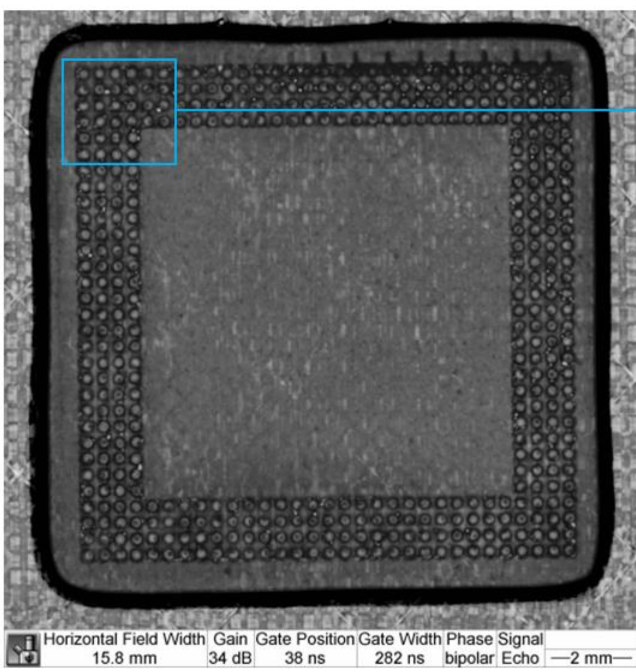


Figure 9 - C-scan mode of an underfilled BGA assembly after micro-mechanical polishing.

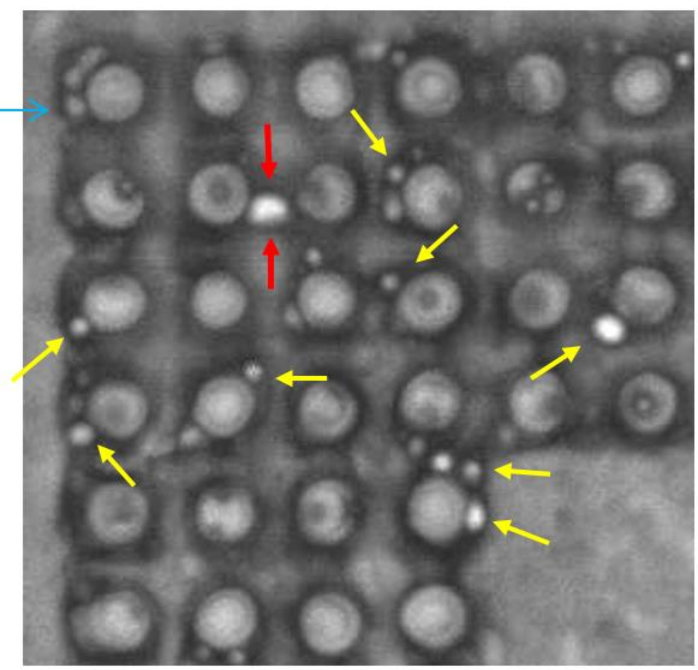
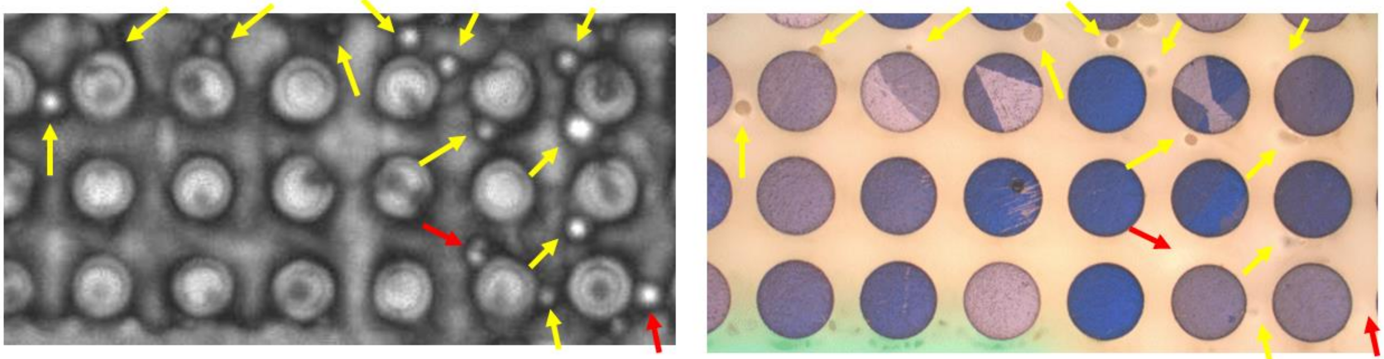


Figure 10 - Detailed view of the underfill between solder joints : Voids in the underfill (yellow arrows) and void that encircles two solder joints (red arrows)

To correlate the voids observed in C-scan, the planar cross-section was pursued step by step from the BGA/underfill interface down to the PCB/underfill interface with optical observations at multiple intermediate depths. Several planar cross-section axes were necessary to observe all the voids revealed in SAM. Some were even hardly seen as illustrated in figures 11. Clearly, the SAM inspection is more exhaustive and displayed a better sensitivity.



Figures 11 - Same area of the underfilled BGA assembly after micro-mechanical polishing in C-scan mode (left) and in optical under polarized light after further planar polishing (right). Voids in the underfill correlated between C-scan and optical inspection (yellow arrows) and voids not detected optically in this planar axis (red arrows)

Case study: failure analysis

The use of SAM after mechanical polishing sample preparation was applied to the case of an underfilled BGA component displaying premature failures in thermal cycling.

For the considered BGA component, electrical failures were recorded after only 645 cycles while all other underfilled BGAs of the same type withstood 3000 thermal cycles. The open connection was electrically localized on the first external row of solder joints.

A preliminary conventional cross-section was performed on the failed row, which revealed some delaminations at the underfill/BGA substrate interface on one side of the row generating cracks in the solder joints. To better understand the failure mechanism and the origin of the delamination, the BGA component was thinned by a planar cross-section until reaching the BGA substrate. SAM performed with a high frequency transducer at 150 MHz permitted to analyze the underfill and correlate the delamination at the BGA substrate/underfill interface. The delamination occurred between the underfill resin and the solder mask of the BGA substrate as illustrated in the figure 12.

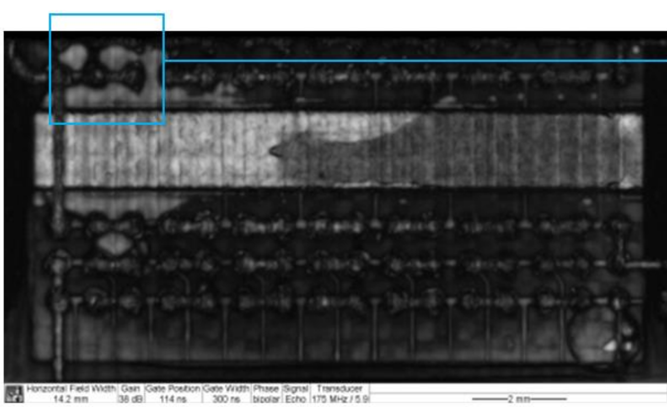


Figure 12 - C-scan mode of an underfilled BGA assembly after micro-mechanical polishing. Evidence of a delaminated area

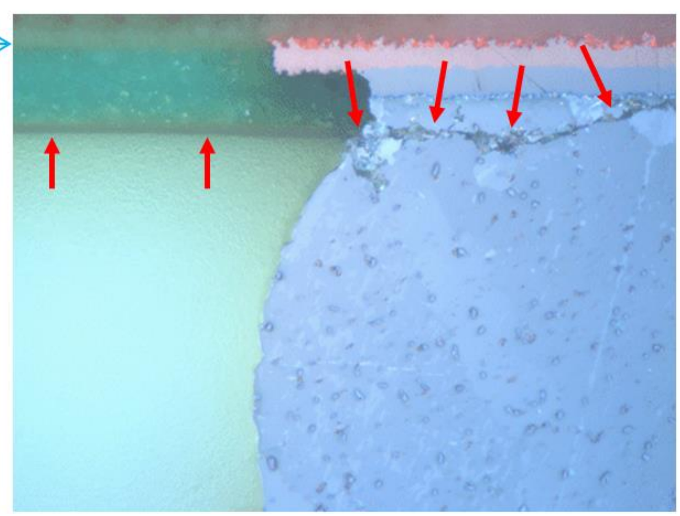


Figure 13 - Optical view in cross-section of the underfill between solder joints : delamination at underfill/BGA interface generating cracks in the solder joints (red arrows)

Conclusions

Underfilling, which is commonly used in micro-electronics and IC packaging, is spreading to a larger spectrum of applications as a response to the growing ruggedization needs driven by miniaturization. This process is currently becoming increasingly used at the board-level for a variety of applications such as fine-pitch BGAs of high-end PCBAs operating in harsh environment conditions.

The quality and the integrity of the underfill deposit have a direct impact on the ruggedization performance and therefore need to be properly inspected. However, as outlined in this paper and the reference IPC J-STD-030A industry standard, limited options are available for the control of underfilled assemblies:

- The most practical visual inspection only permits to check the underfill resin fillets and the overflow on surrounding components, but does not cover the area under BGAs.
- X-ray Computed Tomography turns out not to be adapted to the control of underfilled assemblies due to poor imaging contrast and beam hardening artifact.
-

Scanning Acoustic Microscopy is the non-destructive technology of choice that is used within the IC packaging industry for the control of underfilled flip-chips. At the board-level, SAM can be considered for underfilled WLP and QFN assemblies but is strongly limited for BGA components due to the presence of a PCB substrate. At best, SAM can be used for the detection of large voids.

For proper control of underfilled BGAs, a specific destructive sample preparation is required. As presented here, optimal results are obtained when combining high-precision planar cross-sectioning and SAM which enables an exhaustive control of the whole BGA area in one scan. The technique can provide an accurate X-Y mapping of the underfill defects and detect a variety of voids with an excellent sensitivity. It can also highlight delaminations at the BGA or PCB interface over the entire underfilled area. This method offers the best level of defect characterization and coverage, and thus should be recommended for initial process set-up validations or product qualifications.

Alternatively, optical observations after planar cross-sectioning may be considered to analyze underfilled BGA assemblies. This more convenient technique enables to capture underfill voids within the BGA area, but with limitations. Some defects like cracks or voids may not be detected or properly interpreted if not all located near the same Z-axis. This could be partly compensated by doing multiple observations at different cross-sections planes, which remains time consuming and less efficient compared to SAM.

Acknowledgments
We acknowledge valuable discussions on SAM developments with PVA Tepla.
This work is part of a Thales Group Services Program on assembled printed circuit boards.

Bibliography

[1] M. Pacheco, D. Goyal, New Developments in High-Resolution X-ray Computed Tomography for Non- Destructive Defect Detection in Next Generation Package Technologies, ISTFA 2008

[2] P. O. Moore, R. Bossi, F. Iddings, G. Wheeler, Nondestructive Testing Handbook: Radiographic Testing, vol. 4, 3rd edn. (American Society for Nondestructive Testing, 2002), p. 303

[3] M. Rauer, T. Schreck, M. Kaloudis, X-ray computed tomography as supporting technology in the failure analysis of press-in connections for electronic assemblies. Pract. Metallogr. 3, 205–221 (2013)

[4] M. Rauer, A. Volkert, T. Schreck, S. Härter, M. Kaloudis, Computed-Tomography-Based Analysis of Voids in SnBi57Ag1 Solder Joints and Their Influence on the Reliability, Journal of Failure Analysis and Prevention, ASM International 2014

[5] K-F. Becker, J. Semmens, F. Ansorge, R. Aschenbrenner, H. Reichl, "Qualification of Underfill Materials for Flip Chip Assemblies", Proceedings of the International Acoustic Micro Imaging Symposium (IAMIS), Feb. 26 – 27, 1998, Anaheim, CA.

[6] P. Czurratis, P. Hoffrogge, S. Brand, F. Altmann, M. Petzold, Failure analysis using scanning acoustic microscopy for diagnostics of electronic devices and 3D system integration technologies, 38th International Symposium for Testing and Failure Analysis 2012.

[7] J. Perraud, S. Enouz-Vedrenne, JC. Clement, A. Grivon, Development of advanced non destructive techniques for Failure Analysis of PCBs and PCBAs, 38th International Symposium for Testing and Failure Analysis 2012.

[8] J Colvin ''The state of the art in backside prep'' EDFA Vol 4, No. 2, Publ. ASM Int'l 2002