An Improved Imaging System for Inspecting BGA, CSP, Flip Chip, and Other Hidden Solder Connections

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Abstract

A cost-effective alternative for, or supplement to current X-ray technology for inspecting hidden soldered connections will be described. In addition to the high-powered optical solution which portrays the critical innovation, a linked measurement and control software will be discussed which represents a completely new standard for failure recognition and total quality assurance management.

Introduction

The growing trend in component packaging technology is moving toward Controlled Collapse Chip Carrier connection (C5), such as ball grid arrays (BGA) and chip-scale packages (CSP), as well as Controlled Collapse Chip connection (C4) or flip chip[1]. As tremendous advancements are being made, the number of soldered connections on the PCB are greatly increasing. As small as they might be, however, the simple solder joint represents the weak link in the chain. One poor solder joint, if undetected, can lead to the premature failure of a complete electronic assembly. Product reliability problems are the result, and are ultimately responsible for enormous costs and customer dissatisfaction. Current optical inspection and X-ray technology, both in and off line, provide essential information about the quality of a soldering process. Although state-of-the-art, they are incapable of providing complete information with regards to the lasting quality of those hidden solder joints found under area array packages. The **ERSASCOPE** high-powered optical inspection system can expand current inspection technology by providing the only known non-destructive method to inspect for good solderability by allowing a visual examination of hidden solder joints with failure reference analysis. The implementation of this new technology into the first article inspection process can provide the user with the ability to see and react to hidden production deficiencies, in order to guarantee the quality and reliability of an electronic assembly.

The Soldering Process: the Intermetallic Bond and its Relation to Inspection Criteria

The science of soldering or of joining two metals began with the early Egyptians and has not changed, in principle, since that time. In an electronic assembly, the solder joints serve the purpose of electrically and mechanically connecting the component to the PCB. Contact alone can provide an electrical connection between a copper lead and a copper land. The lasting mechanical connection is achieved via the process of soldering. Tin-lead or solder is introduced to the lead/land junction and is then heated above the melting point. When sufficient activation energy is present, a chemical diffusion reaction ensues, which creates an intermetallic bond between the copper in the lead and tin in the solder and subsequently between the tin in the solder and the copper in the land. When properly created, a soldered connection will last a very long time or better put, sufficiently beyond the warranty period of the product. The heart of the solder joint is shown in Figure 1[2] and is detailed in Figure 2[3].

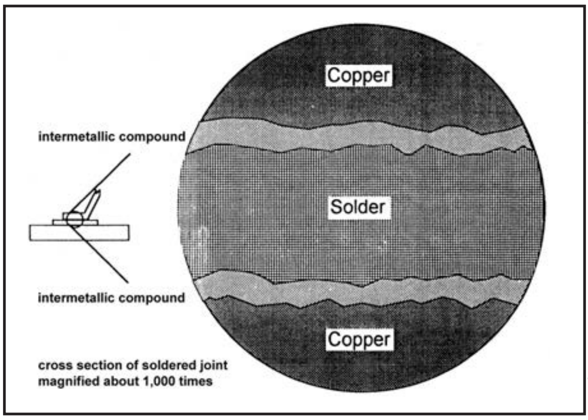


Figure 1 - The Heart of the Solder Joint

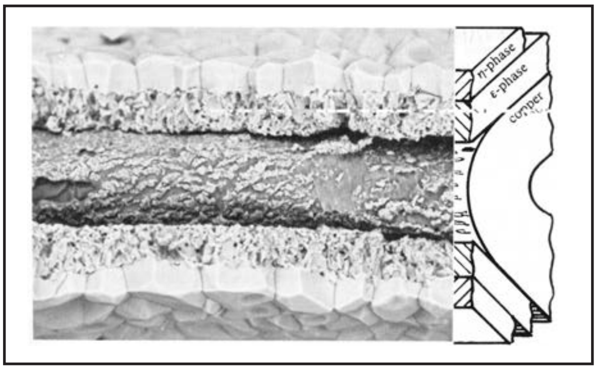


Figure 2 – Scanning Electron Micrograph (SEM) of Fractured Intermetallic Layers of a Solder Joint. Cu3SN (e-phase) and CU6SN5 (n-phase) Make Up the Intermetallic Layers.

An understanding of the chemical and metallurgical background behind soldering is important, and a destructive cross-section and SEM of a joint can provide valuable information about the formation of intermetallics. Over the years, however, operators have learned to rely on their eyes to visually examine solder joints in order to qualify the process. A visual examination of the joint after soldering will provide an indication of the temperature reached during reflow. This can be directly related to the proper formation of an intermetallic bond and the subsequent reliability of the connection.

First Article Inspection – Qualify the Line before Mass Production Begins

When an SMT production line is set up for a new product or PCB assembly, the various critical parameters (paste, flux, screen, placement, conveyor speed, preheating zones, reflow time and temperature, etc.) are checked and rechecked. First article inspection is designed to ensure that all parts of the puzzle fit properly together in order to guarantee that the in-line process delivers the required results. The soldered connection, being the weak link in the chain, must be closely examined at this point in order to accept or adjust certain parameters. Table 1 details the areas which need to be examined with regards to the solder joint.

1	Quantity of solder in the solder joint
2	Shape of solder fillet and alignment – according to industry standards
3	Surface appearance – texture, uniformity, smoothness, color and brightness
4	Surface anomalies – e.g. flux residue

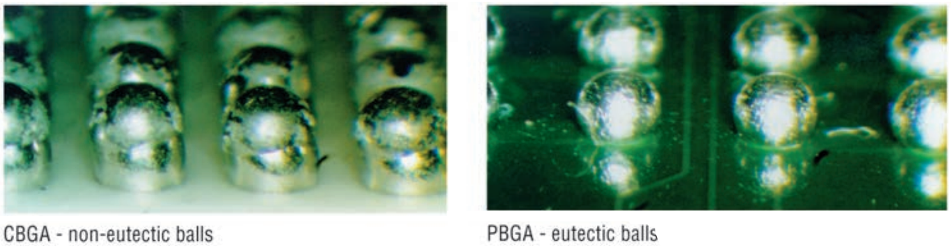
Table 1 - Four Critical Areas to Determine a Lasting Solder Joint Using Visual Indicators

Some visual indicators to look for include: rough, dull, or porous surface; surface deformities, e.g. holes, streaks, scaling and ridges; micro cracking, dilamination, or fracture zones; discoloration; micro-balling or solder splash; excess flux residue; iron and/or dross inclusions in the solder joint.

The information gained via a visual examination enters a closed-loop feedback process of adjusting the variable parameters in the line until the desired goal is attained. While all areas listed in Table 1 are critical to inspect, a visual examination of the surface appearance of the solder joint provides the most information about the mechanical reliability in that it helps determine if an intermetallic bond has been formed during the soldering process. A typical cold solder joint receives enough heat to reach the melting point of the solder, but did not receive enough heat to form an intermetallic bond. These joints will typically appear matt or dull and often have a non-uniform or rough surface. Solder will generally appear smooth, uniform, and shiny on its surface when the proper temperature has been reached. The ability to detect cold solder joints must be a part of the first article inspection process. It is here that production deficiencies must be discovered, and that certain parameters be adjusted in order to qualify the line before production begins.

BGA Production – Typical Physical Effects during a Reflow Process

In general, eutectic solder balls (Sn63Pb37) are always used for area array packages except in the case where the weight of the component is greater than the surface tension of the molten balls during reflow. A CBGA (ceramic BGA) is a typical example of a component that could not be "carried" by the surface tension of the solder balls during the reflow process. In this case, a high melt ball, for example Pb90Sn10, is used because it will remain solid during the normal reflow process. Figure 3 and Figure 4 detail the different wetting zones, and wetting angles between a PBGA and a CBGA and their respective joints.



CBGA - non-eutectic balls

PBGA - eutectic balls

Figure 3 – Ball Comparison Photos

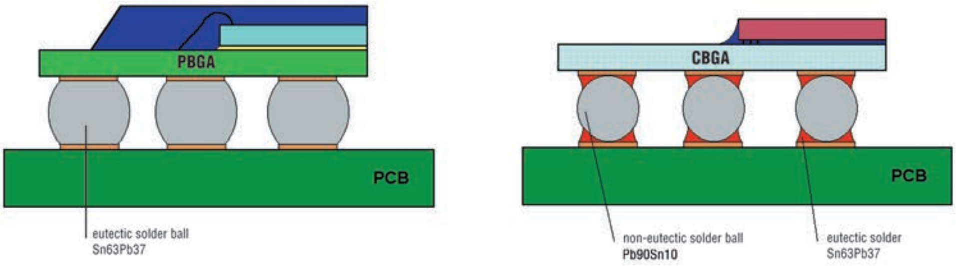


Figure 4 – Comparison of Installed PBGA to a CBGA

The typical physical effects during the reflow soldering process of a PBGA are graphically shown in Figures 5, 6, and 7, with regards to the stand-off height and wetting angle.

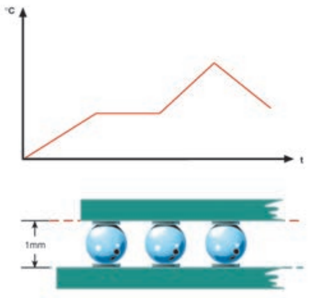


Figure 5 – Condition A
Before Reflow Begins

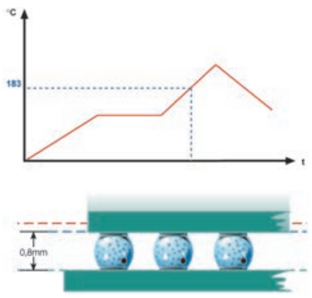


Figure 6 - Condition B
At Solder Melt Point

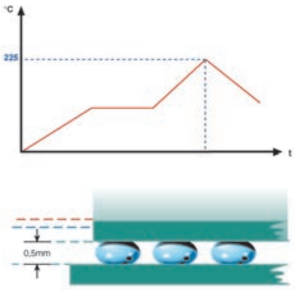


Figure 7 - Condition C
At Proper Peak Temperature

After placement of the component onto the fluxed pad or into the solder paste print, a stand-off height measurement can be taken; in the example in Figure 5, the stand-off height is 1 mm. During the reflow process, and after the flux has been activated, the melting point 183°C of the eutectic solder balls (Sn63Pb37) is reached; e.g. the balls move from the solid to the liquid state. Gravity acts on the component causing an initial or single drop. The stand-off height could be checked at this point in order to determine the amount of the initial drop; in the example shown in Figure 6, the drop can be calculated as 0.2 mm. As the reflow process continues toward the peak temperature, sufficient activation energy allows for a complete wetting of the solder spheres to the entire pad profile. This results in a measurable second or double drop, depicted in Figure 7, which amounts to 0.3 mm. A cross-section of a PBGA 225 after a proper reflow process, as seen in Figure 8, shows the complete wetting to the pad and the proper wetting angle of the flux residue fillets.

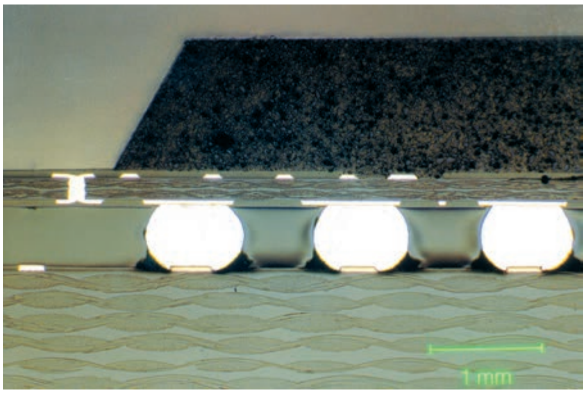


Figure 8 – Cross-section of PBGA 225 after Soldering[4]

Cold Joints: A Potential Problem Associated with BGA Production

A hidden production deficiency associated with BGA production must be discussed and relates to insufficient heat and cold solder joints. Typically, cold solder joints are discovered via a visual examination of the assembly after the reflow process. This non-destructive inspection, however, has not been possible with the hidden joints found under an area array package. The danger of leaving a cold joint undetected can be proven by using a destructive method. A pull test to determine the lasting mechanical reliability of a solder joint would reveal that if the BGA reflow process stopped during Condition B, single drop, as seen graphically in Figure 6 and again in Figure 9, the joint would sheer off at the solder ball-pad interface. The primary force holding the component balls to the lands is cohesion. This force is generally not greater than the epoxy bond of the pad to the substrate and would therefore result in such sheering as depicted in Figure 10.

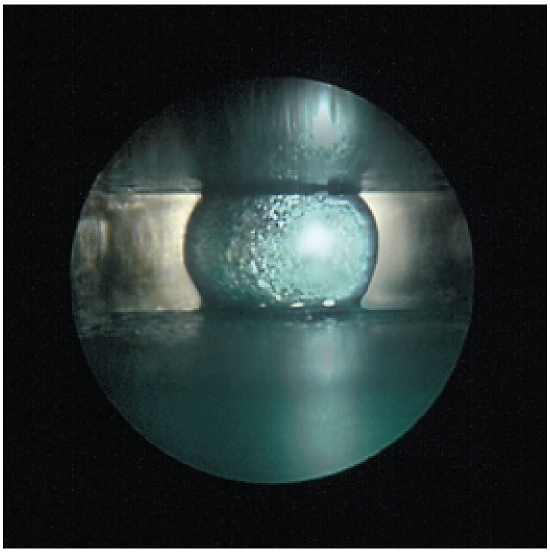


Figure 9 - Cold Solder Joint in Condition B: Initial or Single Drop

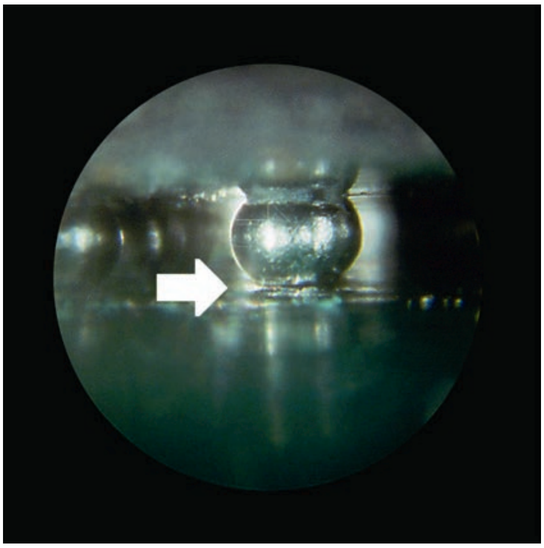


Figure 10 - Pull Test Result of a Cold Solder Joint in Condition C: Second or Double Drop

During a proper or complete reflow process as depicted graphically in Figure 7 and again in Figure 11, sufficient heat has been provided which allows for the formation of the intermetallics. This intermetallic bond is stronger than the epoxy bond between the pad and the substrate. A pull test of a properly soldered component would result in the pads ripping off the substrate. This result can be seen in Figure 12. While such a pull test can provide an indication of expected reliability, by proving the existence of an intermetallic, it is destructive and can only be used on a limited basis. A cold solder joint, as seen in Figure 9, if undetected, can prematurely fail due to either an oxidation layer build-up between the ball and the pad, or due to sheering caused by the stress of CTE (Coefficient of Thermal Expansion) mismatch during thermal cycling. This latter problem is seen most often with CBGA and CCGA components based on the inherent CTE mismatch problems associated with the ceramic material and the substrate. The ability to determine whether the reflow process delivers the quality results as seen in Figure 11, and not the cold joint as seen in Figure 9, must be a part of the total quality assurance associated with first article inspection.

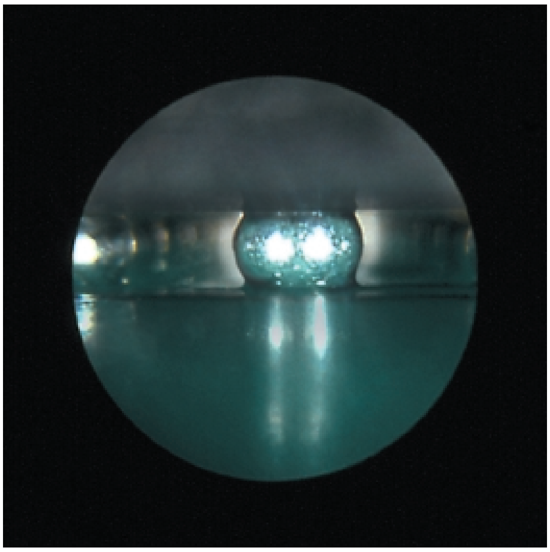


Figure 11 - Good Solder Joint in Condition C: Second or Double Drop

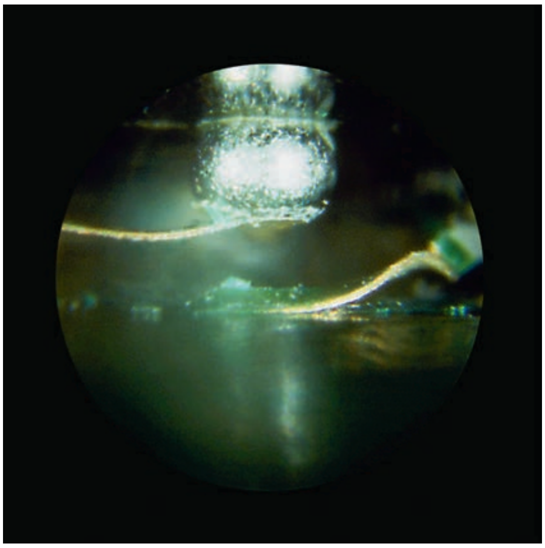


Figure 12 - Image of Pull Test of Good Solder Joint

Test and Inspection Today – Critical Concerns and Shortcomings

An electrical function test alone can provide no answer as to the long term reliability of an electronic assembly. The cold solder joint depicted in Figure 9 would clearly pass a function test for opens or shorts as a proper electrical connection has been established. Additionally, a short term mechanical connection has been established based on the surface tension or cohesional force that causes the ball to fix to the pad. Life cycle tests, however, will reveal premature failure of such cold joints as previously discussed.

With regards to inspection, X-ray has established itself as the primary method for non-destructive both in-line and off-line inspection of hidden solder joints, particularly those of BGA, CSP, and Flip-Chip components. When considering the 4 critical visual inspection areas listed in Table 1, which operators have been looking for over the years, the shortcomings of the technology become apparent. In general, X-ray equipment can inspect for two of the four areas listed in Table 1: the quantity of solder in the joint, the ball and/or fillet shape, the alignment, and for voids. Figures 13 and 14 reveal two examples of the information available from typical X-ray systems.

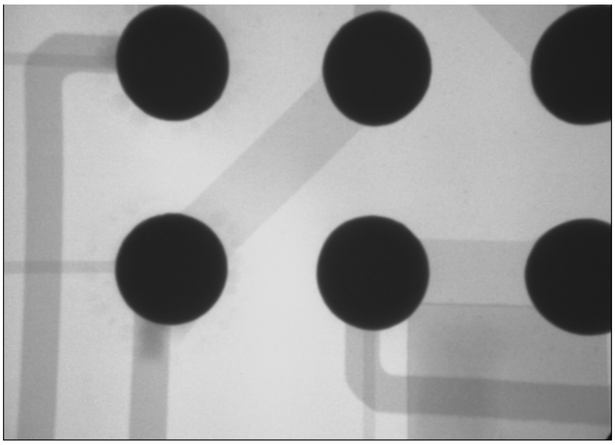


Figure 13 – X-ray Image of BGA-Top View

The most important visual indicator, the surface appearance, however, is inadequately addressed. While great advancements have been made in the standard X-ray and laminography machines, the required information about the color, brightness, surface deformities and anomalies, such as flux residue, remains lost to this technology even today. The cold solder joint depicted in Figure 9 would be extremely difficult, if not impossible, to detect using only the X-ray information seen in Figures 13 and 14. One cold joint, one micro crack, or one small ball improperly soldered to the pad, or excess flux residue left under the component, could lead to the premature failure of the entire electronic assembly, if undetected by current methods. Test and inspection equipment, as part of a quality assurance program, should be implemented in order to reduce the risk of premature failure. Total quality assurance demands that the whole picture is seen and evaluated. The visual inspection of BGA joints must go hand-in-hand with current X-ray inspection equipment in order to properly qualify an SMT line, as it provides the missing information critical to the qualification process. Premature product failures which can be tracked back to solder joint reliability problems have enormous associated service and warranty costs. These costs can be kept to a minimum with the implementation of a more complete inspection process using an improved imaging system.

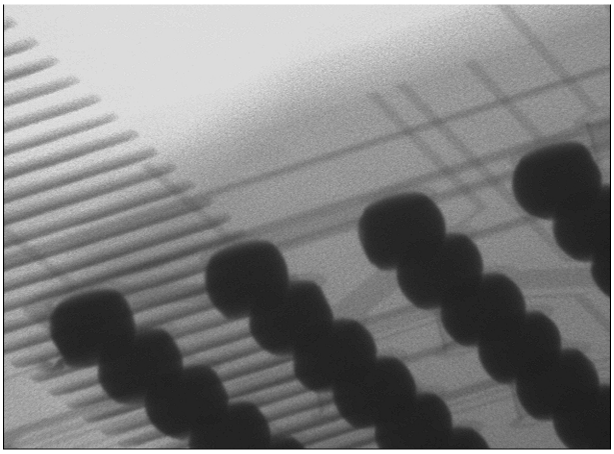


Figure 14 – X-ray Image of BGA-Angled View

Visual Inspection Made Possible – An Advancement Based on Medical and Technical Endoscopy

When faced with the task of looking under an object with a stand-off height of less than 1 mm, two alternatives come to mind. The first is the use of fibre optics. The inherent problem here is that in a 0.5 mm diameter cord, a total of approximately 10,000 optical fibres can be bundled. This cord would provide an image with 10,000 pixels (1 pixel of image data transferred by one optical fibre) which is clearly inadequate from a resolution stand point. The alternative to "go under" the component fails. The second alternative is to use a mirror or prism in order to redirect an image by 90° and to focus under the component from the side. Two difficulties arise, however. The optical center of the pupil must be low enough to the board surface in order to look under a CSP with a typical stand-off height between 0.05 mm and 0.10 mm. Secondly, it is necessary to have sufficient light which becomes more scarce the lower the component is to the board.

The optical solution presented here and as depicted in Figure 15 is an innovative advancement on existing medical and technical endoscopy.

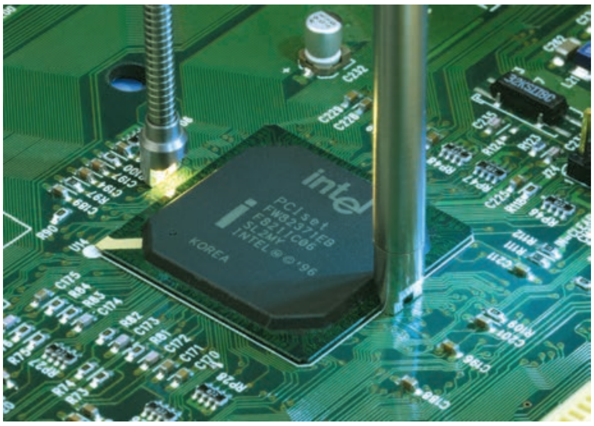


Figure 15 – Optical Instrument

This optical instrument (patent pending) combines integrated split fibre optics, and a total of 42 lenses optically coupled to a highly specialized prism with an optical axis tolerance of less than 2° seconds. The resulting image offers up to 700x magnification of the soldered connections under a Flip-Chip even with a stand-off height of less than 0.05 mm (2 mils). Put into practice, the advantage of this optical system becomes apparent. Figures 16, 17, and 18 address the differing information gained from an X-ray system versus the optical imaging system.

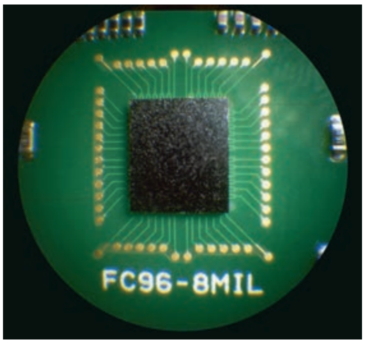


Figure 16 - Flip Chip 96 After Soldering, Before Underfill, Stand-Off 0.05 mm

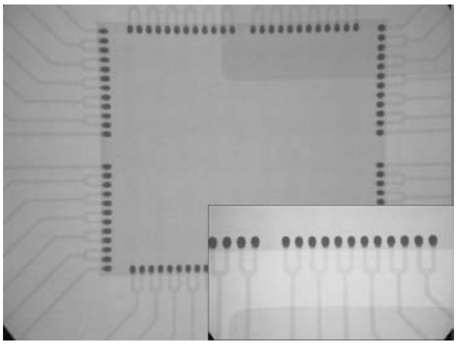


Figure 17 - X-ray Image of Flip Chip 96 After Soldering, Before Underfill

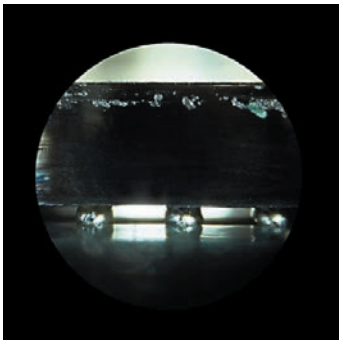


Figure 18 - Image of Flip Chip 96 After Soldering, Before Underfill

It is essential to have total quality assurance for a Flip Chip soldering process. Once the Flip Chip receives its underfill, it cannot be removed from the PCB. The premature failure of this one component would lead to the scraping of the entire PCB. The image seen in Figure 18 can be regarded as an expansion to current inspection technology in that it provides additional and valuable information about the soldering process.

Additionally, an optical imaging system can greatly enhance X-ray by offering a visual image of those problems picked up by both in, and off line X-ray systems. An installed PBGA 225 was X-rayed as seen in Figure 19. It is quite clear that the areas marked A and B in Figure 19 are not ideal. It would be difficult, however, using only the X-ray image to identify the source of the problem in order to correct it. Going hand-in-hand with X-ray, the optical imaging system provides this missing capability for failure analysis. Figures 20 and 21 reveal how the additional visual information can be used in conjunction with the X-ray image seen in figure 19 to get to the heart of the problem in order to correct it.

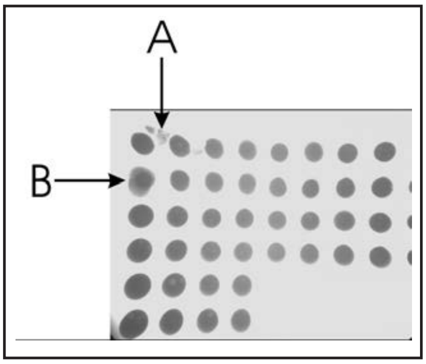


Figure 19 - X-ray Image of PBGA 225:
A and B are Unclear of Source

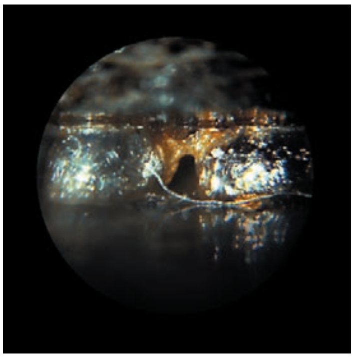


Figure 20 - A. Image Reveals Flux
Residue Bridge with Conductive Particles

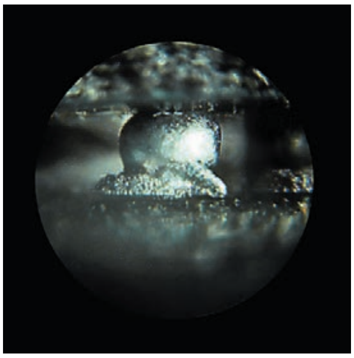


Figure 21 - B. Image Shows
Incomplete Solder Melt of Paste

Instead of removing and scraping a perfectly good BGA component, the improved imaging system could better guide the repair process. The problem shown in Figure 21, for example, could be easily fixed via a controlled secondary heating using an appropriate repair system.

Today’s Microscope – Completely Operator Dependent

Modern electronic assembly facilities have grown to accept the necessity of the common microscope for inspection purposes. While these vital instruments allow the user to "see” better, they do not offer any help with regards to failure recognition and analysis. If 10 operators examined the same object under a microscope, one can expect 10 different opinions about the subjective analysis of that which they see. With regards to failure recognition, e.g. a "go” or "no go” decision, a subjective approach would require intense operator training and would still lead to a 50% chance that the correct choice was made.

"Is that solder joint good?” – this is the question which the inspector must answer. If the solder joint was actually good and the inspector made the decision it was bad, then unnecessary touch-up, rework, or component exchange costs would be the result. If the solder joint was actually bad, and the inspector made the decision it was good, then that assembly would prematurely fail in the field, resulting in even higher costs and customer dissatisfaction. In order to take the subjectivity out of the failure recognition, a new software was written for the imaging system.

Linked Measurement and Control Software – Closing the Quality Control Loop

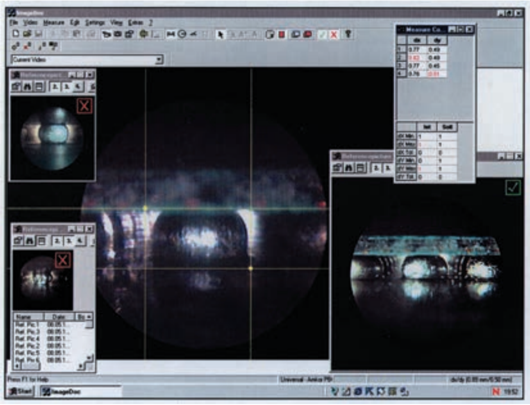


Figure 22 – Measurement and Quality Control Software

Inspection, as it pertains to quality control, combines two critical aspects: to see and to evaluate. The first, is the ability to properly and completely see the object to be inspected. The second, is the inspector's analysis or evaluation of that which he or she sees as being good or bad. Both go hand-in-hand and are critical to the success of an inspection program. In order to assist in the failure recognition process of analyzing information gained from the improved imaging system, a quality control software was written. Figure 22 depicts an inspection example of a typical BGA using the linked software.

In addition to displaying a real time video of those images captured by the optical system, the user can call up good/bad reference pictures as windows or overlays. Component, board, or error-specific reference picture groups can be accessed from the online databank in order to minimize the occurrence of improper evaluation. With the system optically calibrated distance, angle, radius, and point-to-point measurements can be taken with an accuracy of +/- 0.01 mm. Stand-off height, wetting angle, ball radius, and co-planarity measurements can extend the capability of the visual indicators to ensure a more complete and objective inspection process. An automatic measure control function provides a "go"/"no go" based on the automatic comparison of actual and target measurement values which can be stored in a separate measure control databank by the Quality Control Manager. Images and corresponding measurement values can be stored in the main image databank with sub-files containing all pertinent information about the parameters involved in the process, e.g. type of flux, paste, temperature profile, etc. Once a failure or problem is noted via the use of the reference pictures, a online problem/solution databank will present a complete description of the problem, its probable causes, and potential remedies to cure the problem. Images, files and databank information can be printed in document form or sent via e-mail. When used in conjunction with the improved imaging system for BGA inspection, the linked measurement and control software can greatly aid in failure recognition by reducing the subjectivity of the inspection process in order to guarantee total quality assurance.

Conclusion

In today's highly competitive manufacturing environment, the ability to see and react to hidden production deficiencies, in order to guarantee total quality assurance, can mean the difference between life and death of a solder joint, of a product, of a business. Current state-of-the-art inspection equipment is limited in its ability to present the whole picture regarding the quality of a BGA soldering process. The high powered optical system with its quality control software provide the missing information required to properly qualify a process or an SMT line using area array devices. Hidden production deficiencies can be detected and corrected before they become a reliability nightmare.

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