ABSTRACT
Although X-ray inspection of area array packages is prevalent, most users can identify only obvious defects such as bridges, voids and missing balls. Much more information is contained in the X-ray image of the bond shape pattern (the signature). To interpret this information, the stages of reflow must be understood. This paper will discuss the process parameters that influence reflow and show images from actual real-time X-ray movies of BGA reflow as it occurs. The stages of reflow will then be correlated with X-ray image signatures indicating process problems.

Key words: BGA, defect analysis, reflow stages, X-ray inspection.

INTRODUCTION
The use of X-ray inspection for quality control of ball grid array (BGA) bonding has become widespread in surface mount assembly. While the number of equipment suppliers and features has proliferated, the understanding of what the X-ray image of the BGA means has not advanced very far beyond identifying the simple and obvious defects of shorts and missing balls, and raising misplaced concerns over small solder voids. (Figure 1)

It is the intent of this paper to introduce the concept of X-ray “signature identification” as a means of extending the usefulness of X-ray inspection beyond identifying the obvious defects of shorts and missing balls. A better understanding of how the X-ray image relates to the assembly and reflow processes is needed to achieve this usefulness. In addition, signature identification supports rapid and effective X-ray inspection of BGAs with even the most modest investment in X-ray inspection equipment.
THE ANATOMY OF THE BGA BOND
As any radiologist will tell you, before you can start to understand the X-ray image, you first have to understand the anatomy. There are three anatomical features that must be considered before looking at the X-ray image: package type, solder paste and PC board construction.

Package type
BGA package types include CBGA, PBGA, Super BGA, TAB and others. Figure 2) The package type provides information on the thermal effects anticipated, such as thermal expansion, heat capacity and tendency to deform. PBGAs in particular have been observed to deform physically during reflow if they have not been properly baked out. Deformation effects can be detected in the X-ray image.

Solder paste
If solder paste is used, problems can occur from the screen printing of too much or too little paste. This will result in X-ray detectable characteristics.

Construction of the PC board
High-heat capacity boards can affect reflow temperatures and thermal expansions. This too will result in X-ray detectable characteristics.

TYPICAL REFLOW STAGES
By combining real-time X-ray with a rework station, the three stages of reflow have been observed and recorded in real-time X-ray movies as they occurred. They are depicted schematically, and with their corresponding X-ray images, in Figure 3.

In Stage A, the placement of components can result in the BGA being aligned or partially aligned with its corresponding pad.

In Stage B, during initial melting, solder balls start wicking to their pads. The package is pulled into accurate alignment with the pads only when all the balls have melted.

In Stage C, after alignment, a final collapse can be observed wherein the solder wets the pad completely.

How reflow stages affect the X-ray image
In Stage A (pre-heat), the standoff height is equal to the ball height and the diameter of the ball’s X-ray image is equal to the nominal ball diameter.

In Stage B (initial collapse), the standoff height drops to approximately 80% of the initial ball height.
In Stage C (final collapse), the standoff height drops to approximately 50% of the initial ball height and the diameter of the ball’s X-ray image increases approximately 17%, resulting in an increase in projected area of 37%.

Figure 3A “Misalignment”

Figure 3B “Wicking”

Figure 3C “Alignment”

Figure 3 The three stages of reflow. Each action (Stage A, B and C) is shown in schematic form and with its corresponding X-ray image.

The change in size and uniformity of the ball’s X-ray image, after reflow, is the key to the intelligent and informed understanding of the meaning of the final X-ray image.

Uniformity
At this stage it can be stated categorically that, if all the ball X-ray images are uniformly circular and equal in area within 10% to 15%, the probability is very good that no defects are present in the ball bonds. This condition may be called “uniformity.” (Figure 4) Uniformity provides the first and most important characteristic in the use of X-ray inspection for rapid qualification of the quality of a BGA bond.

“Signatures” (or non-uniform patterns)
When non-uniformity exists in the BGA X-ray image, it can be observed that the variations can be either random or have some type of pattern. Both random variations and patterned variations provide a clue as to the possible defect or process problem and what may be causing it.

THE MEANING OF SIGNATURES
With this understanding, X-ray image signatures can be observed and hypotheses formed as to what may have gone wrong in the assembly process.

Insufficient reflow
When reflow is not sufficient, a number of characteristic signatures can be observed. (Figure 5) Elliptical-appearing bonds can result when the BGA is not registered exactly with the pad at placement. When the initial melting stage occurs, the solder wicks to the pad, creating an elliptical image, until full alignment can take place.

If full reflow is not achieved, full alignment does not occur and some or all of the images appear elliptical. These same elliptical images may also be observed if the pad pitch does not match the BGA pitch.
5A and 5B Elliptical X-ray images, the signature of insufficient reflow.

Cold solder joint
The cold solder signature can appear as one or more bond images having irregular edges around the perimeter. (Figure 6)

Figure 6 Irregular X-ray images, the signature of cold solder joints.

“Doming” or “dishing” of the BGA package
“Doming” is sometimes referred to as “popcorning” and the opposite effect, “dishing,” is referred to as “potato chipping.” Both of these defects are caused by the physical deformation of the BGA package. Plastic BGAs are particularly susceptible to this condition if moisture is not baked out prior to placement.

Specific signatures are associated with doming and dishing. (Figure 7) In doming, delamination occurs under the die area, causing the plastic package to dome in the center and resulting in the ball bonds under the die being compressed and enlarged. In dishing, the BGA edges curl upward, causing the bonds on the perimeter to be pulled and become thinner.

Figure 7A Doming (7A) and dishing (7B), the signatures of BGA package deformation, with (7C) showing a visual microscope image of a ball breaking away from the package.

Figure 7B

Figure 7C
Random differences in bond areas
When a signature of random differences in ball bond areas is observed (Figure 8), closer observation usually reveals a corresponding random distribution of solder voids. Since solder voids are easily detected with X-ray inspection, they are usually classified, without a clear understanding, as defects.

However, subsequent studies have shown that some solder voids actually improve the reliability of the solder bond. The question then remains as to what level of solder void is acceptable. This issue is addressed in detail in the IPC Standard 7095, “Design and Assembly Process Implementation for BGAs.”

In this standard, there is a cautionary note regarding the tendency of many commercial X-ray inspection systems currently being used to exaggerate or distort the size of the void as the voltage is increased. This type of distortion occurs only if the type of X-ray imaging device used in the particular system suffers from an effect known as “Voltage Blooming.” (Figure 8) Not all X-ray imaging devices exhibit such voltage blooming.

Using BGA signatures effectively
The use of the BGA signature concept can provide rapid and effective X-ray inspection of BGAs with even the most modest investment in X-ray inspection equipment.

X-ray systems are classified as being appropriate for either the production environment and/or the laboratory. When the signature concept is employed in the production environment, image magnifications up to 40 times are usually adequate. In the laboratory environment, where the concern is failure analysis and where rapid inspection is not required, magnifications of 1000 times or more may be utilized.

Using image processing to aid signature analysis
Employing signature identification entails detecting X-ray image variations with greater than 15% deviation from the nominal bond diameter. This difference can be detected by an operator, but computer image processors can highlight and flag deviant signatures more quickly and repeatedly. Some examples of image-processed flagging are shown. (Figure 9)

Figure 9 Image processing software can highlight and flag deviant signatures rapidly and repeatedly.

After a signature is identified, then what?
Once a signature is identified, it does not necessarily mean that a defect is present, nor does it precisely determine the cause. However, it does indicate the existence of a process problem that can eventually lead to defects.

Returning to the medical X-ray analogy, if the X-ray looks suspicious, it is time for a second opinion. The most effective technique to identify the problem is to employ a side-viewing optical microscopic probe referred to as an “endoscope.” A number of different, commercially available endoscopic designs may be used to produce a magnified optical, video image of the ball itself. (Figure 10)

Endoscopic inspection as a second opinion
Endoscopic inspection of a BGA bond has proven to be an invaluable adjunct to X-ray inspection. For example, it can positively identify cold solder joints, poor contact, cracks and flux residue.

The one disadvantage of endoscopic inspection is that the procedure is often cumbersome and time-consuming. However, when used in conjunction with real-time X-ray and signature identification, the combination becomes the most effective means of inspecting BGAs, Flip Chips and Chip Scale Packages.
The reason for this is that X-ray inspection, using signature identification, qualifies the BGA bonds very quickly as being either acceptable or suspicious. If it is desired to determine the exact cause of the solder irregularity, suspicious bonds can be examined off-line, using an endoscope. Knowing the cause can point to the appropriate process correction.

CONCLUSION
Although X-ray inspection is being widely used for quality control of assembled BGA type packages, its full benefits cannot be realized until the use of signature identification is employed. By understanding the meaning of the X-ray signatures, the process becomes more rapid and diagnosis becomes more precise.
The Jewel Box 70-T
Real-Time X-Ray Inspection System with 500X Magnification

For μBGAs, flip chips, ICs and other advanced components.

**The Jewel Box** delivers superior image quality with excellent resolution and sensitivity for laboratory and failure analysis applications. The system’s high-resolution X-ray camera combined with a 10 micron MicroTech™ X-ray source provides magnification from 7X up to 500X, with resolution of 100 line pairs/mm.

With these advanced capabilities, the Jewel Box 70-T produces images comparable to those from X-ray inspection systems that are much larger in size and higher in cost.

The Jewel Box 70-T generates the sharpest images attainable of solder joints and bonds in advanced technology packages such as BGAs, μBGAs, flip-chips, ICs and other advanced components that cannot be verified by visual inspection. In addition, the system also has the sensitivity to inspect soft materials, such as molded plastics and encapsulants as easily as components and electronic assemblies.

The transparent enclosure on all four sides of the unit allows easy viewing from any angle. The positioner features a five-axis control, including 360° rotation and tilt.

The Jewel Box 70-T employs Glenbrook’s patented, award-winning X-ray camera technology. The system has a compact footprint and includes a rolling cart for easy placement in multiple locations.
Specifications

- Operating voltage: 120v/60 hz or 220v/50 hz
- Anode voltage: 70 kV (adjustable) with optional 80kV (adjustable)
- Anode current: 100 µAmps (adjustable)
- Resolution: 100 line pairs/mm
- Magnification: variable from 7X up to 500X
- Focal spot size: 10 micron
- Focal spot to image plane distance: 13 7/16" (factory preset)

- Nominal exterior dimensions: 35 1/8"W x 43 1/8"D x 64 1/4"H
- Inspection compartment dimensions: 28 1/2"W x 30"D x 23 3/4"H
- Computer console dimensions: 28 3/8"W x 29 3/4"D x 36 3/4"H
- Manipulator: five-axis joystick positioner
- GTI-5000 Image Processing software includes PC, monitor and inkjet printer

MicroTech™ is a registered trademark of Glenbrook Technologies, Inc.

High-resolution inspection applications:

Sample images of defects as viewed on the Jewel Box 70-T:

- Image of a micro BGA, rotated, reveals wire sweeps and solder ball shape.
- Dimensional view of solder balls pinpoints the precise location of solder voids within the balls.
- Insufficient reflow is noted by the variation in ball shape. Also solder voids can be detected.
- A crack in a 1 mil. wire.
- A 3D rendering using the GTI-5000 image processor allows easy identification of solder voids.
- The high magnification and rotation capability allow viewing of an open on a micro BGA packages.
The JewelBox 90T delivers precision x-ray images of ultra high resolution and gray scale accuracy without the aberrations of Voltage Blooming and Pincushioning prevalent in other systems. The patented, award-winning x-ray camera technology, in conjunction with its 90kV, 5 micron focal spot x-ray source, delivers precise x-ray images at magnifications from 7X to 2000X with a resolution of 500 line pairs/mm. The broad energy sensitivity range of this camera permits x-ray imaging of both high density and low density devices.

What’s more, the JewelBox 90T saves you floor space. It’s half the size of comparable systems, yet it provides the most extraordinary microfocus x-ray image quality at the highest magnifications. The JewelBox 90T offers five-axis control of the inspected product, including 360° rotation and tilt.

Applications for the JewelBox 90T include advanced electronic packages such as BGAs, Flip Chips, CSPs, IC Wire Bonds, die attachment, as well as critical medical devices.

Image of a surface mounted IC permits inspection of the wires.

Image of a MicroBGA rotated.

BGA ball with a 1 mil gold wire and void seen through the ball.

BGA ball with un-reflowed solder paste showing actual solder grains in the paste.

Die attach, showing voids in the epoxy.
Specifications

- Operating voltage: 120v/60 hz or 220v/50 hz
- Anode voltage: 90 kV, adjustable.
- Anode current: 100 µAmps (adjustable).
- Resolution: 500 line pairs/mm.
- Magnification: variable from 7X up to 2000X.
- Focal spot size: 5 micron.
- Focal spot to image plane distance: 9-12 inches (factory preset).
- Nominal exterior dimensions: 35 1/8"W x 43 1/8"D x 72 3/4"H.
- Inspection compartment dimensions: 28 1/2"W x 30"D x 23 3/4"H.
- Manipulator: five-axis joystick positioner.
- GTI-5000 Image Processing Software
  Package includes PC, monitor and Inkjet printer.
The RT X-Mini: for real-time X-ray inspection anywhere

Glenbrook’s RT X-Mini™ is a compact, portable real-time X-ray system designed for rapid inspection of multi-layer and assembled printed circuit boards. It may be used on a desk or countertop in an office or laboratory, or hand-carried into a production environment.

The smallest unit of its type on the market, the RT X-Mini weighs 59 pounds and has a footprint of 20 x 6 inches. It is the only real-time X-ray system light enough for overnight delivery.

In common with every other Glenbrook real-time X-ray inspection system, the RT X-Mini is affordable, reliable and easy to use. Its expandable design supports convenient customizing and the addition of options for special applications.

Specifications:
- Operating voltage: 120v, 60 Hz or 220v, 50 Hz (self-switching).
- Anode voltage: 35 kV (internal adjustment).
- Anode current: 30 microamps (internal adjustment).
- Focal spot size: 0.2 mm.
- Focal spot to image plane distance: 4 to 6 inches (factory preset).
- X-ray actuation mode: foot pedal or timer switch.

Options:
- Image processors with advanced image transfer capabilities.
- Multi-feature video micrometer and labeling device.
- Video printer for hard copy.
- XRTV™ Zoom camera for 4X to 50X magnification.
The RTX-113 is designed for heavy production environments where X-ray is used to inspect PCBs and assembled PCBs containing advanced components such as BGAs, uBGAs and Flip Chips. The system is very versatile and features Glenbrook’s patented, award-winning X-ray camera technology that generates high-resolution, high-sensitivity images, revealing defects as small as 0.001 inch with a full one inch diameter field of view.

The RTX-113 provides affordable real-time X-ray imaging, reliable operation and easy servicing.
The RTX-113HV: for real-time X-ray inspection of dense metal BGAs.

With the addition of a higher power x-ray source, the RTX-113HV™ (HighVoltage) provides sufficient power to clearly identify and troubleshoot production faults when inspecting BGAs as well as Flip-Chip, and other advanced packages with more dense metal heat sinks.

The RTX-113HV enables users to perform real-time X-ray inspection on most recently developed BGA technologies. The system incorporates a 70kV X-ray tube and utilizes the patented, award-winning Glenbrook camera technology to provide superior image quality and x-ray tube longevity.

Specifications:
- Nominal dimensions in inches: 53” H (excluding monitor height) x 60” W x 33” D.
- Operating voltage: 120v, 60 hz or 220v, 50 hz.
- Contrast resolution: can resolve 1 mil gold wire.
- Spatial resolution: 20 lp/mm (with MicroTech option, up to 100 lp/mm).
- Anode voltage: 70kV (internal adjustment).
- Anode current: 20 to 50 microamps (internal adjustment).
- Focal spot size: 0.2 mm.
- Black and White Monitor, (Color with GTI-5000 Image Processing Software)
- Focal spot to image plane distance: 4 to 6 inches (factory preset).
- X-ray actuation mode: foot pedal or timer switch.

Options:
- GTI-5000 Image Processing Software™ with advanced image transfer capabilities, and optional BGA Analyzer™ /Void Measurement software.
- Video printer for hard copy.
- MicroTech 10-micron X-ray source with variable magnification up to 225X, for multi-layers and assemblies with BGAs, μBGAs, Flip Chip, ICs and other components.
- Motorized X-Y positioner.
- Variable Angle Viewing allows 45° viewing.
Glenbrook Technologies

A tradition of X-ray innovation

Glenbrook Technologies, Inc. was founded in 1983 to answer the needs of the electronics industry for real-time X-ray systems to inspect printed circuit boards, components and assemblies. In the 1990s, our expertise led us to develop X-ray inspection systems for medical device fabrication and packaging as well as for mail security.

Our in-depth knowledge of X-ray imaging technology has led us to develop many innovations in real-time X-ray technology covered by numerous basic patents. Today, customers in 40 countries realize the benefits of Glenbrook’s superior X-ray imaging technology.

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