Failure Analysis Techniques for Area Array Packages

Reliable estimates put total flip chip production volume at over one billion units for 2000. Most are being used today in low-priced consumer products, such as calculators and watches, where flip chip on board (FCOB) and flip chip on flexible substrates (FCOF) are the preferred applications. The computer and telecommunications markets are also showing good demand for flip chip in package. These high-end applications include microprocessors, ASICs (application specific integrated circuits), and microcontrollers, which are predominantly flip chip in package (FCIP) with ceramic substrates migrating to laminates, mostly of the built-up-material (BUM) variety to handle the high number of I/Os.

X-Ray Imaging

X-ray imaging is useful for looking under area array packages. There are two basic kinds of X-ray systems available, transmission and laminography. Transmission X-ray works like medical X-rays that are used to examine a bone fracture or tooth decay. The x-rays must pass from the source through the sample and into the detector, which measures the intensity of X-rays transmitted and maps that to a gray scale image. Transmission X-ray can find solder bridges, missing balls, flip chip solder extrusions and broken wire bonds. See Figure 1 for an image of solder bridges under a BGA and Figure 2 for an image of flip chip solder extrusions. Transmission X-ray is also useful for checking CSP or flip chip placement alignment on two sided tape during production setup. Laminography is also called tomosynthesis or 3-D X-ray and is similar to a medical CAT scan, which looks at a layer of the sample. Multiple images are acquired at different angles and the layer of interest is then constructed by computations. Laminography can detect...
open solder joints. Data collection times for transmission X-ray are around 20 seconds to 1 minute and for laminography are several minutes to several hours depending on the sample complexity and computer processing speed. Image processing features, such as contrast enhancement, negative edge and integration, are essential to detect the fine details in a flip chip joint. Figure 2 compares flip chip solder joint extrusions with and without a negative edge image processing macro applied.

Dye Penetration Testing

Dye penetration testing can be used to locate fully cracked and partially cracked solder joints in an area array device such as a BGA, CSP or flip chip. The test is relatively inexpensive but destructive. The component of interest must be cut out of the PWB leaving about a .5 to 1 inch border around the component. Clean the assembly by immersing it in isopropyl alcohol or another suitable solvent to remove the flux residue, in an ultrasonic cleaner for 15 minutes. Repeat with fresh alcohol for 1 more minute. Proper cleaning will remove most of the no-clean flux residue and allow the dye penetrant to wick into the solder joint cracks. Several commercial dye penetrants were tested and none have worked as well as Dykem red steel layout fluid #80496 (found in a machine shop supply catalog). The PWB section is immersed in the dye and placed in a vacuum of at least 9 in Hg or better for 1 minute. The sample is then left to soak in the dye for 1 hour. The sample is then removed and dried in an oven at 100°C for 30 minutes. BGAs with rigid component substrates 30 mils or thicker can be carefully pried off with a small screwdriver. CSPs, which normally have thin substrates in the range of 6 to 20 mils cannot be pried off with a screwdriver. The PWB can be repeatedly twisted in alternate directions with two sets of pliers to cause the component to delaminate from the PWB. See Figure 3 for an illustration or CSP removal by PWB twisting. The
fracture surfaces that exist prior to component removal are red after component removal. After removing the component, the joints that were cracked prior to testing will appear red. Some joints are found to be partially red, which indicates that a crack was propagating through the joint, but that it was not completely fractured when the package was removed from operation or thermal cycling.

**Scanning Acoustic Microscopy**

BGAs, CSPs, and flip chips all utilize materials that are not hermetic and therefore absorb moisture through interfaces and surfaces. During reflow the absorbed moisture can outgas leading to popcorn delamination. Here the expanding water vapor creates a pressure that is sufficient to delaminate and possibly crack the package. Acoustic microscopy is currently the best method to look for delamination since it is non-destructive and the physics is well understood. There are several modes of acoustic microscopy but C-mode or C-Scanning Acoustic Microscopy (C-SAM) will be described here.

C-SAM is useful for detecting air gaps, voids and delamination in BGAs, CSPs and flip chip underfill, as well as standard plastic packages. In order to propagate the ultrasound from the transducer to the sample, the sample must be immersed in a water bath so that the water acts as an acoustic couplant. Ultrasound is emitted from the transducer, carried by the water bath and then penetrates into the component. At the interface of two different materials there is a partial reflection of the ultrasound [1]. The same transducer that emitted the ultrasound also detects the reflection. The acoustic impedance of the materials at the interface determines the magnitude and polarity of the acoustic reflection.

![Figure 3: PWB Twisting for CSP Removal](image)

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![Figure 4: Dye Penetration Testing Results (Joints that were still intact will not have red dye on the fracture surfaces)](image)

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Some acoustic impedance values are listed in Table 1 [1]. Acoustic impedance is defined mathematically as:

\[ Z = \sqrt{K \rho} \]

where,

\[ K = \] Bulk Modulus (also referred to as Stiffness, Rigidity or Modulus of Compression in some Mechanics of Materials textbooks) [2]. Physically, Bulk Modulus is thought of as the hydrostatic pressure divided by the change in volume per unit volume.

\[ \rho = \] Density.

The computer translates the magnitude and polarity of the acoustic echo into a black and white or color image called an acoustic image. The C-SAM system is adjusted to collect an image of the layer of interest based on knowing the approximate layer thickness and observing the peaks and valleys in the amplitude scan, which is also called the A-scan. Figure 5 shows a typical A-Scan from a plastic overmolded CSP on an organic component substrate. The following scenarios describe the acoustic reflection as the ultrasound from the transducer traverses from one material to another:

1) When ultrasound propagates from relatively high acoustic impedance material on top to lower acoustic impedance material beneath, the result is a negative reflection;

<table>
<thead>
<tr>
<th>Material</th>
<th>Acoustic Impedance (Kgm^2/s)</th>
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<tbody>
<tr>
<td>Water</td>
<td>1.5 \times 10^6</td>
</tr>
<tr>
<td>Air</td>
<td>0 \times 10^6</td>
</tr>
<tr>
<td>BGA Molding Compound, Underfill, Epoxy Resin and Most Polymers</td>
<td>2.0 to 4.5 \times 10^6</td>
</tr>
<tr>
<td>Copper</td>
<td>42.0 \times 10^6</td>
</tr>
<tr>
<td>Silicon</td>
<td>20.0 \times 10^6</td>
</tr>
</tbody>
</table>

Table 1: Acoustic Impedance of Select Materials [1]

![Figure 5: Typical Shape of a C-SAM Amplitude Scan (A-Scan) from a Plastic Overmolded CSP on a BT Component Substrate](image)

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2) When ultrasound propagates from relatively low acoustic impedance material on top to higher acoustic impedance material beneath, the result is a positive reflection;
3) If delamination or voiding is present, the interface becomes low acoustic impedance or high acoustic impedance (it doesn't matter in this case) to air which has zero (very low) acoustic impedance, resulting in total negative reflection, and therefore the reflection has a very large amplitude and a negative polarity.

The investigator must know something about the sample materials to estimate the acoustic impedance of each. The approximate thickness of the various layers must also be known. Based on the acoustic echo polarity expected for a bonded interface, either a symmetric or asymmetric color map is selected. The amplitude scan is then interpreted to understand the package construction and whether or not delamination or voiding is present. Then a color map and acoustic scanning parameters are selected so that the resulting acoustic image (picture) correctly portrays the sample condition and convention adopted, such as "red is bad/delaminated".

Figure 6 shows a C-SAM image of a Tape Ball Grid Array (TBGA) that outgassed and delaminated during reflow.

**Shadow Moiré**

Out of plane deflection measurements are made using Shadow Moiré Interferometry. Laser Moiré or Moiré Interferometry is the technique that is used to measure in-plane deflections.

![Fringe Pattern Images for UIC - Sample: 35 mm PBGA, Globtop 388 I/O](image1)

**Figure 7: Unprocessed Shadow Moiré Images of a PBGA at Various Temperatures During Simulated Reflow**

![Universal Instruments - Sample: 35 mm PBGA Globtop, 388 I/O](image2)

**Figure 8: Processed Shadow Moiré Contour Plot of a PBGA at 220 °C (Contour plot on the bottom is made from calculations using the three unprocessed images on the top) Reflow**
In Shadow Moiré, white collimated light is shined through a reference grating onto a sample. The reference grating lines cast a shadow on the component. The interference between the reference grating lines and the shadows cast cause a pattern of fringes to appear on the sample as shown in Figure 7. The distance between the fringes correlates to the distance between the reference grating and component. Since the reference grating is fixed, the varying fringe spacing indicates the sample height variation or warpage. The sample and reference grating can both be put in a batch oven that simulates the reflow profile. Images are obtained at various temperatures during the heating cycle. Figure 7 shows Shadow Moiré images of a 35 mm Square PBGA at various temperatures during simulated reflow. Image analysis software can be utilized to convert the Shadow Moiré images into a contour plot in order to facilitate interpretation. Figure 8 shows Shadow Moiré images and a computer generated contour plot of the warpage on a 35 mm PBGA at 220 °C. Shadow Moiré can be conducted on both components and PWBs and can be useful to identify the cause of bridges and opens in area array packages. Figure 9 shows a 3-D plot of the Shadow Moiré data from a 45 mm EPBGA and the PWB that it mounts to.

Figure 9: PWB and 45 mm EPBGA Warpage Comparison

Conclusion
Area array packages have introduced new materials, manufacturing challenges and failure modes. Application of X-Ray, acoustic microscopy, dye penetration testing and shadow Moiré warpage measurement can be used to identify these failures and lead to corrective actions.

References

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Biography
Scott Anson is a Process Research Engineer working in Customer Process Support at Universal Instruments' SMT Laboratory. Prior to joining Universal Instruments, Scott worked for a contract manufacturer where he was responsible for both through-hole and SMT process develop-
ment and support. Since joining Universal Instruments Scott has worked extensively on component qualification and new product introduction, including SMT process development, reliability testing and failure analysis. Scott holds a NY state Professional Engineering License in Mechanical Engineering. Scott also holds an AS in Engineering Science from Broome Community College, Binghamton NY, and both a BS and MS in Mechanical Engineering from Binghamton University, State University of New York. His Master's thesis was on solder paste tackiness testing and he has written technical articles on solder paste. While in graduate school, Scott conducted research under an Advanced Research Projects Agency (ARPA) project to implement no-clean solder paste for military SMT assemblies.

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