Using AXI to Ensure Solder Joint Reliability

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A test strategy that includes AXI can cost effectively minimize the chance that poor solder joints are shipped.

Ideal solder joints form reliable, electrically continuous and mechanically sound connections. To ensure that they perform this function requires that an appropriate design for reliability (DFR) exists so the solder joints, when manufactured to good quality, can perform in the operational environment of the product for its design life.

The need for an appropriate DFR procedure has been well documented, but little has been said about ensuring good solder joints in a technically effective and economic manner. Workmanship guidelines and industry standards have been issued, but verifying that good solder joints are produced is difficult and less than repeatable. However, automated x-ray inspection (AXI) provides the means of effectively and economically ensuring the quality of solder joints.

AXI verifies the structural integrity of solder joints by using appropriate built-in algorithms that map image gray level to solder thickness. This density-mapping allows AXI to verify that proper solder joints with structural integrity have been achieved. AXI users have reported improved product reliability by using AXI to locate poor solder joints.

Solder Joint Quality and Field Failures

A solder joint in isolation is neither reliable nor unreliable; it becomes so only in the context of the electronic components that are connected via the solder joints to some substrate. The characteristics of these elements, with the use conditions, design life and acceptable failure probability for the electronic assembly, determine the reliability of the surface-mount solder attachment with quality solder joints. Thus, good solder joints are a necessary prerequisite to ensure the reliability of an electronic assembly.

Solder joint quality is important in preventing solder joint failures, particularly in the near-term. However, manual visual inspection has been less than fully effective in detecting solder joint failures. In the MIL-spec days, attempts were made in vain to inspect reliability into the assemblies. “Nearly 50 percent of all solder joint failures...analyzed...were field failures that had passed visual subjective industry standards.”

Further, a study by AT&T Bell Telephone Laboratories has shown that manual visual inspection is subjective and unreliable. Given the same assemblies to inspect twice, any two of four inspectors had only 28 percent agreement and only 6 percent agreement existed among all four inspectors.

The Billion Solder Joint Study

To determine if poor quality solder joints are common, an extensive industry study was conducted. The study collected test data for over 1 billion solder joints. The data represented several months of AXI test results from 15 large printed circuit assembly (PCA) manufacturers in North America and Europe. The total market capitalization of these companies is over US$800 billion.

FIGURE 1: The billion solder joint fault spectrum.
To ensure unbiased data, every defect in Figure 1 was verified by visual inspection. The marginal or poor solder joints account for 28 percent of the defects (shown in reddish tint in the figure). The data show that poor solder joints are common. These reliability-related defects cannot be found with in-circuit test (ICT) methods. Some defects may be caught by manual visual inspection and never shipped to the end customer. However, with today’s high-density packaging technology, limited visual inspection cannot reliably find all of these poor solder joints. For ball grid array (BGA) packages, identifying poor solder joints by manual visual inspection is impossible.

How AXI Catches Poor Solder Joints

In-circuit tests locate defects by doing electrical measurements on the PCA. Anomalous results indicate the presence of defects, but their location and nature have to be determined by further analysis.

In contrast, AXI finds defects by comparing the density signatures of every solder joint to the signatures of solder joints with known structural integrity. AXI measures such variables as average solder thickness, heel thickness and solder volume and compares these measurements to known, acceptable measurements.

As compared to ICT, AXI typically provides greater than 95 percent fault coverage of the defects shown in Figure 2. The x-ray fault spectrum is both overlapping and complementary to ICT. AXI can improve product reliability because of its unique fault spectrum. AXI is able to find insufficient solder, poor fillet shape, wetting problems and other characteristics of poor solder joints. Many manufacturers rely on manual visual inspection, but AXI is a technology that can reliably and repeatedly find these defects.

Insufficient Solder: Fine-Pitch Gullwings

Figure 3 shows two pins from a 208-I/O fine-pitch gullwing component. The cross section and x-ray images of Pin 3 and Pin 156 respectively demonstrate the best and the worst solder joints in the spectrum of quality differences in this component. The cross sections of the solder attachments of Pin 3 and Pin 156

![FIGURE 2: AXI and ICT fault coverage comparison.](image-url)
correlate with the physical differences shown in the enlarge-
ments of the x-ray images of their solder attachments.

The leads of this fine-pitch gullwing component are not of
optimum design from a reliability perspective; a good reliability
design has a foot length of at least three times the lead width.
These leads have a foot length of about twice the lead thickness,
which is always less than the lead width. A lead foot this short is
very stiff and will rock during global thermal expansion mis-
matches, even if the rest of the lead is very compliant. The result
is an increased likelihood of crack initiation at either the heel or
the toe fillet of the solder joint.

The heel and toe fillets of Pin 3 are marginally adequate for a
fine-pitch lead. The heel and toe fillets of Pin 156 are not ade-
quate even for a fine-pitch lead. Further, the solder joint geom-
etry may indicate inadequate wetting as well as insufficient sol-
dier. This solder joint geometry creates stress concentrations at
both the heel and toe fillets, which make a premature solder
joint failure that much more likely.

The graph in Figure 3 shows the relative measurements of the
solder joint heels, the center section of the solder joints, and the
solder joint toes of Pin 3 and Pin 156. The latent defect of the
Pin 156 solder joint is clearly defined in comparison with the
measurements from Pin 3.

The quality differences in the solder joints are automatically
measured by the AXI system. The measured values are compared
to standard acceptable values. These standard values can be
defined by engineers to correspond to measurable quality fea-
tures, and, thus, AXI can automatically differentiate between
acceptable and defective solder joints. In contrast, with manual
visual inspection, line inspectors make subjective judgments on
solder joints that are at best difficult to see.

**Floating Surface-Mount Connectors**

In Figure 4, cross sections of soldered leads and the related x-
ray images from two different surface-mount connectors are
shown. The solder joint on the right appears to be floating on
top of the solder and is clearly less robust than the solder con-
nection on the left.

For the untrained eye, looking at these x-ray images may not
provide significant information about the quality of these solder
joints. However, the measurements of the solder joint features,
extracted by AXI algorithms and shown in the Figure 4 chart,
clearly show the differences in the quality of the solder joints.

The algorithm determines the location of the solder joint
heel by averaging the locations of all the high-density (darkest)
Ensuring the quality of solder joints in an economically viable manner is an important consideration in whether AXI makes sense.

areas resulting from the solder heel fillets. Ordinarily, this technique works very well; in this case, no solder joints on this connector have heel fillets. Thus, the location of the highest density mapping is not the heel but the location underneath the lead foot where the solder joints actually start; the relative density/thickness from the actual heel location is estimated in the chart. Despite the mislocation of the solder joint heel, the AXI recognition algorithm correctly flagged the solder joint as defective because the heel/center comparison does not meet the solder joint features for a robust joint.

Measurements of heel thickness larger than the center thickness indicate the presence of a heel fillet. The larger the difference, the more of a heel fillet exists. The x-ray image on the right in Figure 4 shows very little difference between the heel and center measurements for its joint, but a significant difference for the joint on the left.

Surface-mount connectors frequently are not mechanically staked. Thus, the surface-mount solder joints have to withstand any mating/unmating stresses as well as the stresses from any thermal expansion mismatches between the connector body and the PCB. Therefore, the solder joints for unstaked surface-mount connectors must be mechanically sound and as robust as possible. AXI can effectively find solder joints not meeting these criteria.

**Insufficient Solder Joint: Resistor Chip**

The defect in Figure 5 is readily apparent both with manual visual inspection or x-ray inspection; the solder fillet on one side of the component is missing. The x-ray inspection is automatic and would find this poor quality joint with 100-percent assurance. Such certainty is unlikely with manual visual inspection, particularly for assemblies with a large number of small components.

However, this component has some solder wetting underneath the resistor chip between the chip metallization and the solder pad on the PCB. Thus, this defect would not show up during electrical or functional testing. However, during environmental stress screening (ESS) or after a short time in the field, this latent defect is likely to result in a fractured solder joint. This fractured solder joint might result in a complete electrical open but, more likely, would be a difficult-to-find intermittent open.

The increased threat to reliability comes from the geometry of the filletless solder joint and the unequal strength of the two solder joints. The geometry of the filletless solder joint makes early crack initiation much more likely. The unequal strength of the two solder joints shifts the load toward the solder joint with the fillet, thereby substantially increasing the stress/strain on the weaker solder joint.

The density/thickness measurements in the Figure 5 chart for the chip resistor’s two solder joints clearly show how different these numerical values are and how unambiguous the detection and flagging of solder joints with latent defects is using automated x-ray inspection.

**Economics**

Manufacturers today can do exhaustive testing, including ESS and cross sectioning, to ensure good quality solder joints.
However, most manufacturers do not do these tests because the costs are prohibitive. Thus, ensuring the quality of solder joints in an economically viable manner is an important consideration in whether AXI makes sense.

AXI can have a very positive economic payback. In addition to potentially reducing field failures, AXI users have reported one or more of the following benefits:

- reduced rework at ICT and functional test
- faster time-to-market
- faster manufacturing cycle times
- reduced failures at ESS
- elimination of ESS
- lower cost and higher coverage prototype test.

The economic impact of using AXI depends on the product, volume, reliability requirements, cost of repairs at various test stages, field failure rate, consequences of failure and other factors. Typically, larger, more complex boards, or boards with limited access, have the strongest economic payback.

The cost of a single field failure can be dramatic. Repair costs can range from a few dollars to hundreds of thousands or even millions of dollars. As an example of the economic impact of reducing field failures, consider the following assumptions:

- a board has approximately 5,000 solder joints
- cost of field repair, \( c_1 = $400 \)
- cost of testing board, \( c_2 = $3 \)
- boards tested per AXI system in 1 year, \( n = 400,000 \)
- percent reduction in field failures, \( p \)
- savings, \( S = (c_1 \times p \times n) - (c_2 \times n) \)

Using these assumptions, the savings based on reductions in field failures are shown in Table 1. The reason for the AXI cost savings is fairly simple: AXI typically replaces manual visual inspection and is much more effective at catching and pinpointing the defects. Repair costs for defective solder joints found using AXI are very low because AXI locates the defects. In addition, AXI does not require physical access to the board. These facts, combined with the improvements in AXI equipment in the past few years, mean that AXI can often deliver a very good economic value.

**Conclusion**

AXI can effectively and economically ensure the quality of solder joints. AXI has built-in and definable fault spectra that can identify poor solder joints. The billion solder joint study showed that these poor solder joints are common in the industry. These solder joints are often electrically and functionally good after assembly but are potential field failures.

To ensure the long-term reliability of solder joints, both DFR procedures and good solder joints are necessary. A test strategy that includes AXI can cost effectively minimize the chance that poor solder joints are shipped.

**References**

13. Study conducted by Agilent Technologies, Loveland, CO.

**TABLE 1**: Savings based on reductions in field failures.

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<thead>
<tr>
<th>% Reduction in Field Failures</th>
<th>Yearly Savings from 1 AXI System</th>
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<tr>
<td>1</td>
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