X-RAYS

Expose Hidden Connections

With an x-ray inspection system, you can check the quality of the solder joints under a BGA.

Ever since Wilhelm Roentgen discovered x-ray radiation in 1895, people have been using x-rays to reveal hidden structures in almost everything — vegetable, animal, and mineral. In the electronics industry, inspection systems using x-rays prove particularly adept at examining hidden solder connections on PCBs. In fact, x-rays provide the only practical way to inspect the connections between ball-grid arrays (BGAs) and a PCB (Fig. 1).

Using x-ray systems on a production line that incorporates BGAs into products makes a great deal of sense. The systems are available at reasonable cost; they come in several types; they're easy to set up; and they let users quickly change from one type of PCB to another. Unlike many electrical testers, x-ray systems require no fixturing, so they're ideal for short runs and prototyping.

Test engineers use x-ray systems to look for several types of defects at BGA solder joints, including missing connections, solder bridges, solder voids, open connections, and misregistration of parts:

- **Missing connections.** Although BGA manufacturers inspect packages to ensure that all solder balls are in place, nothing is perfect, and a BGA or two may arrive at the production line missing a solder ball. Also, mishandling a BGA during production could dislodge a solder ball. Placing a BGA with a missing solder ball on a PCB results in a missing connection — an open circuit. In an x-ray image, missing connections appear as light areas where a good BGA would show a dark solder ball.

- **Solder bridges.** Solder bridges between contacts — essentially short circuits — result from excess solder or misplaced solder, often caused by a dirty solder-paste stencil. Bridges also can occur after rework of a BGA because of the difficulty of perfectly rescreening solder paste on the reworked area. Bridges show up in an x-ray image as dark connections between two or more adjacent PCB pads (Fig. 2).

- **Voids.** Solder paste may include voids, which appear as light spots within the dark ball area in an x-ray image (Fig. 3).
Trapped materials such as solder flux cause voids; entrapment can result from a lower-than-ideal reflow temperature that prevents flux from escaping. Voids also can result from matter picked up by the solder paste from an improperly cleaned PCB.

Most products can tolerate some void volume, usually called “voiding”. In most cases, manufacturers specify tolerable voiding as a percentage of the solder area in an image of a ball: The value depends upon how they define the edge in an x-ray image between a void and the surrounding solder. When done manually, the measurement is subjective, but image-processing software can set rules that reproducibly measure the voiding in a connection.

Test engineers and quality-control staff must decide what amount of voiding they can accept. As a rule of thumb, a void area (in the image) of less than 20% of the ball area is generally OK. Too much voiding means that a joint may not stand up well to stress. If a board won’t undergo much stress, the customer may accept a higher percentage of voiding rather than incur the cost of rejecting boards that will function properly under benign conditions.

Some amount of voiding may actually enhance reliability by providing a bit of strain relief and compliance in solder joints. At present, though, the electronics industry has no standards to cover voids and the amount of voiding that is acceptable or unacceptable.

- **Open connections.** An open, or cold-solder, joint indicates a poor or nonexistent connection between a solder ball and a PCB pad. These poor connections result from improper reflow of the solder between a solder ball and the PCB pad. By looking at the solder joints from the side, an oblique view, an x-ray system can show you solder that hasn’t reflowed properly and has not collapsed the balls into place on a proper joint (Fig. 4). Cold-solder joints exhibit a different texture than properly reflowed solder joints, but the industry lacks a standard for the appearance of a “proper” joint. You must determine through experience what types of joints look good and what types don’t.

- **Misregistration.** Misregistration occurs when PCB pads, solder balls, solder paste, or PCB solder mask are

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**Where Do X-Rays Come From?**

Wilhelm Conrad Roentgen (1845-1923) discovered x-rays while experimenting with cathode-ray discharge tubes in 1895. Roentgen noticed that when he used such tubes, a nearby chemical compound fluoresced, even when shielded from the tube by thin sheets of metal. He deduced that the energised tubes were producing a new type of radiation, which he named the x-ray, or unknown ray. For his discovery, Roentgen received the first Nobel prize in physics, bestowed in 1901.

When high-energy electrons — such as those in Roentgen’s tubes — collide with a metal target (anode), the rapid deceleration of the electrons produces x-ray radiation, photoelectrons, Auger electrons, and much heat. Depending on the target (usually copper, molybdenum, or tungsten), the energy of the electron beam, and the amount of vacuum, an x-ray tube can produce white x-ray radiation and also several discrete wavelengths of x-ray radiation. By harnessing that radiation, people have put x-rays to work inspecting things that are otherwise difficult or impossible to view.—Jon Titus
not properly positioned, or “registered”. An x-ray image of misregistered components (Fig. 5) will show the dark solder balls slightly offset from the lighter PCB contacts. Misregistration also may appear as tadpole-like tails that trail off from solder balls.

Measure Quantitative Data, Too

Depending on the sophistication of the x-ray system you plan to use and the software that works with it, you also can measure quantitative information such as solder-ball diameter, circularity, flattening, and thickness. These characteristics can reveal characteristics of good or bad joints, but how the measured values relate to good joints varies by package type, ball size, and manufacturers’ tolerances.

In most cases, you’ll make the quantitative measurements listed above right after the solder-reflow process. You can perform x-ray inspections prior to reflow, but experience shows that a post-reflow inspection works just as well — and it can catch true misalignments. During reflow, surface tension exerted on the solder balls by the molten solder tends to pull the BGA back into position. Thus, slight out-of-registration errors found prior to reflow may turn out to be false problems.

Gross misalignment can be a problem, though, so consider using x-ray inspection often as you bring a production line into operation. Several x-ray inspections can help you determine whether solder printers properly position paste on boards, pick-and-place equipment aligns parts within spec, and so on. The x-ray images can help you detect process problems so you can correct processes before initiating full-scale production.

Inspect Everything?

You may wonder if every joint on every board needs inspection. You can inspect everything, but a company that produces boards containing only two or three BGAs may find that an x-ray image of only one device lets it monitor what goes on during production. As an alternative approach, once a process runs well, a manufacturer could inspect every nth board, or a sample lot of boards.

Some companies do demand 100% inspection to ensure high reliability of the products they ship. Tracey Raglan, a test engineer at Agilent Technology’s Printed Circuit Assembly facility (Loveland, CO), says about 120 of the printed circuit board assemblies (PCBAs) at the Loveland facility get x-ray inspection. Of these 120 PCBAs, approximately 80% receive 100% inspection.

Inspection systems come in a variety of types that range from basic manual off-line systems for low-volume production to completely automated in-line systems for high volumes (see the Box “Manufacturers of X-Ray Inspection Equipment” on page 12). The inspection techniques used in these systems vary from single x-ray transmission to sophisticated tomography and laminography. (See For Further Reading.)

A transmission image shows the results of passing an x-ray beam through everything in its path, regardless of where it exists on a PCB. Thus, a basic transmission image works well for boards that have components on only one side; the image of a double-sided board would contain images of parts from both sides and would be difficult to read. In contrast, tomography and laminography can visually separate components on both sides of a board. Several systems use sophisticated software-processing techniques to produce three-dimensional views of solder balls and connections (Fig. 6).

Choose Manual or Automatic

In a manual system (Fig. 7), you posi-
tion a PCB and use the x-ray system to capture an image of the hidden connections. Then, you view and interpret the x-ray image. You can manually adjust the magnification, position, and viewing characteristics when you need to see a joint in more detail. In some systems, you can rotate the PCB to view the board at an angle. Manual systems may include software that can perform metrology and image-analysis tasks, such as measuring dimensions, determining the area of voids, and so on. You set the acceptable tolerances for measurements such as voiding and solder-ball size.

An automated system provides a computer that assumes control of the x-ray inspection system. The computer’s software directs it to position the board, tells it what parts of the board to examine, and specifies what control system settings to use. The software contains test parameters — the characteristics of good and bad connections — that you have established for a product. After inspecting a board, the system provides a pass/fail report along with information for use during rework and for adjusting production processes.

Automated systems also provide manual controls so an operator can take complete control of the system as needed, perhaps to zoom in on a connection or problem area. Using these manual controls, an operator can check prototype and development assemblies without needing to program the x-ray system for a new product.

**Operators Will Need Training**

Unlike ATE systems that require extensive test-software programming, testing, and debugging, an x-ray system can rely on a trained operator and a combination of CAD data and product specs to perform its measurements. Operators and test engineers must receive training on an x-ray system before they can use it properly. Training ranges from a few days to a week or more, depending on the complexity and the capabilities of a system.

For all systems, operators must know how to set up and operate the system and also know what defects and good joints look like. Automated systems and systems that use software require training so operators can establish test programs and program the system with the parameters for the inspections they want to perform. When a board incorporates a new

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**Assess the Real Cost of X-Ray Inspection**

Stephen F. Scheiber, ConsuLogic Consulting Services

When you evaluate x-ray inspection as an alternative to in-circuit test, your concern may centre on the higher apparent cost of an x-ray system. X-ray system prices can significantly exceed those of in-circuit testers, and in some cases a single inspection system may not let you achieve adequate production throughput. So how can you justify the cost?

A thorough cost comparison must examine equipment purchase prices and incorporate additional costs that change the economic balance. Consider the impact of missed faults. Today’s boards make extensive use of BGAs, flip chips, and other surface mount technologies that block access to critical nodes. Lack of access often reduces fault coverage to unacceptable levels, thus passing problems down the line, where finding them is much more expensive. X-ray inspection can reveal faults that in-circuit testing may not identify properly, so an x-ray inspection can reduce the number of boards you must scrap.

Remember that an x-ray system requires no fixtures, thus saving many thousands of dollars per test station. On a low-volume, high-mix production line, fixture costs represent expensive overhead. And unlike in-circuit test systems, x-ray systems require no conventional program development. X-ray system manufacturers claim start-up times of a few days versus several weeks for in-circuit test systems.

Often, the time and cost required to develop a bed of nails for electrical testing discourages initiating in-circuit testing of prototypes. And prototype boards change frequently, so fixture rework adds even more cost to in-circuit test.

Yet, analysing prototype boards and using test results to adjust manufacturing processes — or the design — can hasten ramp-up and increase manufacturing yields once production begins. An x-ray system lets you start testing with the first prototype board, and you can continue testing right through to production. Someone may remind you that an x-ray system cannot determine whether the proper components are on a board. That’s true, but proper process monitoring and control will ensure that incorrect components are used rarely, if at all.

Perhaps the most compelling technical argument in support of x-ray inspection relates to its ability to detect process problems that pass electrical test but may lead to field failures. For example, a joint with insufficient solder can crack from mechanical board stresses that may occur during normal operation. In-circuit test can’t detect a lack of solder, but x-ray inspection can.

No one suggests that x-ray inspection is inexpensive. But if you examine its benefits over the entire production process, you may find it less expensive than other, “cheaper” alternatives.
type of component, the operator must know how to add the new component to the system's parts library.

You may wonder why such capable inspection systems aren't more widespread in production facilities. Many engineers still think of x-ray inspection as an esoteric technique and they aren't aware of how well an x-ray system can find hidden problems. Also, they think an x-ray system costs a lot. These days, costs range from $50,000 for a basic manual unit to $500,000 for a completely automated in-line inspection system. When compared with the costs of field returns and the costs of producing marginal products, the cost of an inspection system should seem more reasonable (see the Box “Assess the Real Cost of X-Ray Inspection” on page 11).

For Further Reading