PCBs are becoming more complex in many different attributes: component physical characteristics, performance requirements and end-use. These characteristics change based on design and market goals. The combination of these forces drives different manufacturing strategies to match the desired end-customer experience and create new testing challenges. In-circuit testing has been the industry’s main workhorse. Its technology has been successfully applied to almost all product types. PCB changes have made it more difficult for ICT to identify defects, not to mention consistently reduced electrical access. Test vendors have responded with innovative solutions to slow the loss of access\(^1\). X-ray inspection has become an important part of manufacturing strategies for medium-to-complex assemblies. As x-ray has matured as a testing solution, new package types, increasing line speeds and a need to continually reduce conversion costs also have challenged it.

New package types will continue to be required to deliver tighter density and performance. A relatively recent package innovation is PolarPAK. This thermally enhanced package improves MOSFET heat removal by providing cooling from the package’s top and bottom sides while reducing size and cost. For x-ray, it presents a new solder shape to be analyzed to determine solder quality.

For example, **Figure 1** shows a properly soldered component. The two outside pads are drains; the two connected pads are source pads, and the fourth column from the left is the ground pad. The red circle highlights the correct solder wicking of the source pads. **Figure 2** shows an example of a defect. The defect result is insufficient wicking of the solder onto the package pad. The result shows the improper joint formation on the FET source pads. After investigating this defect, the cause was insufficient solder paste applied to the pad. Other types of defects that have been seen are voiding, package placement and nonuniform solder distribution.

### Reduce Conversion Costs

Many available economic models perform x-ray inspection cost/benefit analyses. The key benefits are primarily derived from early detection and extensive coverage of manufacturing defects and the corresponding low-cost repair actions. X-ray inspection directly identifies solder joints that do not meet manufacturing standards. The corresponding repair time is relatively small compared to the time required after ICT or the failure analysis required if a defect escapes to functional test. The increase in cost to find and repair the defect at functional test is caused because of poor failure diagnostic capability. Savings caused by the increase in first-pass yield at test steps following x-ray typically result in a strong, positive return on investment. Regardless of the ROI, there is always a drive to improve profitability and reduce conversion costs. In analyzing x-ray inspection costs, one can create relatively straightforward financial
cost models that include inputs such as test volumes, line speeds, assembly characteristics, expected assembly defect per million opportunities rates, system cost, depreciation schedules, operational maintenance costs, test step effectiveness, operator costs, repair costs and repair efficiencies. Using such a model for a manufacturing scenario featuring 600,000 boards per year, typical boards with 15,000 joints and 4,000 components, and average industry defect levels, the cost per board for x-ray inspection and repair is approximately $10.50 to $12 (using U.S. labor rates) depending on defined labor rates. This cost can be reduced to $3 to $5 by manufacturing in a low labor-cost region.

X-ray inspection and repair cost per board is strongly dependent on the direct labor rate required for repair. Approximately 52% of the total cost is associated with actual repair. This cost does not include the cost of the component being replaced. The remaining 48% comes from the actual system cost and inefficiencies associated with repair. X-ray users impact the cost model by manufacturing in regions where there is low direct labor rate or by implementing sampling techniques, thereby reducing the total amount of test required. X-ray vendors help reduce the conversion cost by focusing on lowering the capital equipment cost, increasing the effectiveness of the solution call rate, and increasing the system throughput.

**Capital Cost Reductions**

X-ray capital cost reductions are achieved in much the same way as other electronics:

- Move manufacturing operations of the test equipment to low-cost regions.
- Design for lower cost.

For x-ray, moving manufacturing provides such benefits as lower direct labor costs, lower parts costs and lower shipment costs. Complex machine assembly such as x-ray is labor intensive. For example, stage solutions tend to be more complex than those of AOI systems. If the components are sourced from the same region, they too can be lower as they benefit from localization. Finally, a large portion of x-ray users resides in these same low-cost regions. Therefore, final system shipment is correspondingly reduced. Agilent has seen shipment costs of $1.00 – $2.51/kg to ship to Asia, $3.30/kg to ship to the U.S., and $6.17/kg to ship to Europe.

To design for lower cost means R&D needs to take different approaches. For example, some x-rays require expensive laser mapping to create a surface model of the panel under test. In older solutions, this is required to ensure that the system can focus at the right z-height. As an example of cost reduction, Agilent has eliminated the laser-mapping require-ments through innovative focusing algorithms. This reduces system cost, decreases program development time, and increases machine effectiveness.

A system throughput increase has a direct impact on conversion cost by reducing the number of systems required to meet manufacturing volumes. Typically, throughput increases have come incrementally by increased efficiency in panel handling, image acquisition or image analysis. Increases in panel handling efficiency include faster movement of the panel within the system, panel vibration reduction and panel loader use. Image acquisition speed increases can include elements such as reduction in image overlap, parallel image capture, faster detector readout and improved x-ray to light conversion. Image analysis speed is typically addressed by using efficient analysis algorithms and by leveraging Moore’s Law. As an alternative to increasing the basic speed of the system, some solutions rely on using a combinatorial approach of 2-D and 3-D x-ray inspection. 2-D x-ray inspection has been traditionally much faster than 3-D. This is achieved by using a large field of view (FOV). For single-sided or simple double-sided boards where the designer has followed strict design-for-x-ray guidelines, 2-D is an effective solution for detecting soldering defects.

A combinatorial strategy is to inspect most of the board with 2-D and then augment defect coverage with 3-D on a small portion of the board as necessary because of joint shading. This strategy breaks down quickly as the complexity of the board increases. In a recent evaluation of different board types, the percentage of overlapping solder joints caused by double-sided boards ranged from approximately 8 to 40%. The 8% was on a typical, low complexity automotive double-sided board. These boards are usually designed to be inspected by 2-D x-ray. This shows how difficult it is to design a double-sided board without overlapping solder joints. The combinatorial strategy can currently provide high throughput and high defect coverage on this type of product. In typical medium-to-high complexity communications products, 25 to 35% of solder joints are overlapping. Using 2-D alone on these products has an immediate and significant coverage loss. Furthermore, these overlapping joints are often spread throughout the board. This requires a significant amount of (much slower) 3-D inspection for coverage.

The general manufacturing trend of increased joint density is in conflict with the overall long-term success of a combinatorial strategy. To meet manufacturing needs then, high-speed 3-D
X-Ray Inspection

To Sample or Not

Some manufacturers use either board- or device-based sampling techniques to increase automated x-ray inspection (AXI) throughput. The implication of any sampling strategy is that a user is trading off throughput against defect coverage. Several studies\(^2\) have indicated x-ray inspection is the single best step for capturing solder-related defects. In many cases, defects detected cannot be found at any other test step. Therefore, the very nature of sampling in a continuous flow environment means that defects that would have been caught at x-ray are passed to the next test step. This is true of board- or device-based sampling. Thus, sampling can be an effective test strategy when the end product has three characteristics:

- Very high first-pass yield into ICT or functional test.
- High defect coverage at ICT or functional test.
- Low cost/risk associated with field failures.

Typically, repair cycles at either of these steps take longer than x-ray. At functional test, which typically has poor repair diagnostic resolution, repair time can be 10 times greater than repair time at x-ray. The second condition is necessary to reduce the number of escapes that will make their way to the end-user.

Manufacturing defect phenomena have traditionally been categorized as either systematic or random. Systematic defects can be those caused by situations like a clogged stencil at paste deposition or an incorrect reel at the pick-and-place system. These types of defect causes affect multiple boards in sequence. Typically, the earlier in the process that this type of defect cause is detected, the lower the overall repair cost. AOI-based solutions for solder paste or pre-reflow inspection have been developed specifically for finding these structural types of defects quickly and efficiently. As the name suggests, random defects have no readily identifiable cause. The frequency of this class of defect, product cost and overall warranty cost of an escape drive the manufacturing defect containment solution. X-ray has been shown to be an excellent solution for capturing the broadest range of defects. The level of sampling at x-ray directly correlates to the number of random defects that escape to the next test steps. The following formula\(^3\) approximates the turn-on rate based on the number of defect opportunities (n) and the defect rate of the process (DPMO).

\[
Yield = \left[1 - \left(\frac{DPMO}{10^6}\right)^n\right]
\]

This formula is a reliable predictor of yield for totally random defects. Figure 3 shows the estimated yield of a board with 20,000 solder joints; an excellent solder joint defect rate of 50 DPMO will have a turn-on rate of about 37%. Without a solution to effectively detect these defects, the result will be a large number of boards failing functional test or escaping to the end-customer with the potential for field or warranty failures.

References


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