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Both provide access and information that electrical and functional testers no longer can

Comparing costs and ROI of AOI and AXI

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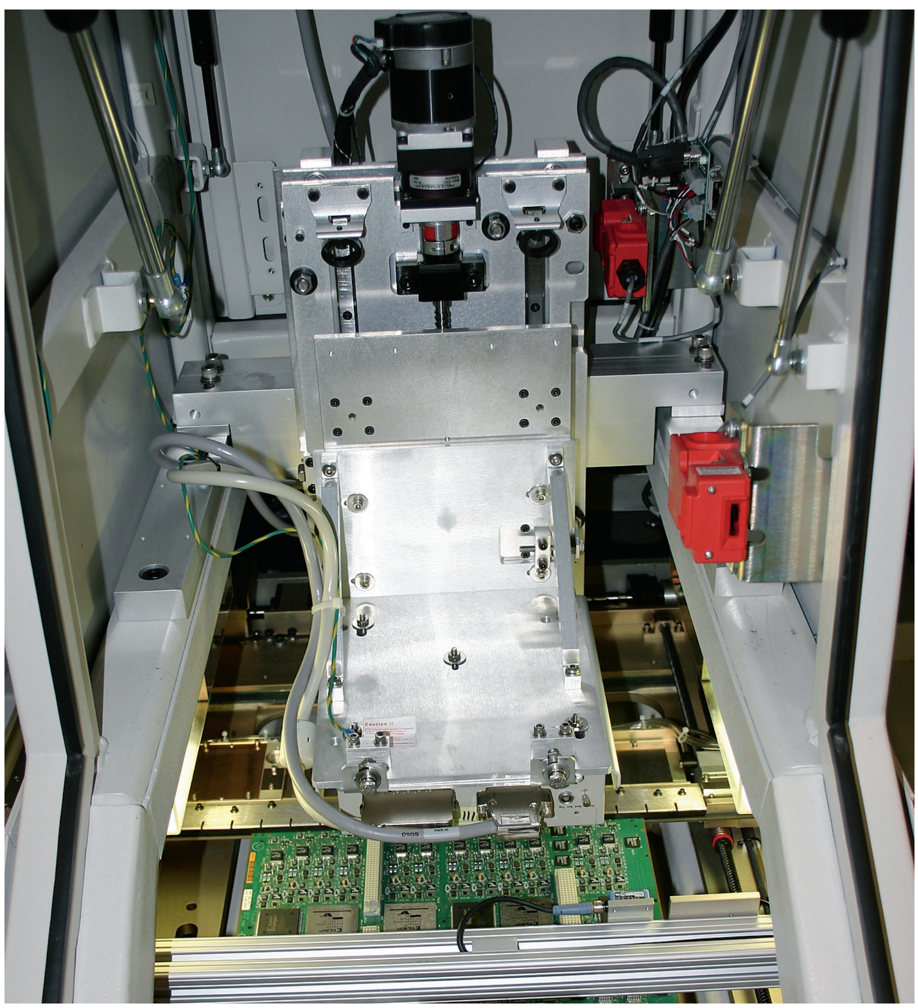
PCB architectures have continued their steep trend toward greater complexities and higher component densities. For quality control managers and test technicians, the consequence is significant. Their ability to electrically test these products is compounded with each new generation. Probe access to high density boards loaded with micro BGAs using a conventional in-circuit (bed-of-nails) test system is greatly reduced. The challenges and complexity of creating a comprehensive functional test program have all but assured that functional test will not fill the widening gap. This explains why sales of automated-optical and automated X-ray inspection (AOI and AXI) equipment have dramatically risen.

Both systems provide valuable access and information that electrical and functional testers no longer can. AOI and AXI solutions each offer their own set of advantages and drawbacks. AOI generally costs less to implement and is typically easier to set up than AXI. Manufacturers using AOI also have more flexibility in terms of where to inspect a product within the various production stages. AOI can examine solder pads, for example, before the board contains any components. It can be used for both pre- and post-reflow inspection. Its biggest drawback is that it requires line-of-sight access. When nodes are hidden by BGAs and other large components, as well as by EMI shields and heat sinks, AOI cannot achieve the levels of fault coverage needed to meet today's demands. And as board complexity grows, many manufacturers find that AOI produces an inordinate number of false calls, further increasing the burden on repair and test activities.

Unfettered by line-of-sight restrictions, an AXI system's ability to locate faults is far less limited by board layout. It can detect a greater variety of solder problems, voids, tombstones and other solder quality defects that are otherwise invisible to optical systems. As a result, AXI produces fewer false calls. Nevertheless, its higher initial system cost and complex programming procedures have discouraged some manufacturers from considering it for their production line. As this article will demonstrate, however, the return on an AXI investment is considerable.

The long-term economic benefits of AOI and AXI include many more factors than their initial pur-



A view of Teradyne's new XStation 3-D AXI system

XStation MX is Teradyne's new 3D X-ray inspection station

	3D AXI	AOI	ICT	FT	System
Test Access	99 %	75 %	80 %	50 %	25 %
Fault Coverage – Structural	98 %	97 %	80 %	60 %	60 %
Fault Coverage – Electrical	0 %	0 %	89 %	85 %	99 %
Test Coverage – Structural	97 %	73 %	64 %	30 %	15 %
Test Coverage – Electrical	0 %	0 %	71 %	43 %	25 %
Test Coverage	88 %	66 %	65 %	31 %	16 %
False Fail Rate (PPM)	500	1250	50	10	2

Table 1: Defect coverage and system compatability data

Verification

AXI: 10 % % of real defects incorrectly verified
AOI: 15 % % of real defects incorrectly verified

AXI: 98 % % of false fails verified correctly
AOI: 97 % % of false fails verified correctly

chase price. The industry has long proved that finding faults earlier in the test and inspection process is significantly less expensive than uncovering them later. And processing a high number of false failures only subjects boards to unnecessary repair cycles that waste both time and money. Given their respective capabilities, fault coverage and costs to implement and maintain, which of these two inspection methods will yield the higher return on investment (ROI)?

Differing expectations

Before examining the economic effect of introducing inspection to a production line, it is important to consider the fundamental differences between these techniques and more conventional testing. Functional test verifies that the whole board operates correctly under something resembling normal conditions. In-circuit test examines the board in electrical sections, and helps to ensure that those pieces work together.

Inspection, on the other hand, examines the board to determine if the physical attributes are correct. A joint containing insufficient solder may work perfectly in the board's target system (although it certainly represents a reliability risk), so it will pass electrical test, but proper inspection will identify it immediately as a defect. On the other hand, a cold solder joint may look perfectly normal, but it may not be making proper contact at all. In addition, an assessment of whether a solder joint is good or bad must take into account the range of what "good" solder joints can look like, a limitation that helps to explain optical inspection's relatively high false-failure rate. Therefore, a fair comparison of the two inspection techniques requires one to include their economic and logistical impact on the repair cycle and other downstream processes as well as the direct monetary outlay.

Also, most boards that fail electrical test go to a diagnosis and repair area, after which the boards return for a second test cycle. Only after several (often three to five) cycles is the board rejected as scrap. A board that fails either AOI or AXI inspection goes from the repair bench to the next step – usually in-circuit test – because the repair itself introduces manual solder joints that look considerably different from those produced in the reflow oven, so inspection may not consider them to be "good" joints.

The human manual nature of diagnosis and repair has other implications as well. Repair technicians often label real failures as false and some false failures as real, only complicating the downstream

Board Assumptions						
Number of solder joints	4.000					
Number of components	400					
Annual production volume	50,000 boards					
Value of board if/when scrapped	$ 600					
Total opportunities for error	4.400					
Repair Assumptions						
Repair yield	90 %					
Number of repair cycles permitted	3					
PCB scrap rate	0,10 %					
Component scrap value per repair	$ 5					
Defect Rate Assumptions (Process Capability)						
Electrical DPMO (ppmC)	160					
Structural DPMO (ppmJ)	250					
Board DPMO	242					
Qty of structual defects per board	1					
Qty of electrical defects per board	0,064					
Debug Diagnostics and Repair Costs		**AXI**	**AOI**	**ICT**	**FT**	**System**
Hourly labor costs of verification/diagnostics		$ 30,00	$ 30,00	$ 30,00	$ 30,00	$ 30,00
Hourly labor cost to repair		$ 35,00	$ 35,00	$ 35,00	$ 35,00	$ 35,00
Time to verify/diagnose one defect (minutes)		0,08	0,08	5	10	60
Time to repair one defect		10	10	25	50	50
Cost to debug/diagnose one defect		$ 0,04	$ 0,04	$ 2,50	$ 5,00	$ 30,00
Cost to repair one defect		$ 5,83	$ 5,83	$ 14,58	$ 29,17	$ 29,17
Re-Test Cost		$ 0,00	$ 0,00	$ 1,00	$ 1,50	$ 3,00
Cost of Field Failures/Returns	$ 2.500					
Current Field Return Rate without AXI	0,10 %					
Annual Equipment Costs		**AXI**	**AOI**			
System + Operation + Maintenance Amortized of 5-years		110.000	30.000			

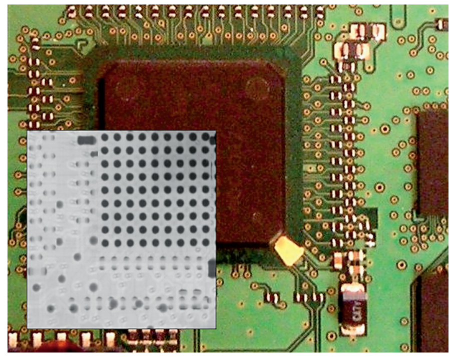
Table 2: Board assumptions and costs (USD) for a typical PCB assembly process

	ICT	FT	System	Costs
Structural defects before test (per board)	1,00	0,36	0,25	
Structural defects after test (per board)	0,36	0,25	0,21	
Electrical defects before test (per board)	0,06	0,02	0,01	
Electrical defects after test (per board)	0,02	0,01	0,01	
Structural defects found (per board)	0,64	0,11	0,04	
Electrical defects found (per board)	0,05	0,01	0,00	
Total defects found (per board)	0,69	0,12	0,04	
First pass yield	50,4 %	89,1 %	96,0 %	
Overall test effectiveness	64,0 %	31,0 %	15,0 %	
DPMO remaining on board after test	86	59,7	50,5	
Annual cost of verification	$ 85.696	$ 28.958	$ 60.635	$ 175.289
Annual cost of repair	$ 499.893	$ 168.924	$ 58.950	$ 727.768
Annual cost of component scrap	$ 171.392	$ 28.958	$ 10.106	$ 210.456
Annual cost of PCB scrap	$ 27.167	$ 4.795	$ 1.477	$ 34.099
Annual cost of retest	$ 24.810	$ 8.203	$ 5.943	$ 38.956
Annual cost of field failures and returns				$ 125.000
Total	$ 784.148	$ 231.636	$ 131.167	$ 1.311.567

Table 3: Test costs using electrical tests only

	AOI	ICT	FT	System	Costs	AOI Savings
Structural defects before test (per board)	1,000	0,382	0,137	0,096		
Structural defects after test (per board)	0,382	0,137	0,096	0,082		
Electrical defects before test (per board)	0,064	0,064	0,018	0,011		
Electrical defects after test (per board)	0,064	0,018	0,011	0,008		
Structural defects found (per board)	0,618	0,244	0,041	0,014		
Electrical defects found (per board)	0,000	0,046	0,008	0,003		
Total defects found (per board)	0,618	0,290	0,049	0,017		
First pass yield	53,9 %	74,8 %	95,2 %	98,3 %		
Overall test effectiveness	58,0 %	65,0 %	31,0 %	16,0 %		
DPMO remaining on board after test	101,3	35,4	24,3	20,4		
Annual cost of false call at verification	$ 10.417				$ 10.417	($ -10.417)
Annual cost of false repairs	$ 43.750				$ 43.750	($ -43.750)
Annual cost of AOI system	$ 30.000				$ 30.000	($ -30.000)
Programming cost, 2 hrs at $ 160/hr	$ 3.840	(3 days per program)			$ 3.840	($ -3.840)
Annual cost of verification	$ 1.516	$ 36.226	$ 5.383	$ 25.573	$ 68.697	$ 106.592
Annual cost of repair	$ 180.359	$ 211.318	$ 71.530	$ 24.862	$ 488.070	$ 239.698
Annual cost of component scrap	$ 192.094	$ 72.452	$ 12.262	$ 4.262	$ 281.070	($ -70.614)
Annual cost of PCB scrap		$ 15.294	$ 2.791	$ 775	$ 19.521	$ 14.578
Annual cost of retest		$ 5.952	$ 1.598	$ 1.108	$ 8.657	$ 30.298
Annual cost of field failures and returns					$ 50.478	$ 74.522
Total	**$ 461.976**	**$ 335.290**	**$ 91.966**	**$ 55.472**	**$ 1.004.500**	**$ 307.067**

Table 4: Costs of AOI plus electrical test



X-ray of a BGA using ClearVue

analysis. In the following discussion, we will assume that the repair station identifies 10 % of real defects as false and passes them to the next step, while flagging 2 % of false defects as real, which initiates unnecessary repair cycles and their associated costs. Some studies have indicated that incorrect verification of false calls tend to be much higher than 10 %, reaching as high as 50 % in some cases. However, to keep the ensuing analysis conservative, we will use the more conservative number.

How many faults?

Table 1 presents the relative fault coverages of the different methods we are considering for the test strategy. In this example AOI can see/inspect 75 % of the nodes on the board, although on some dense boards this number will be significantly lower. As the figure shows, AXI – particularly three-dimensional AXI – can usually access almost all of the board's nodes. This fact alone gives AXI an advantage in overall coverage.

Users' experience suggests that AOI generates more than twice as many false failures as does AXI because of its visual reliance on minimal color variances in the reflective properties of the board and the inconsistency of angled views. Clearly AOI's preponderance of false failures will increase its operating costs during production, especially in high-volume applications, where these extra costs will rapidly overwhelm the method's lower initial capital outlay.

An example

For the purpose of discussion, assume that a full-featured inspection system, including operation and maintenance, costs $150,000 for AOI and $550,000 for AXI. Using standard 5-year straight-line depreciation, the annual costs come out to $30,000 and $110,000 respectively. Consider a medium-complexity board (see table 2) with 400 components and 4,000 solder joints for a total of 4,400 fault "opportunities". Production volumes are 50,000 per year, and the board has a scrap value (the cost to make another one if one is scrapped) of $600. The manufacturing process generates 160 electrical and 260 structural defects per million opportunities (DPMO). We therefore expect one structural and 0.064 electrical defects per board. Repair will fix 90 % of the identified faults with three cycles permitted before a board is scrapped. The resulting scrap rate is 0.10 %. Assume an average component scrap value (which includes resistors worth pennies and expensive

BGAs) of $5. A field failure – including diagnostic, shipping, and lost goodwill – costs $2,500, and the manufacturer gets a 0.1 % return rate without AXI inspection. Table 2 also presents typical North American and European labor rates and repair costs (in US dollars).

Table 3 shows all of the costs associated with the "do nothing" option – that is, retaining the in-circuit/functional test strategy with no inspection. Based on the assumptions above, making this board will cost over $1.3 million per year.

Table 4 presents results using the same assumptions after adding AOI to the mix. Note that AOI provides substantial savings. Faults that AOI finds can be detected and repaired earlier and more inexpensively than before. Optical inspection also reduces the number of escapes and therefore the number of field failures, the most expensive component of the cost calculations. AOI's advantages are mitigated somewhat by its lack of absolute visibility and its high number of false failures. Nevertheless, in this example AOI reduces costs by around $310,000 per year, or about 24 %.

Despite its higher initial outlay, selecting AXI rather than AOI provides additional savings, as figure 5 demonstrates. The higher visibility and lower false-failure rate mean that fewer defects survive as far as in-circuit test and beyond. According to our analysis, AXI reduces the defect rate from 242 DPMO in the base case to just 43.4. As a result, costs in the downstream processes fall dramatically. As the figure shows, adding AXI saves about $440,000, about 34 % altogether, or about $130,000 more than AOI.

Obviously, every situation is unique. Your specific operating conditions may differ significantly from the assumptions made here. Our analysis suggests that AXI's advantages increase with increasing board complexity. On a board with 6,000 solder joints and 1,800 hidden joints, for example, AOI access falls to only 70 %. In that case, AOI still reduces costs by about $440,000, but with AXI they fall by an additional $228,000. On the other hand, on a board with 400 components, 500 hidden solder joints and 1,000 joints overall, AOI can achieve 88 % visibility, and X-ray's advantage falls to about $57,000.

Before deciding to add AOI or AXI to your test strategy, it is important to carefully examine your own situation on all of the products you manufacture. Labor rates, board-replacement (scrap) costs, component (scrap) costs, node visibility, and other factors will determine the relative advantages to you. Only then can you make the most cost-effective choice.

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External controls of the XStation make user operation simple

	AXI	ICT	FT	System	Costs	AXI Savings
Structural defects before test (per board)	1,000	0,127	0,046	0,032		
Structural defects after test (per board)	0,127	0,046	0,032	0,027		
Electrical defects before test (per board)	0,064	0,064	0,018	0,011		
Electrical defects after test (per board)	0,064	0,018	0,011	0,008		
Structural defects found (per board)	0,873	0,081	0,014	0,005		
Electrical defects found (per board)	0,000	0,046	0,008	0,003		
Total defects found (per board)	0,873	0,127	0,022	0,007		
First pass yield	41,8 %	88,1 %	97,9 %	99,3 %		
Overall test effectiveness	82,0 %	66,0 %	34,0 %	17,0 %		
DPMO remaining on board after test	43,4	14,6	9,7	8		
Annual cost of false call at verification	$ 4.167				$ 4.167	($ -4.167)
Annual cost of false repairs	$ 11.667				$ 11.667	($ -11.667)
Annual cost of AOI system	$ 110.000				$ 110.000	($ -110.000)
Programming cost, 2 hrs at $ 160/hr	$ 12.800				$ 12.800	($ -12.800)
Annual cost of verification	$ 2.021	$ 15.842	$ 5.383	$ 11.125	$ 34.371	$ 140.918
Annual cost of repair	$ 254.678	$ 92.409	$ 31.398	$ 10.816	$ 389.301	$ 338.466
Annual cost of component scrap	$ 228.295	$ 31.683	$ 5.383	$ 1.854	$ 267.215	($ -56.759)
Annual cost of PCB scrap		$ 10.402	$ 1.966	$ 487	$ 13.514	$ 20.584
Annual cost of retest		$ 5.952	$ 1.598	$ 1.108	$ 8.657	$ 30.298
Annual cost of field failures and returns					$ 19.771	$ 105.229
Total	**$ 623.628**	**$ 150.336**	**$ 44.130**	**$ 24.282**	**$ 871.463**	**$ 440.102**

Table 5: Costs of AXI plus electrical test

ZUSAMMENFASSUNG

AOI- und AXI-Lösungen haben jede für sich eine Reihe von Vor- und Nachteilen. Beide Testsysteme bieten wertvollen Zugang und Informationen, die elektrische und funktionelle Tester so nicht länger bieten können. Der langfristige, wirtschaftliche Vorteil von AOI und AXI beinhaltet mehr Faktoren als nur den Anschaffungspreis. Um herauszufinden, welche dieser beiden Inspektionsmethoden die höhere Rendite erzielt, muss man die Unterschiede beider Techniken im Vergleich zum eher konventionellen Testen genau betrachten. Bevor man sich entscheidet, AOI oder AXI in seine Teststrategie aufzunehmen, ist es wichtig, die eigene Situation mit Blick auf alle Produkte, die man herstellt, sorgfältig zu untersuchen.

RÉSUMÉ

Les solutions AOI et AXI ont chacune leurs avantages et leurs inconvénients. Les deux systèmes d'essai offrent un accès et des informations que les testeurs électriques et fonctionnels ne sont pas en mesure de fournir. L'avantage économique à long terme de l'AOI et de l'AXI repose sur des facteurs plus variés que le simple prix d'achat. Pour déterminer laquelle de ces deux méthodes d'inspection permet d'obtenir le meilleur rendement (ROI = Return on investment), il faut considérer précisément les différences fondamentales de ces deux techniques comparées aux méthodes d'essai plus classiques. Avant de décider d'intégrer l'AOI ou l'AXI à sa stratégie de test, il est important d'étudier en détail la situation propre à l'entreprise, notamment tous les produits fabriqués.

SOMMARIO

Le soluzioni AOI e AXI presentano una serie di vantaggi e svantaggi. Entrambi i sistemi di test offrono un accesso prezioso e informazioni che i tester elettrici e funzionali non sono in grado di fornire. Il vantaggio economico a lungo termine di AOI e AXI concerne diversi fattori e non solo il prezzo di acquisto. Per scoprire quale di questi due metodi di ispezione è più redditizio (ROI = Return on investment), occorre osservare attentamente le differenze fondamentali delle due tecniche rispetto alle procedure di test convenzionali. Prima di decidere se integrare nella propria strategia di test il sistema AOI o AXI, è importante studiare a fondo la propria situazione specifica, prendendo in considerazione tutti i prodotti.

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