INDUSTRY 4.0 FOR INSPECTION IN THE ELECTRONICS INDUSTRY

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ABSTRACT

The digital transformation with concepts like Industry 4.0, Smart Factory and the Internet of Things will change production, work processes and business models in electronics manufacturing radically and forever. It is all about connecting, gathering and exchanging big data. It is all about connectivity, and the gathering and exchange of big data.

This paper will investigate how the connected at-line x-ray system can improve the production yield and lower production costs of the manufacturing process when connected to the production line via Automated X-Ray Inspection (AXI) or 3D Automated Optical Inspection (3D AOI). This paper will demonstrate the logic and benefits of SmartLink technology where at-line x-ray can compensate the limitations of in-line inspection solutions.

Key words: Industry 4.0, AXI, 3D AOI, at-line x-ray, SmartLoop

INTRODUCTION

The term Industry 4.0 refers to the fourth industrial revolution and is comprised of growing trends in automation, the internet of things, big data, and cloud computing technologies.

Figure 1. General model of Smart Factory

Just like steam power, electricity, and digital automation of the past, cyber-physical systems will create the factory of the future; the smart factory.

The term "Industrie 4.0" was used for the first time in 2011 at the Hannover Fair. In October 2012 the Working Group on Industry 4.0 presented a set of Industry 4.0 implementation recommendations to the German federal government. The main purpose of Industry 4.0 is to increase an overall production yield and decrease the manufacturing costs. It is predicted that the adoption of Industry 4.0 will benefit production due to increased connectivity across entire businesses as manual factories are transformed into smart factories.

It is all about gathering and exchanging big data. However, big data itself does not bring any specific value to the end user, it needs to be interpreted, understood and acted upon. Collecting all possible characteristics and statuses of the production line will end up with a big mess, unless there is a way to collect and process only relevant data in real time, then visualize these on a sophisticated Manufacturing Information System (MIS) dashboard and initiate proactive measures to improve the quality of the production. The general expectation of the industry is that all processes should be self-optimizing, self-controlling, and totally connected. The reality is that self-optimizing, self-controlling, and totally connected factories are often not possible due to either the age of the existing hardware or the high costs necessary to gain full connectivity.

Secondly, when talking about completely integrated production environments and proactive decision-making, three critical aspects should be considered. It is the quality of the raw data, the availability of sufficiently powerful analytical tools and the ability of the systems to find and fix the root cause of the issues. Without these, we cannot talk about real Industry 4.0 solutions. Therefore there has to be some intermediate solutions which allow to use existing hardware to collect big data and enable informed decision-making.

AXI AND 3D AOI CAPABILITIES AND LIMITATIONS

In a connected Smart Factory, all machines and systems become essentially smart sensors, collecting all possible data from the production line and the boards themselves. It is obvious that the quality of the raw data is one of the core components. Therefore, the accuracy and sensitivity of those sensors is very critical, especially in quality control systems like AOI and AXI. Without diminishing the strong characteristics of the in-line inspection equipment, these still need assistive technologies for the verification of some challenging faults that appear at the same pace as the miniaturization of electronic assemblies.

In recent years Package on Package (POP) and Bottom Termination Components (BTCs) devices are becoming very important and widely used in the PCBA manufacturing process. Two of the most challenging PCBA process failures are component warpage and HoP defects.

Therefore, achieving the best possible solder joint quality becomes an increasingly important consideration for the PCBA manufacturers. Most of the solder joints of a POP and BTC device are invisible by optical means, thus X-ray inspection is the only way to examine the solder quality in a non-destructive way. At the same time, the only method for assessing the warpage and co-planarity issues of the component is 3D AOI.

As a consequence AXI and 3D AOI are becoming more frequently used at the SMT lines. However, both these technologies have certain limitations that may need assistive technologies for the verification of possible false faults. The false fault rate of the inspection system, one of the key items of the fault coverage, affects the overall efficiency of defect detection. Simply put, the more false faults you pass on to a repair station for validation the more real defects get missed. False faults generate costs. Each defect reported by AOI or AXI must be verified. If the reported defect turns out to be a false alarm, then its verification effort is a cost that could have been saved, because the verification did not create any real value. False alarm verification costs include labor, capital equipment and other related costs such as maintenance and panel handling.

The reality is that due to the continuous miniaturization of SMT components and complexity of the assemblies, false faults have not been eliminated so far and smart verification strategies should be implemented.

Component Warpage and Head on Pillow (HoP)

Component warpage. For PoP packages, the warpage issue is always one of the most difficult issues for SMT process engineers, because it is easy to cause an open solder joint problem. The typical SMT defect modes, such as non-wet open, solder bridging, head and pillow, and non-contact open (Image 2) are applicable to both the joints between the PoP bottom package with the board and the PoP memory package.

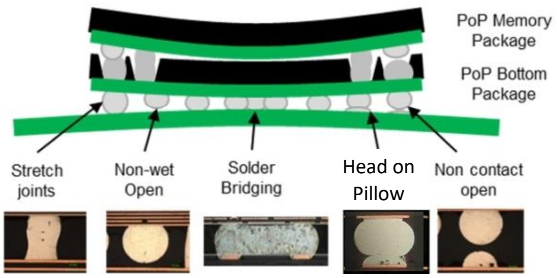

Figure 2. Typical SMT defect modes

There is wide recognition that package warpage is a primary factor in the formation of HoP. In fact, several industry consortia efforts are currently in progress to help characterize factors influencing package warpage behavior in an attempt to define mitigation measures. These include the iNEMI Package Warpage Qualification Criteria and the HDPUG FCBGA Package Warpage projects.

Virtually all BGAs warp, certainly plastic ones and some ceramic; particularly the ones that have a complex internal structure and they are not thermally balanced. When talking about a BGA warping, the corners are going to have the largest displacement causing open and potentially bridges because of them either warping up (concave) and lifting above the circuit board or warping down (convex) and pushing into the solder paste therefore causing bridges (Image 3).

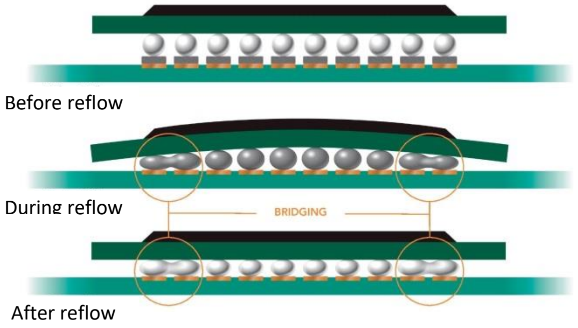

Figure 3. Behavior of the BGA in the reflow

Once an open solder happens, the board will fail in the function or reliability tests and will need to be reworked. In addition, the rework of PoP packages is a challenge compared to the normal single BGA. Therefore it is critical to avoid unnecessary rework if the connection is still reliable despite the warpage of the component.

HoP. Open circuit at the ball interface is a failure mechanism that is becoming an even bigger issue since BGA components have been converted to lead-free alloys and lead-free solder is the norm in assembly and higher reflow temperatures are needed.

However, there is some confusion about this critical defect. Head on Pillow defects can often be attributed to a chain reaction of events that begins as the assembly reaches reflow temperatures.

Components generally make contact with solder paste during initial placement, and start to flex or warp during heating, which may cause some solder spheres to lift. This unprotected solder sphere forms a new oxide layer. As further heating takes place, the package may flatten out, again making contact with the initial solder paste deposit. When the solder reaches the liquidus phase, there isn't sufficient fluxing activity left to break down this new oxide layer, resulting in possible HoP defects as shown on Image 4. Warping of the PCB causes the same fault, as does insufficient solder paste and poor stencil aperture design.

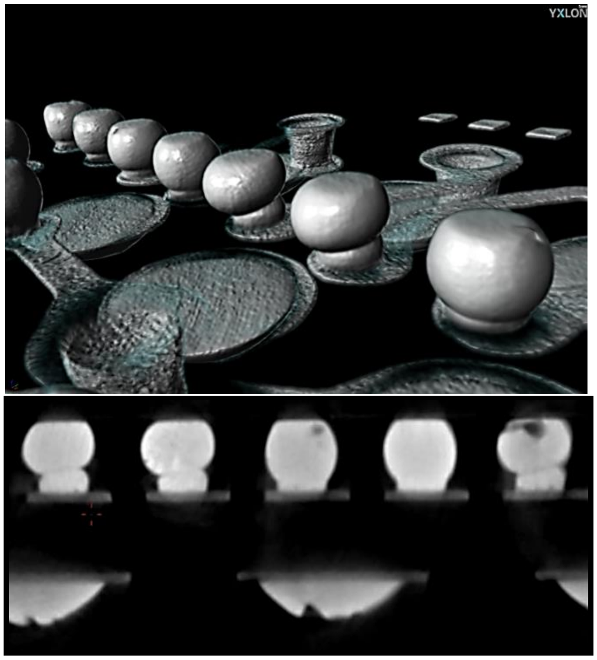

Figure 4. HoP, the slice of micro bumps (60µm diameter)

On other hand, HiP defects are actually very rare and are even harder to detect. In this case the shape of the solder ball may not have changed. The solder paste has reflowed, wetting the pad and molding around the solder sphere. This type of defect is also referred to as Ball in Cup and many other names. A HiP defect can appear in the situation when the preheat time is too long and or dwell temperature lower than required and the flux exhausts its activation and cleaning capability as seen in Image 5a where we can see dried out solder paste that is not coalesced. If the BGA ball is contaminated and does not wet then we get a result as shown on Image 5b.

Figure 5a.

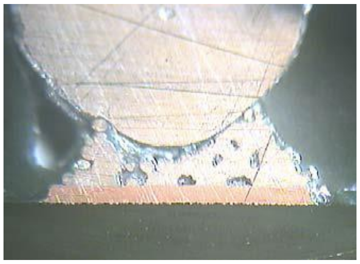

Figure 5b. SEM of HiP defect

In both cases, due to the lack of solder joint strength and contamination, these components may fail with very little mechanical or thermal stress. Eventual separation of what was never a proper metallurgical bond can lead to late stage manufacturing defects and even early stage field return issues.

This potentially costly defect is not usually detected in functional testing, but can be detected by x-ray systems. If not detected these only show up as failures in the field after the assembly has been exposed to some physical or thermal stress.

3D AOI as a sensor

The continuing evolution toward advanced miniature packaging has led to ever increasing PCB density and complexity. As the manufacturing process becomes progressively more complicated, there is an ever increasing probability for defects to occur on finished PCB assemblies. For years the Automated Optical Inspection (AOI) industry has relied solely upon two-dimensional (2D) inspection principles to test the quality of workmanship on electronic assemblies. While advancements in conventional 2D optical inspection have made this technology suitable for detecting such defects as missing components, wrong components, improper component orientation, insufficient solder, and solder bridges; there is an inherent limitation in the ability to inspect for co-planarity of ultra-miniature chips, leaded devices, BGA and LED packages. True co-planarity inspection of these challenging devices is an absolute necessity and literally requires the addition of a third dimension in inspection capability; 3D inspection technology.

Although 3D inspection technology has existed for many years in the electronic inspection industry, this technology has primarily been reserved for inspecting solder paste depositions on printed circuit boards directly after the screen printing process. Over the past few years, however, 3D inspection has emerged as a viable technology for testing gull-wing and BGA devices as well as a host of other co-planarity sensitive circuitry on finished PCB assemblies. Of course, the main reason for the industry trend toward 3D inspection technology is to compensate for the limitations of conventional 2D inspection.

There are basically two different methodologies by which 3D inspection is employed in AOI machines. The first is Laser Measurement; the second is Multi-Frequency Moiré Phase Shift Image Processing.

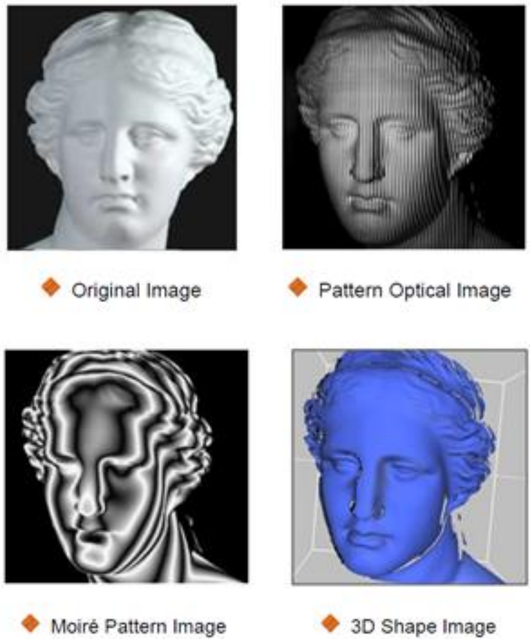

Figure 6. Moiré 3D Phase Shift Image Processing

Multi-Frequency Moiré is by far the most advanced methodology for testing true co-planarity of virtually any given region of interest on the PCB. Moiré 3D Phase Shift Image Processing is a methodology by which a single or multiple projectors are used to project a shifting pattern of lines on a given region of interest. A digital camera then captures the image of deformed lines as they are shifted across the test surface. By applying phase shift analysis and phase unwrapping techniques, the 3D profile of the test surface can be reconstructed for precise measurement.

Multi-Frequency Moiré takes this one step further in that two or more line patterns of differing frequencies are projected onto a given test surface in order to characterize objects of varying heights.

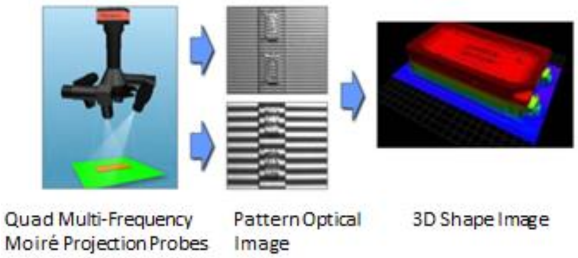

Figure 7. Multi-Frequency Moiré

The only limitation of 3D AOI is being an optical inspection system – it cannot see underneath of any black devices like BGA, PoP, QFN, etc. Therefore it does not allow the system to make a conclusive decision if the solder joints of the black devices are still acceptable despite co-planarity or warpage issue.

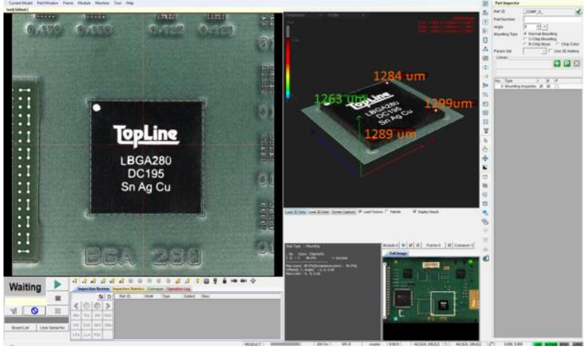

Figure 8. User interface of 3DAOI

As shown in Image 8, three corners of the BGA are lifted, but are the solder joints still acceptable? It requires an additional verification in an off-line x-ray system or under a microscope. Manual inspection is always slower and more costly but in many cases the only way to verify the findings of the in line systems. In this particular case it came out that the reason for co-planarity was one loose small component underneath the BGA, shown in Image 9.

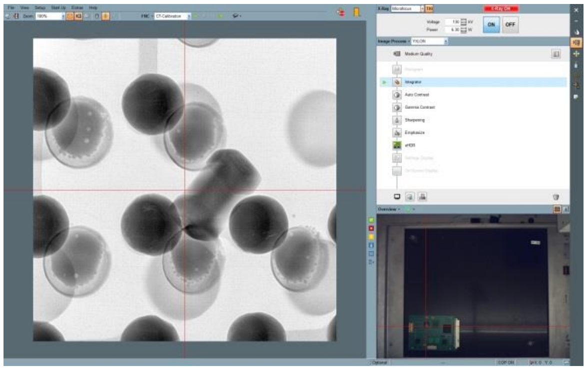

Figure 9. User interface of at-line x-ray

AXI as a sensor

The use of AXI for printed circuit board inspection continues to grow in manufacturing, especially on high-density/high complexity boards. The AXI is an effective test tool for solder joint inspection, and it usually detects about 90% of the total defects on a circuit board assembly. The AXI uses 3D x-ray testing to locate manufacturing defects; this is especially important to increase coverage on boards with limited access. The AXI pinpoints the exact location of defects, and thus repairs are both fast and inexpensive. The AXI is an ideal tool for testing high-reliability boards with medium-to-high-complexity designs and components which have limited visual and electrical access. The AXI covers most of the process fault spectrum, including: short, open, insufficient/excess solder, misaligned and missing components, reversed polarized capacitors, and even unreliable solder joints that might escape electrical tests.

One of the challenges in AXI performance is to detect HoP and open defects for optically hidden solder joints such as BGA, BTC, POP, and other advanced packages at electronic manufacturing services companies.

The in-line x-ray inspection systems try to find HoP defects by looking at BGA balls in at least 3 different positions – the PCB Pad slice, the BGA Mid-ball slice and The Package Slice.

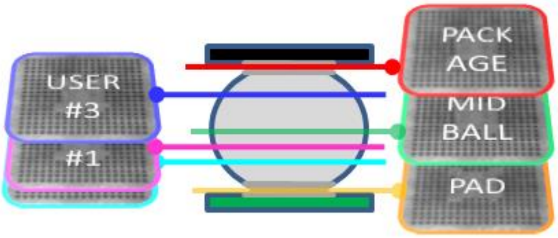

Figure 10. Working principle of AXI

The images are automatically analyzed with the original CAD-based designs and user definable settings.

The advanced algorithms and adjustable magnification allow defining if the particular ball is smaller or bigger than its neighbours like in image 11. With challenging components the number of slices can even be increased, but then the time taken also increases.

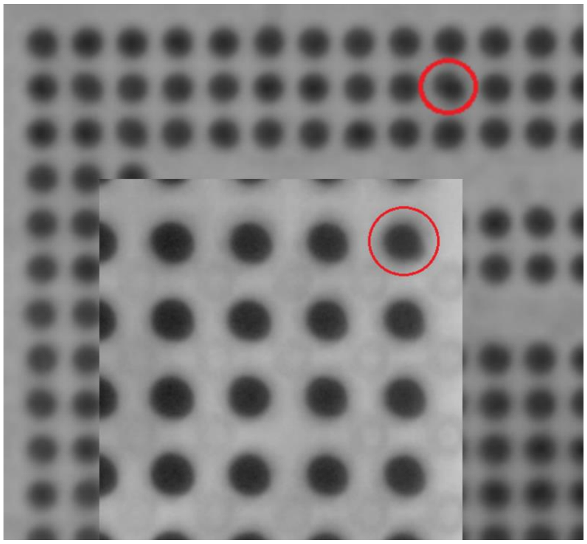

Figure 11. AXI 3D Slice

However, most in-line x-ray inspection systems have rather high false fail rates. False failure calls cannot be eliminated completely but the rate has to be reasonable for the production line. These findings should be confirmed either on verification station or inspected again on a high-end at-line x-ray system.

The reason is simple, AXI can easily detect HoP joints at standard magnification but if the BGA ball size falls below 250 microns, this becomes much harder even at high magnification and it is more likely to miss HoP defects.

In these situations the proper search of HoP defects requires high-resolution oblique view images like Image 12.

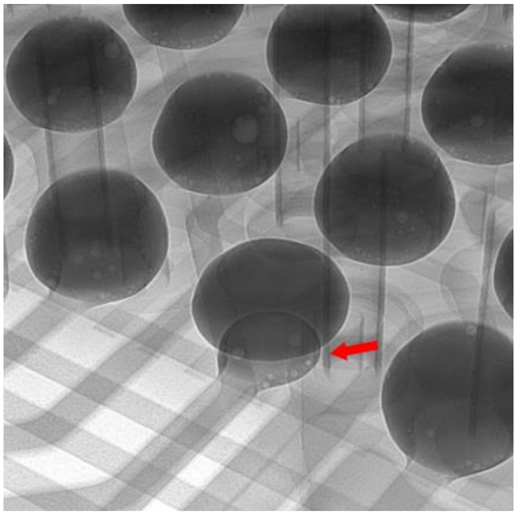

Figure 12. HoP defect

These high resolution images can be generated by an off-line or at-line x-ray system. These systems have mostly open type transmission x-ray sources and some can perform in three different modes – nanofocus, microfocus and high-power modes. Due to the mechanical design an at-line system can also gain better <3000x geometrical magnification.

Most importantly, more advanced development of the image chain in at-line systems allows processing images during the image stream, and as a result, all the images viewed on the monitor are enhanced. The distinction can be significant. When viewing a crack in a solder ball (Image 13), for instance, instead of selecting images that appear to best show the crack and then processing those images, the viewing of an enhanced image of the crack can occur in real-time, while the position of the sensor (or the specimen) is changed to provide multiple viewing angles.

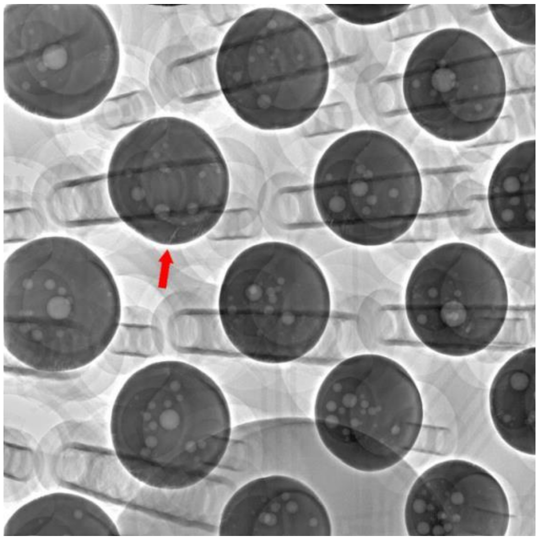

Figure 13. Oblique view of BGA with 16bit DFP

Another high value tool for live image analysis is µHDR (Image 14) which is averaging the exposure of the overall image and showing in glance the structure of the sample object.

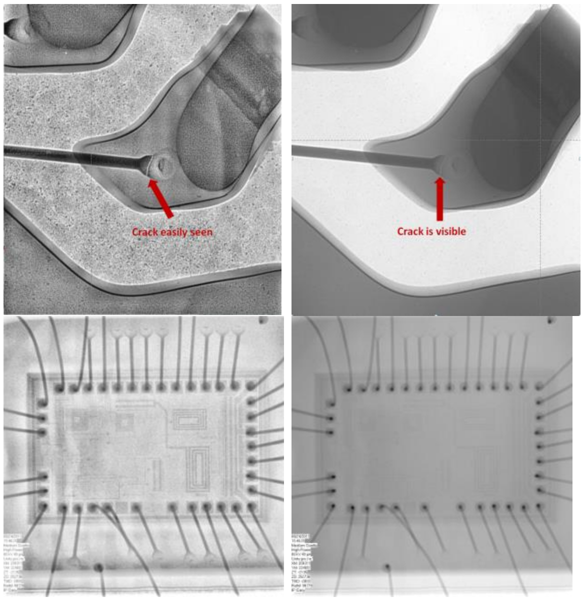

Figure 14. µHDR live filter activated (left)

SMARTLOOP

As said earlier, smart manufacturing should be a proactive and independent decision-making environment where connected systems or machines will “talk” to each other. That “discussion” is, however, based on algorithms. By definition an algorithm can give us only one single answer. But does this provide us the right answer or one from three or four or five alternatives? Will it provide the same response every time or different ones for the same issue? Many MIS systems are not ready to manage big data, due to the lack of smart analytic tools. Without human intervention to make those critical decisions, based on knowledge and experience, we still cannot talk about completely effective and efficient smart production. Therefore the reliable solution combines human brains and algorithms together, allowing Process Managers to make informed decisions after seeing all the data from various collection points. This data is relayed to a single screen where they also have historical information and everything needed to make a truly informed decision. This is definitely a Smart Solution, it is not a “Lights Out” fully automated Smart Factory but it is much better than many factories today. It allows real time monitoring of production flow and the changing of settings and limits to ensure that the product produced remains within the optimum process window, giving potentially 100% acceptable product coming off the line, at least in terms of assembly defects. It is also a big step towards “full automation” and therefore well worth embracing as a way of improving yields and reducing costs.

Considering all this, an at-line x-ray system should become an additional high-end sensor that can compensate, for example, for the limitations of AXI or 3D AOI.

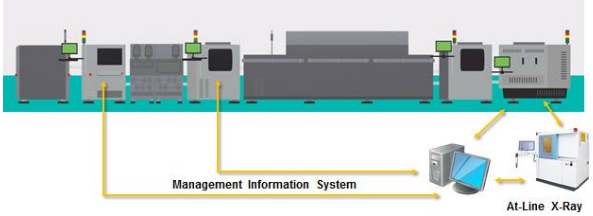

Figure 15. at-line x-ray concept

An at-line system is essentially an off-line system that is linked to the production line and placed beside it, allowing real-time response to issues and making the x-ray system a tool of the production and QA teams and not simply a test machine in a lab, used by QC staff.

This solution is simple to implement and therefore reliable. The at-line x-ray can be connected to an in-line 3D AOI or in-line AXI inspection system directly where it becomes a smart verification tool where only questionable and unsolved faults will be transferred for repeat inspection on a high-resolution at-line x-ray system. The inspection results can be stored on the system PC, but can also be exported to the customer’s MIS.

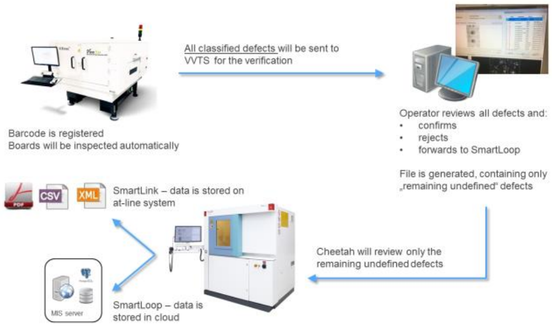

Figure 16. (full size illustration in Appendix 1)

The connectivity of the at-line system is based on Internet Protocol (IP) via Transmission Control Protocol (TCP). Further use of data (collation and visualization of results from different inspection systems) depends on the end customer’s demands and capabilities. The collected data allows to understand the happenings in the past and make predictive analyses about future trends. The general task is to provide a dashboard view to the Process Manager who can track down the possible problem areas and initiate proactive measures to improve the quality of production, before rejects or scrap units are produced.

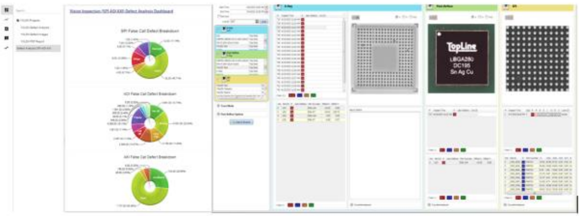

Figure 17. The dashboard of MIS

ADDED VALUE OF SMARTLOOP SOLUTION

The ultimate target for this solution is to increase production yield and reduce the manufacturing costs, including troubleshooting and rework.

In high-reliability products, like for aerospace, military and automotive products, there is no room for uncertainties. All possible defects have to be verified and reworked. Conventional methods for troubleshooting are the ICT, microscope, etc. These are usually quite expensive and should be avoided at any costs.

As a reference we can use 700 USD as the hourly cost of the ICT method (incl. technology, labor and overheads). 400 USD per hour will be an average cost of a PCB rework. Obviously these numbers vary from country to country but should reflect the industry standard.

The value of the SmartLoop to the user will be on-demand locations scanned from 2 different inspection systems – 3D AOI and X-Ray – which can be compared side-by-side so that the user can make an informed and conclusive decision on the defect calls.

CONCLUSION

Based on our studies, we conclude that the AXI and 3D AOI algorithm threshold settings are critical for detecting certain PCBA process failures. The AXI and 3D AOI program optimization is based on its measurement data analysis. Per current AXI and 3D AOI performance, it is beneficial to utilize the AXI or 3D AOI equipment jointly with an at-line x-ray system for verifying defective location for AXI and 3D AOI algorithms optimization process. A solution like SmartLoop can add value to the production in different phases of production. The major value of SmartLoop comes from regular production where a company with an average production yield of 90% can increase it to 99,5%. At the moment, the best Smart Factory quality control solution is the combination of human brain and algorithms.

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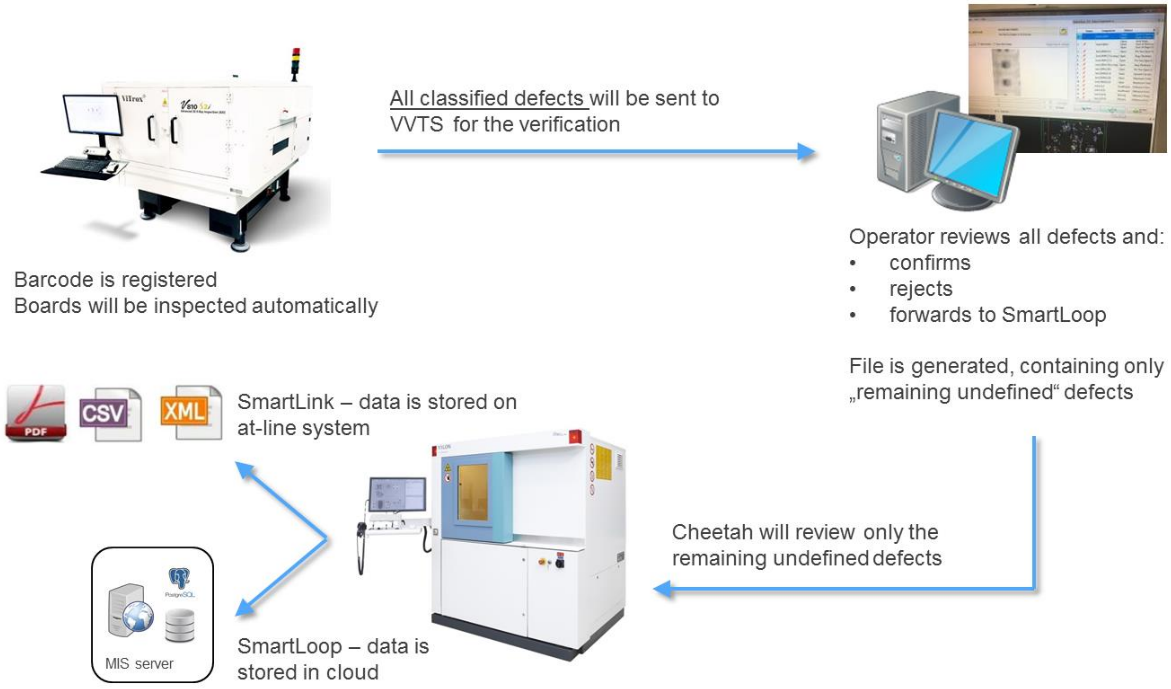
APPENDIX 1



Barcode is registered
Boards will be inspected automatically

All classified defects will be sent to VVTS for the verification

Operator reviews all defects and:

- confirms
- rejects
- forwards to SmartLoop

File is generated, containing only „remaining undefined“ defects

Cheetah will review only the remaining undefined defects

SmartLink – data is stored on at-line system

SmartLoop – data is stored in cloud