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Selection Criteria for X-ray Inspection Systems for BGA and CSP Solder Joint Analysis

Dr. David Bernard, Dage Precision Industries,
158-29 Hua Shan Road, Feng Qiao Industrial Park, SND Suzhou City, Jiangsu Province China, P.C: 215129
d.bernard@dage-group.com

Abstract

As the benefits of using area array packages / chip scale packages / flip chips are applied to more and more products, the need to ensure the quality of the optically hidden joints of these devices during the PCB assembly process makes x-ray inspection an increasingly vital process tool. Therefore, when selecting the appropriate x-ray system to acquire and use for BGA, flip chip and CSP applications, both now and in the future, it becomes crucial to understand the capabilities and differences of the x-ray equipment available in the market today.

To this end, this paper will:

- Review the basics of x-ray equipment operation
- Discuss the different types of x-ray systems available and their relative merits for BGA and CSP applications. This will consider 2-dimensional and 3-dimensional x-ray imaging systems and the effect different system components have, such as x-ray tube and image capture device, on the operation and capability that such systems can provide.
- Provide example images of what an operator should be looking for during BGA/CSP examination
- Suggest the selection criteria that should be considered for today's applications

Introduction

The use of area-array products such as BGA, flip chip and other chip scale packages (CSPs) becomes ever more common. Therefore, the need to ensure the quality of the optically hidden joints of these devices produced during PCB assembly makes the use of x-ray inspection an increasingly vital process inspection tool, as it is able to see through the package and interrogate the quality of the joints directly. The continuous trend in the evolution of semiconductor devices and their packages is to become smaller. So when considering the acquisition of an x-ray inspection system, it is necessary to consider the capabilities of such a system not only for what it can provide now but also how it can be used in the future, with ever smaller components. Therefore, the most appropriate x-ray system for use will have to be able to provide the x-ray image clarity that will allow the necessary analytical information to be seen (e.g. opens, shorts, etc.). This will require that the x-ray system provide sufficient magnification to see the features that are to be inspected now, and in the future. In addition to having sufficient magnification, optimum analysis for BGAs and CSPs also requires that oblique views of these devices can be investigated. Without oblique views, that is to say only x-ray inspecting from directly above the solder balls, it is possible that the size and density of the solder ball itself will obscure useful analytical detail. This need for high magnification and also oblique angle views has implications for what different manufacturer's can offer with their x-ray systems.

The variety of x-ray inspection systems available today can be defined into a number of broad categories. The appropriate system for use will depend on the specific applications for which it will be needed. Therefore, certain applications may lend themselves to using lower specification systems, where the magnification and image resolution that is possible with other systems is compromised, for example, in return for the potential benefits that might suit certain working practices. An example, which is discussed in more detail below is using, so-called, in-line x-ray systems for high-volume low-mix applications.

The key factors that define the quality and analytical usefulness of the x-ray images produced by an x-ray system are the resolution that the system can achieve and the magnification that the system offers at this resolution. These are crucial as they make the features that need to be inspected available at sufficient magnification to make analysis quick and easy. Therefore, if only large objects/features ever need to be inspected, the resolution, clarity of feature presentation and magnification need be much less than in other applications, permitting a more modest system specification that can be used. However, with BGAs and flip chips being small, and becoming ever more so, the resolution and magnification necessary from an x-ray inspection system will tend to have to be at the much higher levels to meet the inspection requirements now and in the future.

Above the basic requirement of the x-ray system being fit for purpose, i.e. being able to investigate the necessary features, will be the need to consider the operational factors of implementing such a system into the manufacturing process. As such, it is also necessary to consider how easy it is to use the x-ray inspection system. For example, can the x-ray system be used by less skilled operators, so that more, and better, test and inspection can be undertaken whilst keeping the test overhead as low as possible? The opportunity of using an x-ray system to provide better product end-quality but without requiring expensive, and highly trained operators, offers economic advantages. This may justify not only the acquisition of an x-ray system but also quickly provide the return on investment spend through reduced manufacturing failures and fewer scrap boards. However, any decrease in the test overhead must be achieved without losing the analytical quality that will ensure better product quality resulting in improved customer satisfaction.

2D and 3D X-ray Inspection

The x-ray systems that are available from manufacturer's today, and which should be considered for BGA and CSP applications, can be defined as being from either of two general types, 2-dimensional (2D) systems or 3-dimensional (3D) systems. All of the systems are capable of being operated off-line and therefore used in a batch inspection, or selective inspection, mode. This allows boards from any part of the production line (after paste, after placement, prior to reflow and after reflow) to be investigated by simply removing samples and testing them prior to their replacement into the line. Some manufacturers are able to offer their systems for in-line use and these are generally placed after reflow. The decision for selecting an in-line, as opposed to an off-line, x-ray capability will depend on the application and usually the volume that need to be inspected. In general, the substantial additional costs associated with complying with in-line protocols and safety requirements tend to bias in-line systems towards high volume, complicated board and low mix applications. However, the in-line x-ray system is substantially the slowest part of the line, which can have productivity implications as fewer boards are produced per hour with an in-line x-ray system in place. Therefore, even for high volume applications, configuring the test procedure for an off-line approach, i.e. using batch inspection such as used for high-mix low-volume and medium-mix medium-volume applications, may need to be considered because of the flexibility and cost benefits it offers. As an example, an in-line system must be dedicated to only one production line whereas multiple lines can use the off-line approach.

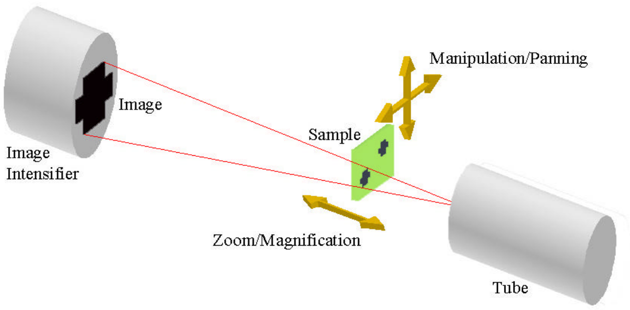

Figure 1: Basic 2-D x-ray system configuration

All x-ray inspection systems, whether 2D or 3D, are basically x-ray shadow microscopes (see figure 1). An x-ray light source (x-ray tube) produces x-rays, which pass through the sample. The differing materials within the sample absorb more, or less, of the x-ray radiation depending on their density and atomic number, and cast a shadow of that material at the detector. The denser the material then the darker the shadow. The closer the sample is moved to the x-ray tube then the larger the shadow becomes and this is how magnification, called the geometric magnification (see figure 2), is achieved.

2D x-ray inspection systems provide a two dimensional image that shows all of the components in the board, from both sides, simultaneously. 3D x-ray systems take a series of 2D images and then reconstruct the data such that x-ray images of only a certain slice through the board is produced. The analogy that can be used is that 2D systems provide similar information to that of a medical x-ray of a broken limb whereas 3D systems are like computerised tomography systems (CT) where x-ray slices can be generated at horizontal levels through the sample. A further variant of the 3D x-ray system is called laminography which reconstructs the PCB slice of interest by constructively integrating the x-ray data produced for that slice whilst destructively integrating, and therefore deleting from view, data from other slice levels. 2D systems can be in-line or off-line. Laminography systems can also be in-line or offline but can be slow to use in-line, because of the time to take the number images needed to produce the data. CT x-ray systems are off-line as they need to take many 2D images and use complicated algorithms to reconstruct the data that takes many minutes to accomplish. As such, CT type x-ray systems tend only to be used in specialist applications where the time to produce the images is not important, and will be excluded further from consideration in this paper. The other 2D and 3D systems must be configured to optimise image quality and results in the minimum time so as to reduce cost overheads for this test operation.

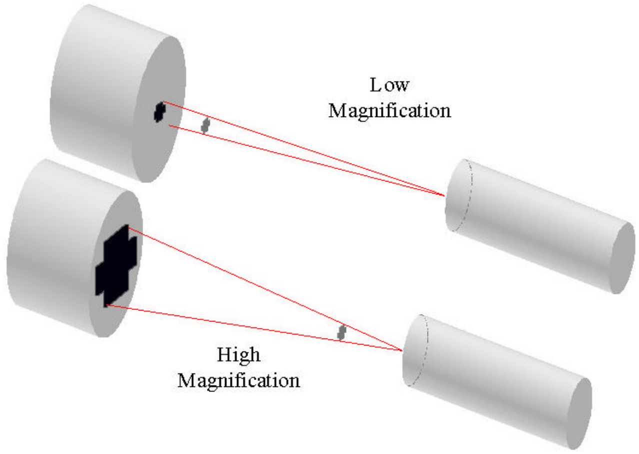

Figure 2: Geometric magnification

Features of X-ray systems

All x-ray systems, 2D or 3D, have the same general features (see figure 1):

- An x-ray tube to provide the x-ray radiation for the system.
- A sample manipulator to move the sample around to allow inspection of different areas on the sample as well as to alter the magnification. Manipulation is also required to achieve oblique angle views.
- An image capture device that takes the x-rays that pass through the sample and converts it into an optical image that can be presented to the user.

Property	Closed Tube	Open Tube Single Focus	Open Tube Double Focus
Min. feature recognition	5 microns or more	2 microns	< 1 micron
Max. tube kV	90, 150	160	100, 160
Serviceable	No	Yes	Yes
Available magnification	Low	High	High
Cost of ownership*	Medium-High	Low	Low
Target thickness	Large	~ 5 microns	2 – 3 microns

Table1: Features of open and closed tubes
*** - based on 10,000 hour closed tube lifetime**

X-ray Tubes

The heart of all x-ray systems is the x-ray tube. Selection of the appropriate x-ray tube for BGA and CSP applications has been discussed in reference 1 and the appropriate tube must be selected for specific applications (see table 1). The choice of x-ray tube within the x-ray system defines the resolution that the system can achieve. The x-ray tube also directly influences the system magnification and the range of samples that the system can inspect.

The features of x-ray tubes that must be considered and chosen, which then effect the system capabilities are (see ref 1):

- Tube type – open (demountable) or closed. The type selected effects the resolution that can be achieved and has implications on operational lifetimes. The better the resolution then the smaller the feature that can be recognised by the system. If only large objects are to be inspected then poorer resolution can be acceptable. For the smallest features in BGAs and CSPs, however, higher resolution such as 2-micron feature recognition, or less, is generally needed.
- Target type - transmissive or reflective. The type selected effects the proximity, or how close, that a sample can be placed in relation to the focal point of the x-ray tube and therefore directly affects the available magnification that a system can achieve.
- Tube kV and power. The greater the kV, or accelerating potential used, then the more penetrating are the produced x-rays, allowing denser and / or thicker objects to be inspected. The greater the tube power then the brighter the image for a given kV value. Typical kV values from manufacturers for PCB applications are 160kV and 100kV. Using lower kVs is more appropriate if all the samples to be inspected are thin. However, higher kVs are likely to be needed to see voids in BGA solder balls and as the number of layers in the PCB increases. Care must be taken when comparing tube specifications from different manufacturers as tube power values can be shown to be large but only at the expense of increasing tube focal spot size, and hence poorer resolution. Therefore, comparisons should always be made at the same tube power and resolution / spot size.
- Number of focussing stages within the tube. One or two sets are possible. Extra tube focussing will reduce the tube focal spot, improving resolution but at the price of reduced power and therefore a dimmer image requiring a longer time to acquire sufficient data to present a useful image to the operator.

When selecting the best tube for use in the x-ray system the following comments have been made (reference 1) and are summarised in table 1. Closed x-ray tubes, offer an integrated package that does not allow servicing of the tube components

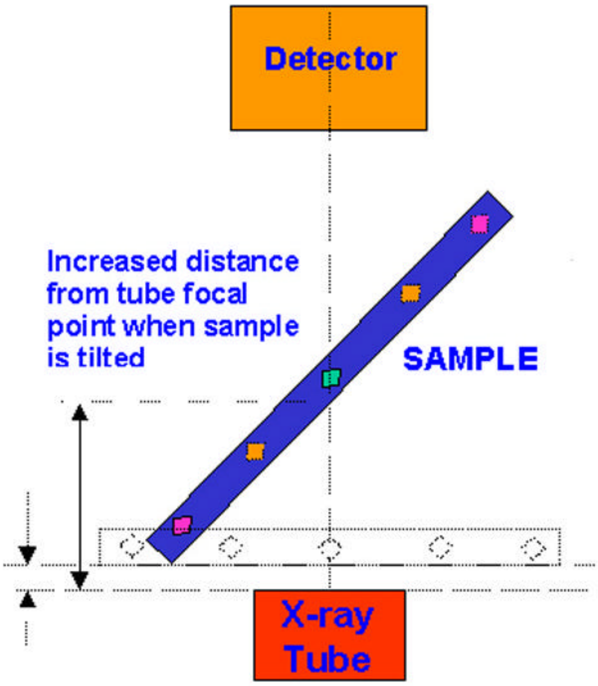

Figure 3: Tilting the sample moves it away from the x-ray tube so as to prevent any collision with the tube. This increases the sample distance from the tube focal spot and so dramatically reduces the available magnification

but offers relatively long lifetimes compared to open tubes. However, the achievable factory specification of a closed tube may only be available for the initial portion of the tube's life. Closed tubes also offer poorer resolution and less magnification than open tubes in x-ray systems. The cost of eventual replacement of the whole closed tube when the unit fails is very high compared to the serviceable (consumable) components - filaments and targets - in an open tube. The cost of ownership over the lifetime of an x-ray system would therefore be much higher with a closed tube system. For operational considerations, closed tubes are usually preferred for 3D and in-line x-ray systems.

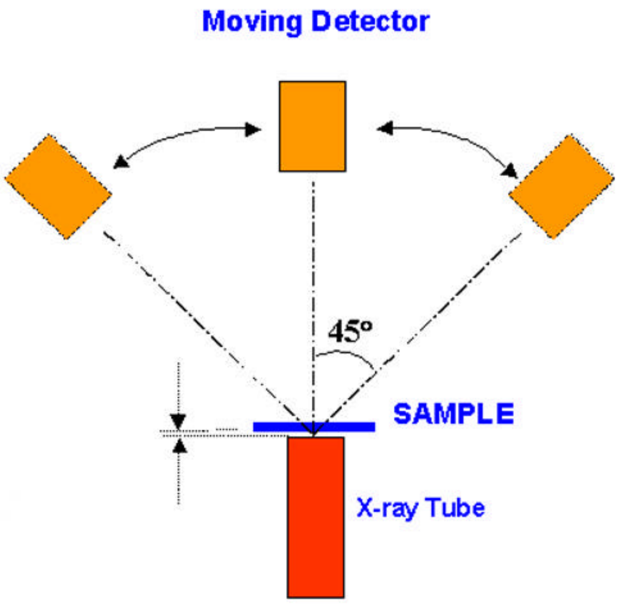

Figure 4: By moving the detector to make oblique angled views, the sample remains horizontal at all times so there is no compromise to the available magnification when an angled view is required.

With open x-ray tubes, the resolution that is possible can be enhanced by reducing the focal spot on the target using a combination of some, or all, of the techniques described in reference 1. The ultimate resolution of an open tube can be more than 5 times that of the highest specified closed tubes (1 micron or less). The price that must be paid is that this resolution is only possible under very specific conditions and, very often, with specially prepared samples. This may not be appropriate for the vast majority of applications. Instead, most open tube manufacturers compromise the performance of their tubes so as to still have 3 – 4 times the resolution of the closed tube (<2 microns) but provide a more robust system that can be used reliably within realistic working environments. Open tubes are most commonly used in off-line systems today because of their enhanced magnification and resolution that is so important for the smaller BGA and CSP devices.

Sample Manipulation

Figure 1 shows the basic layout of 2D and 3D x-ray systems. Being able to pan the sample in the x and y plane relative to the x-ray tube allows selection of different areas on the sample for inspection. Movement in the z-direction adjusts the distance between the sample and the tube focal spot, which, as figure 2 shows, alters the geometric magnification. The nearer the sample gets to the tube the greater the magnification that is achievable.

The simplest method for sample manipulation, in whatever x-ray system is considered, is to hold the sample in a manipulator that allows movement in the x, y and z directions, with the tube and image detector being fixed in position. However, a variety of configurations also exist, usually related to in-line systems, where sample load /unload requirements usually necessitate that the sample can only me moved in the x and y plane with the magnification (z-movement) achieved by moving the tube instead. Splitting the various movements can have implications as to how close the tube can get to the sample (affecting maximum available magnification). There may also be issues over how the operator has control over these various movements, which may make system operation more difficult to learn.

The above manipulation limits inspection to only looking from directly above the sample. However, oblique angled views are now needed to help with inspecting for opens, etc. that may be obscured by the ball shape if you can only inspect from above. Simple 2D systems achieve oblique views by adding a tilt, and sometimes even a rotate mechanism into the x, y, z sample stage. Tilting the sample relative to the tube / detector allows views of grazing incidence of the sample. However, the limitation of this approach is that as the sample is tilted it is necessary to move the sample away from the x-ray tube to prevent any collision of the sample with the tube, the detector or another part of the system (see figure 3). Therefore, the geometric magnification must decrease as a result because the sample is now further away from the tube focal point.

To overcome this limitation, a number of systems have become available in recent years that enable oblique views to be shown without compromising the available magnification. Different manufacturers have slightly different approaches to achieving this and one example is shown in figure 4. Generally, the approach is similar and the sample is kept horizontal at all times, and therefore is able to be as close as possible to x-ray tube. The oblique angle view is obtained by moving the image intensifier and not tilting the sample. So available magnification is not lost when an oblique angle is required. An example of the different viewpoint and information that oblique views provide can be seen in comparing figure 5 and 6.

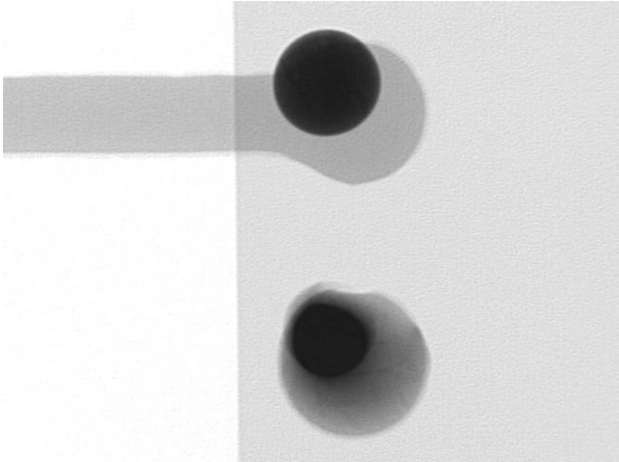

Figure 5: Normal view (from above) of flip chip connections. Each solder ball is around 190 microns in diameter. *Image courtesy of Dage Precision Industries.*

Typically, oblique angles of up to 45 degrees are readily available. Some systems can achieve higher values but when looking at BGA balls, for example, looking at > 45 degrees makes neighbouring BGA balls overlap and may not provide any additional analytical information than lesser angles.

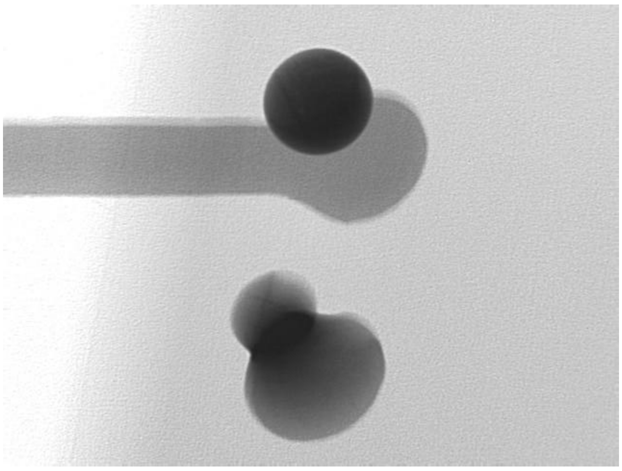

Figure 6: Oblique view of flip chip connections seen in figure 5. The difference between the reflowed (bottom) and un-reflowed (top) joint becomes very clear. As the sample has not been tilted to achieve the oblique view there is no loss in magnification from figure 5. *Image courtesy of Dage Precision Industries.*

With the extra axes of movement needed to provide oblique views, some consideration should be given to how the system is operated. If there are complicated controls, the system may be limited to only being used by higher skilled, and therefore more expensive, operators. Usually, in-line 2D systems do not offer any angled views, as the extra time required to potentially move the x-ray tube and/or detector to make an oblique view would slow the inspection time still further and reduce productivity even further. However, by only looking from above, these systems may miss information hidden under the solder balls, for example.

With in-line 3D (laminography) systems, the need to have an oblique view is not required. This is because it is possible to select a slice at which the ball to pad interface is present and any variation in the reflow should be seen as a variation in the joint compared to its neighbours. There can be issues about selecting the correct slice for inspection, especially if there is warpage on the board. However, it must be considered that because these systems use closed tubes for operational considerations, the resolution of the images produced is much poorer than open tubes would provide. Furthermore, the method of producing the 3D images also further degrades the image quality and so may effect the analytical quality of the data produced.

Using the 3D laminography approach allows gray-scale algorithms to be used to automate joint analysis for both BGA / CSP and standard SMT components where a differing thickness of solder produces a change in the gray scale that the x-ray detector sees. Variation in this gray scale at different levels of the joint can then be used to identify areas of concern on the board, once programming of the test method has been completed for the sample. This approach is called automatic x-ray inspection (AXI). AXI may also be offered with 2D and off-line 3D systems. When considering if this approach is appropriate for an inspection application, apart from the technical specification of the system, consideration may need to be given to the broader operational requirements that such an approach requires. For example, there may be the need for additional high-level / high-skill personnel to program and run these systems which will increase the test overhead. In addition, the accuracy and reliability of the algorithms used for AXI need to be investigated to see if they are suitable. For example, the more complicated analytical applications, such as inspecting for opens under BGAs, requires much greater subtlety in the image analysis algorithm. This level of sophistication may not be present and may result in the propensity of these AXI algorithms to generate a high level of false-positive results. False-positive results are when a fault is flagged but which, on subsequent inspection by a human operator, is passed as being no fault at all. The need to have additional operators, perhaps of a highly trained background, to provide confirmation / rejection of false-positive calls can impact on the test overhead as well as potentially devalue the perceived use of the inspection tool. Therefore, although AXI allows more automation of the test procedure, the balance has to be struck between the use of such approaches and the effects / reliability false-positive results have on the operational usage of such systems.

Image Capture Devices

Traditionally, x-ray sensitive film was used as the detection device, requiring wet chemistry to develop the images off-line. Film has been replaced for PCB applications by real-time x-ray imaging. The most commonly used method is to use an image intensifier. Image intensifiers have an x-ray sensitive phosphor that detects the x-rays reaching it through the sample. This phosphor converts the x-ray light into visible light, which is then imaged by an analog, optical CCD camera that is fed into the x-ray operating system and presented on-screen for the operator to use.

More recently, an entirely digital approach has become possible for capturing and presenting the x-ray images. This has come from using detectors originally developed for medical imaging applications, for example CMOS flat panel detectors. Although these detectors can offer improvement over the detection capabilities of image intensifiers in terms of pixel resolution and gray scale sensitivity, to date they have been much more expensive than an equivalent image intensifier and so have been unavailable, except for the most expensive, high-end applications. This is because such detectors are difficult to fabricate over large areas without having within them many pixel, and other quality, defects that will interfere with the analytical information necessary for PCB applications. Flat panel detectors also require up to 10 seconds to produce each reasonable image to the operator and so are not real-time in their imaging. This may be acceptable within a laboratory environment but of little use in the production environment, where speed and throughput, as well as clarity of image, are more important. For example, trying to move over a sample from one area of interest to another without real-time imaging will prove inconvenient. Flat panel detectors are still in their infancy for PCB applications where high resolution and speed of use is demanded. However, they may well provide future opportunities for x-ray inspection.
The most recent digital detector development for x-ray inspection is to combine the best of image intensifier and medical camera technology, together with recent advances in digital signal processing and the use of high-resolution, digital monitors. In this system approach, the cost effectiveness of the image intensifier is coupled to the high resolution, and excellent gray scale sensitivity, of larger format, digital, optical CCD cameras. In this way, the same performance to that of flat panel detectors is achievable in real-time without having any missing pixels. The added advantage of having real-time, high-resolution x-ray images is it provides the ability to have greater inspection throughput because analytical details may now be visible at lower magnifications. Therefore, inspection routines can be simplified with the number of inspection steps reduced, providing more, and better, testing in the same time.

Conclusion

The criteria for selecting any x-ray inspection system will ultimately depend on the application(s) for which it is to be used. However, BGA and CSP joint analysis requires the ability to look at smaller features with oblique views, now and in the future, so as to have the best opportunity of inspecting for opens and other faults. Therefore, BGA and CSP inspection requires that an x-ray system offer, as a minimum, high magnification, high resolution and oblique views available at high magnification. Therefore, this suggests that the optimum combination for an x-ray inspection system for this purpose should include an open x-ray tube, a sample manipulator arrangement that provides oblique angle views without compromising the available magnification and a high resolution, digital, real-time detector.

The question of if such a system should be in-line or off-line must be considered against the economic benefits these two approaches offer. However, the compromises that in-line systems usually have to make, which decreases the throughput time to match line speeds, may reduce the effectiveness of such systems. There is also the question that if the system is in-line then it cannot be used for inspecting product from other lines. Off-line systems enable a flexible approach for testing over many production lines, as well as offering testing opportunities at different stages during manufacture, if needed. Although 2D off-line systems are more flexible, with large sample runs batch testing of samples, instead of inspecting every one, is required.

Apart from the technical specification of an x-ray system, consideration should also be given on the broader, economic impact that any system will provide to production processes. Questions should be raised on the ease of use of the system. For example, who will use the system and what are their costs, not just in terms of manpower but also the training and experience needed? What will be the implications of using different test regimes to that currently used so as to be appropriate for the products being inspected?

The ease of use can be qualified by using equivalent samples, of similar type to those that the system will investigate in the future, and running these samples directly in the different machines. The easiest to use will allow the least trained operator to be able to analyse the potential production faults. Using similar samples on all x-ray systems being considered also allows a direct comparison between the systems that will be independent of the varying specifications that manufacturers may offer.

References

1) X-ray tube selection criteria for BGA / CSP X-ray inspection, D. Bernard, published in The Proceedings of SMTA International Conference, Chicago, September 2002