Time Delay Integration detector based solution for Industrial X-Ray NDT Inspection

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Abstract
Recent experimental results achieved with Time Delay Integration (TDI) X-ray detectors for inline NDT inspections are presented. We focused on different industrial applications that include inline inspection of integrated circuits for fast detection of counterfeits components and the inspection of powder metallurgy parts with automated defect detection. Both applications have been developed under ChipCheck and AutoInspect R&D projects financed by the European Union FP7 programme, and are using the Argus TDI X-ray detectors manufactured by the company Teledyne DALSA. Two basic set-ups for inline X-ray TDI experiments are described. The first, that reached a resolution of 18 microns, is based on using a low-cost minifocus X-ray source. The second system, by using a microfocus X-ray source in a variable magnification set-up, could reach around 4 microns resolution.

Keywords: X-ray, TDI (Time delay integration), powder metallurgy (PM), electronic components, counterfeit components, inline scanning

1. Introduction

X-ray inspection allows volumetric inspection which typically is able to reveal more information about a component's internal structure than any other non-destructive inspection technique. Traditionally, in a factory environment X-ray inspection is a standalone offline system and is reserved for testing selected components from batches or when components are known to be defective (component debugging). For higher production environments though it is desirable to inspect all components inline and during production. It is also useful to be able to inspect for quality issues early on, or at various stages of the production line before too much value is added to the product. However, there is a reluctance to place X-ray systems inline because they are expensive to implement, can slow production throughput and can cause a production bottleneck. The work presented here investigates the use of low cost digital radiography setups and, in particular, the utilisation of TDI X-ray detectors for two different industrial applications. The project called ChipCheck has been developed for X-ray imaging of electronic components and detecting counterfeits while the project AutoInspect has been developed for the inline inspection and sentencing of powder metallurgy (PM) parts.

2. TDI Detection Principle

A variety of digital X-ray detectors are available on the market aimed at specific intended applications. One such detector is the Teledyne Dalsa Time Delay Integration (TDI) linear array detector which uses micro-electromechanical systems (MEMS) technology to ensure the smallest possible gap between individual image sensors in order to provide a flexible detector customizable to different field-of-view requirements. This detector offers many advantages over flat panel and linear detectors. The most important advantage over a flat panel is cost. TDI is a method of inspection in which a detector produces a continuous video image of a moving object by means of a stack of linear arrays. By synchronising the data transfer timing with the movement of the object, the signal is integrated without smear. As a result, TDI provides higher sensitivity than standard line scan detectors. It is an ideal technology for high-throughput X-ray applications that require high sensitivity and high resolution.

Teledyne Dalsa Argus TDI X-ray detectors [1] are used in the presented work. They offer a physical resolution of 4080 (H) x 256 (V) pixels with a pixel resolution of 54μm; at 3.5x magnification, this equates to a 15μm image pixel size. The X-ray resolution of the standard Argus detector is up to 8 lpm (lines per mm), with a line acquisition rate of 2000Hz and a maximum scanning speed of 10cm/s.

3. ChipCheck

3.1 The Problem

Counterfeit electronic components are a growing issue within the electronics industry. The consequential costs to electronics manufactures of inadvertently purchasing counterfeit components includes lost yield, field failures, product recalls and damage to reputation etc. This is in addition to the safety issue. Despite extra precautions taken for sourcing components for safety critical electronic systems, there have been reports of counterfeit components entering the supply chains for both the defence and aerospace industry. The detection of counterfeits has become increasingly difficult because the majority of these parts have the same or similar markings as their qualified genuine component. Currently, systems manufacturers cannot check all components at "goods inwards". Although, some larger sized manufacturers make random checks on single components from batches of components, it is impossible to check all components in a low cost and effective manner. This is especially so when considering that surface mount components are supplied on feeding mechanisms such as reels or tubes where the number of components can range typically from 1,000 to 20,000 pieces.

3.2 The Solution

The work in the ChipCheck project seeks to address the issues described above through the development of counterfeit electronic component detection digital radiography (DR) based systems that automatically inspect components in their original packaging. In order to make such a system more attractive to the user, X-ray imaging of single passive and active components and PCBs will also be possible, alongside the imaging of components supplied on standard tape & reel and tube packages.

A number of technical solutions have been investigated and implemented, but this paper presents only the experimental results from using a TDI detector in a laboratory setup. Figure 1 shows the radiography geometry setup used. A Thermo Scientific KEVEX PXS5-925 mini focus X-ray source with voltage of 45-90kV and focal spot of ≤ 14μm (at 8 watts) was deployed.

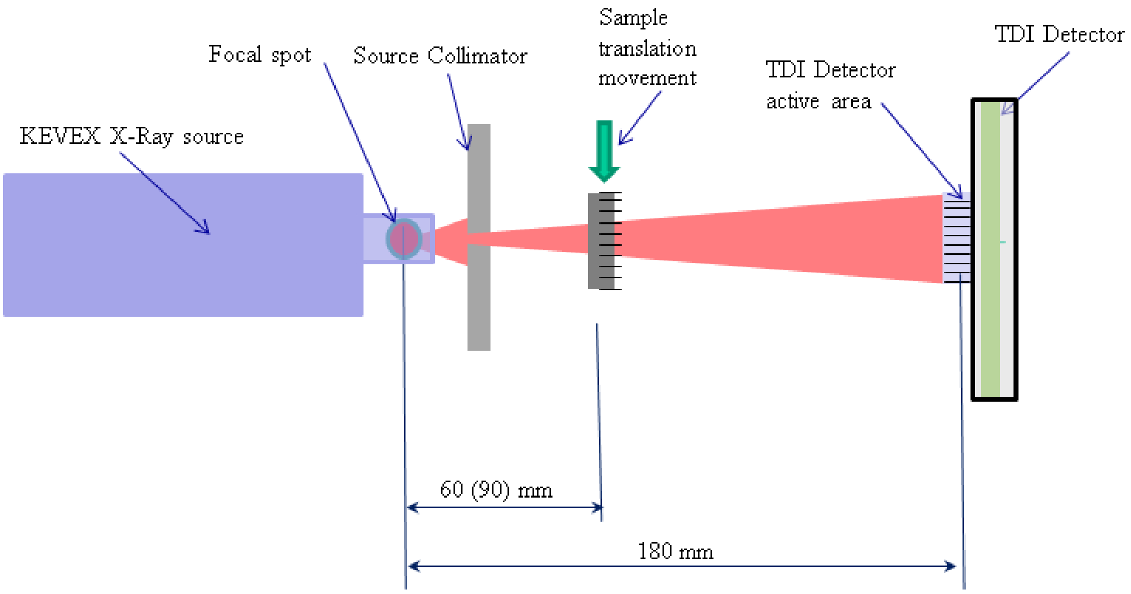


Figure 1. Setup geometry used in experiments

Figure 2, shows the X-ray setup as implemented in the Accent Pro laboratory radiography bay. A mechanical stand supports the X-ray source and TDI detector in a fixed position. A manipulator moves the component(s) in the vertical direction.

Using a TDI linear detector means that, in the vertical direction, component size or number of components is not limited. As such, multiple components can be inspected in one scan pass. The components presented in this paper are a XILINX Integrated Circuit (IC) (PQFP package type), two Texas ICs (FK package type) and a TWI wire bond reference tool. The components are affixed to the manipulator at their edges by double sided tape. A custom developed LabVIEW program is used to control the source and detector, and provides a graphical user interface (GUI).

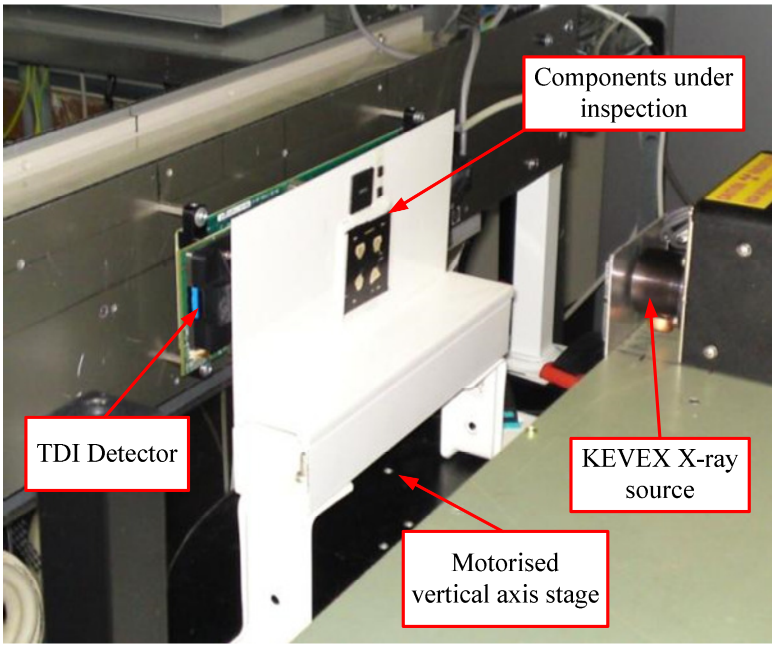


Figure 2. X-ray setup showing the components mounted on the manipulator

3.3 Results

The collected data forms a high resolution image. Figure 3 shows the result of a single scan of the component as presented in the developed LabVIEW control program. The scanning speed was at 2cm/sec. The X-ray energy used was 70kV at 110µA. With a magnification of x3, an image pixel size equivalent to 18µm was achieved. By digitally zooming into areas it is possible to visualise the detail within the ICs. Figure 4 shows the XILINX IC, when the same collected data is digitally zoomed. The XILINIX IC was later set in a resin block and machined down to reveal the bond wires in order to confirm the bond wire diameter size. Optical inspection performed at high magnification confirmed 25µm diameter bond wires.

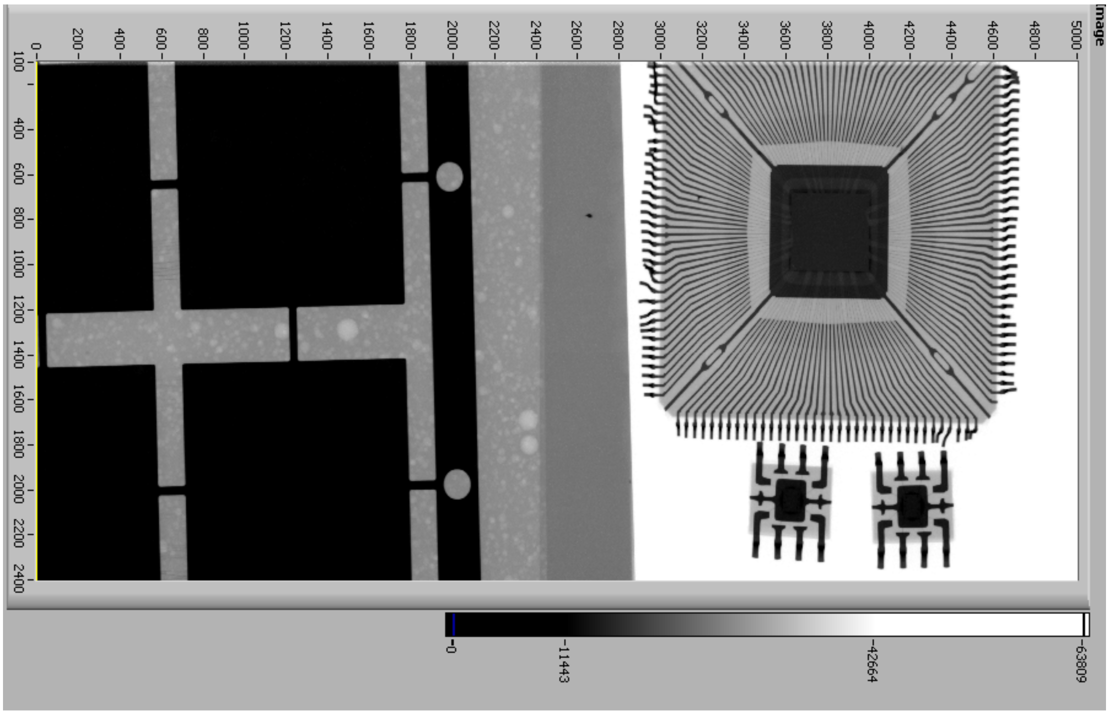
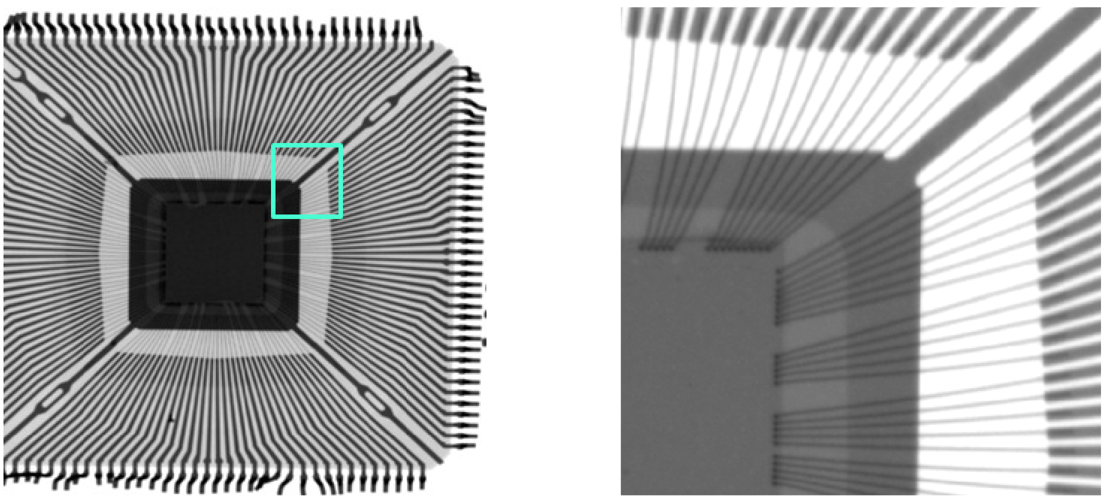


Figure 3. X-ray scan results achieved in a single scan



a) Digitally zoomed in region showing XILINX IC in detail

b) Further digitally zoomed in region of interest of XILINX IC

Figure 4. Digitally zoomed X-ray image of XILINX IC

One of the revealing differences between a genuine and counterfeit component can be the bond wires. These can be missing, broken, positioned in a different place, have a different diameter or comprise a different material. Generally, bond wires are gold (Au) but can also be aluminium (Al). However, copper (Cu) wire bonding is starting to be used as the interconnect, replacing gold as the interconnection of choice in the semiconductor manufacturing industry.

Wire bond diameters start at 15μm and go upwards, with 25-27μm being a typical value. However, smaller diameter wire is likely to be a reality in the future as electronics implementation technology improves and chip manufacturers load more functions onto smaller silicon chips.

In order to prove the detection capability of the setup for wire bond size and material, TWI produced a wire bond reference tool. The wire bond reference tool comprises a silver plated lead frame of four square areas, each separated by a small gap from each other. Across the horizontal gap, groups of 5 wires run between bonds positioned on each square. Each group of wires represents a particular wire bond size and material. The whole wire bond reference has been encapsulated to be representative of a real integrated circuit package.

Figure 5, shows the digitally zoomed-in region of the wire bond reference. From the results the ChipCheck TDI based system detection of gold bond wires of diameters 25μm, 17.5μm and 12.5μm is shown.. A bond wire diameter size of 12.5μm represents the current state of the art in the electronics industry. Gold bond wires are the easiest of bond material to detect as they have a high density, and as a result provide well contrasted X-ray images for analysis, even for interconnection wire diameters of 12.5μm. Copper has less than half the density of gold, and therefore the 17.5μm and 25μm diameter copper wires appear far less distinct in the X-ray image. However, it is possible to conclude that copper bond wire with diameters as small as 17.5μm can be detected with the ChipCheck setup used in the field trials. Aluminium has a density even lower than copper and it was not possible to image any aluminium bond wires. This is because the density of the wires was so low compared to the background densities of the package.

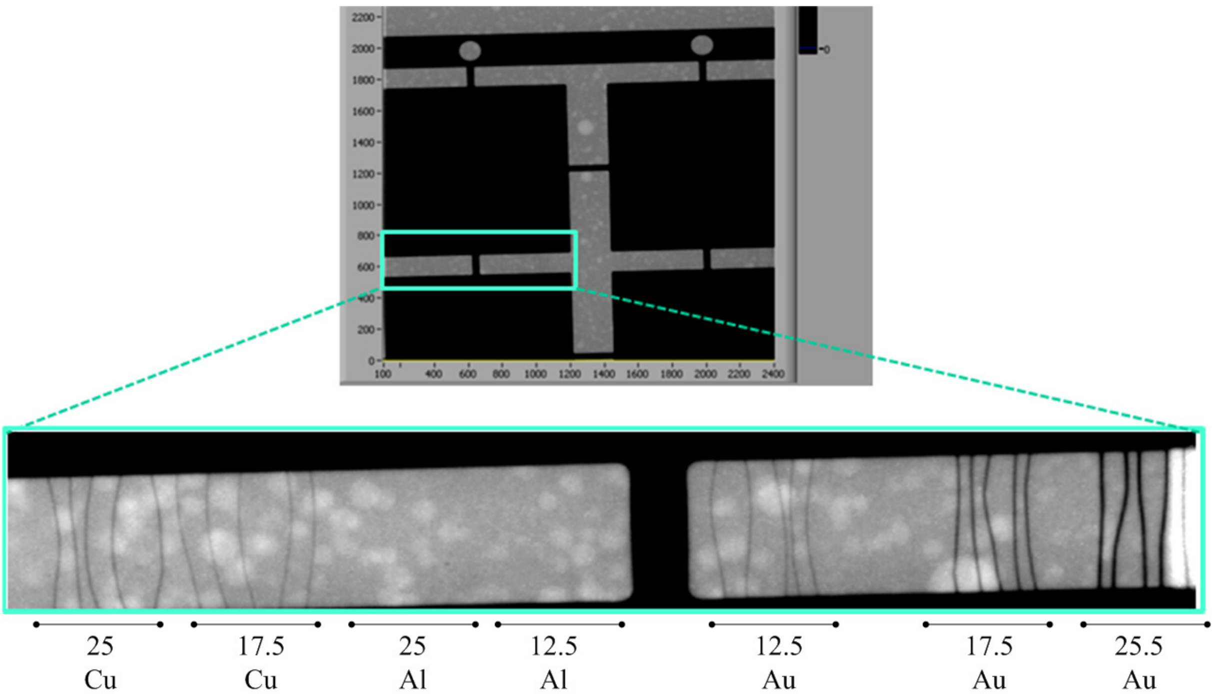


Figure 5. Zoomed in X-ray image for wire bond reference tool

4. AutoInspect

4.1 The Problem

The requirements for inspection within the powdered metallurgy (PM) industry are very different to that necessary in the detection of counterfeit electronic components. A key difference is that the products manufactured are a lot thicker and larger in size. PM components are manufactured from metal powders that are compacted into net shape, forming a weakly cohesive structure, and then sintered through application of high temperatures. The components can be complex in shape and produced in high volumes. The vast majority of PM components are destined for the automotive, defence and aerospace markets, where quality control is crucial and 100% post-manufacture inspection is essential. The typical defects that can be found in PM parts include porosity, cracks and impurity inclusions, which can all affect the mechanical properties and therefore performance of the part [2,3,4].

There are a number of non-destructive testing techniques for inspection of PM parts which have been applied for both green and sintered product states with varying degrees of success. Depending on the complexity of the PM component to be inspected, these inspection techniques are typically used at the end of the production line and are not suitable for high volume manufactured part inspection. They typically involve manual or part manual processes, which are slow and require subjective interpretation by an operator. The AutoInspect consortium, led by Accent Pro, has developed a digital radiographic system for the inline inspection of sintered powder metallurgy and metal injection moulded parts.

The automated X-ray inspection prototype developed by the AutoInspect consortium is believed to be a timely approach for determining and separating good/bad PM parts in a production line.

4.2 The Solution

The AutoInspect system has been developed to address the quality control necessity for 100% inline inspection of PM components as they come off the production line, and to indicate defective parts before they enter the wider supply chain and the final product. The use and novel implementation of TDI X-ray detectors in this system has led to a robust and cost-effective solution.

The main features of the AutoInspect system, shown in Figure 6, are:

- A digital radiography inspection technique, able to inspect powder metallurgy parts in seconds,
- Two embedded TDI linear X-ray detectors to allow the supply conveyor to run continuously, while a row of PM parts is simultaneously scanned. The TDI technique creates very low-noise X-ray images with resolution up to 13.5µm pixel size, depending on X-ray set-up magnification,
- A dedicated image analysis algorithm for the automatic recognition and detection of defects with pre/post processing and an enhancement algorithm to sentence good/bad components.

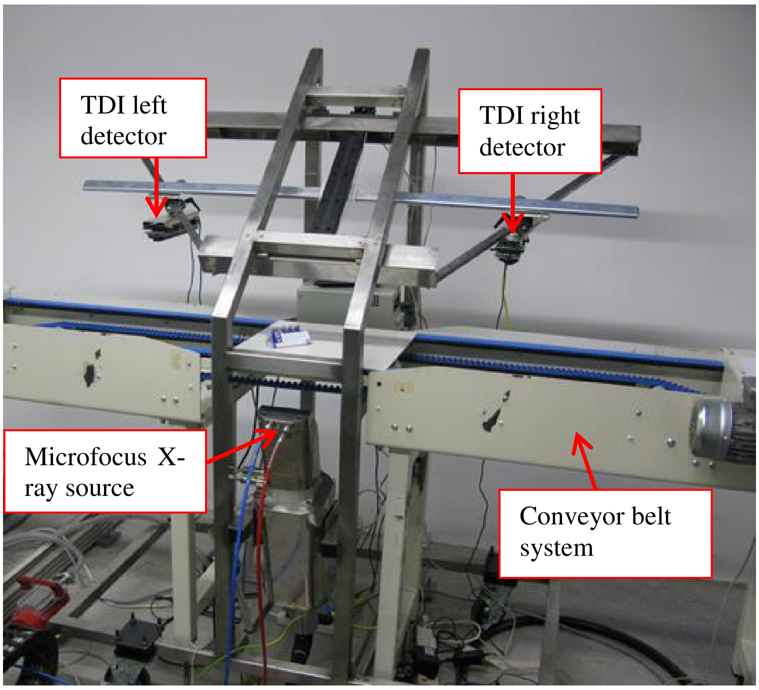


Figure 6. Front view showing the AutoInspect system as implemented in a walk in X-ray chamber

As shown in Figure 6, the AutoInspect system comprises a microfocus X-ray source, two TDI linear X-ray detectors, and a conveyor belt which passes the PM samples through the X-ray beam. The detectors are mounted on vertical manipulators to allow the image magnification to be set between x1.7 and x4 dependent on the requirements of the component under test. This yields a minimum image pixel size of 13.5µm. As with the ChipCheck project, the PM samples are moved between the source and detectors. For AutoInspect this is achieved using a fed conveyor and radiographic images are acquired as the samples move past detectors.

The innovative aspect of the AutoInspect system is that the two TDI detectors are positioned such that they acquire two orthogonal radiographic images of the PM parts whilst using only a single X-ray source. The two orthogonal views ensure that any normally hidden, overlapping or perpendicular planar defects in a single view would be clearly visible in the second viewing angle, therefore imaging all defects present. The vertical manipulator is precisely aligned such that this orthogonal view is maintained across the range of magnifications. The use of a single X-ray source in this dual-view implementation, rather than the typical necessity of two sources, means that the cost of the system is greatly reduced. Sensors ensure that radiographic images are acquired only when a sample is in the field of view of the X-ray detectors.

The X-ray WorX XWT-225-SE microfocus X-ray source implemented in the AutoInspect system is capable of voltage up to 225kV, allowing the penetration of sintered PM components of 20-25mm in thickness. The focal spot size is 4µm, minimising so the degree of unsharpness contribution from the source. The X-ray source provides a special ellipsoidal cone X-ray beam with beam angles of $120^{o}/40^{o}$, which is wide enough to cover the 90^{o} separation of the detectors governed by their orthogonality.

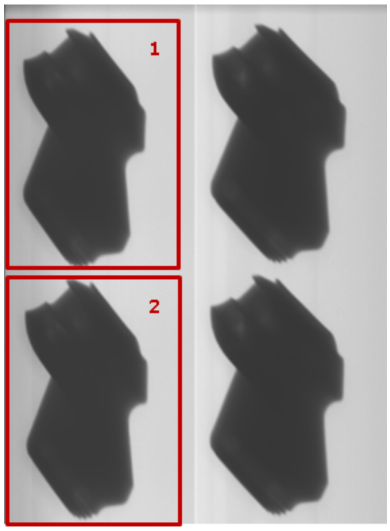
For the AutoInspect project, the TDI detector was optimised by Teledyne Dalsa to suit the project high-energy specification requirements, and the improvement was conducted in two main directions. Firstly to include a scintillator that would provide 5-6 lp/mm resolution at X-ray energies of at least 160kV, and secondly to reduce the afterglow discharge to a value that would allow scanning at high speed (5-10cm/s typicaly).

Dedicated control, acquisition, image processing and defect detection software was created in the LabVIEW development environment for the operation of the AutoInspect system. The defect detection is carried out through the subtraction from a reference image within the database of a pre-determined good sample.

4.3 Results

Figure 7 shows the use of the AutoInspect system on four individual, 8mm thick, sintered PM components. An X-ray energy of 160kV, 600μA and 3x magnification was used. Figure 8 shows the result when the enhanced image is zoomed in. A scale is shown to give an indication of the image resolution.

a) Sintered PM components to be inspected arranged on pallet

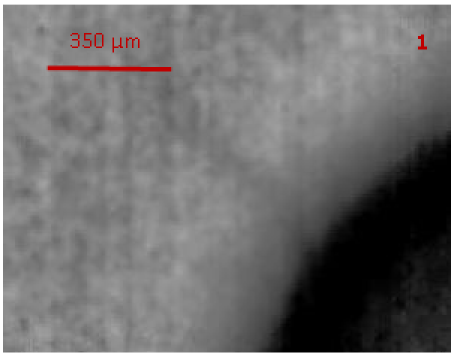


b) X-ray raw data image acquired from right view detector

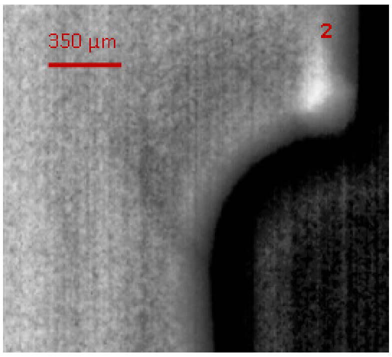
c) Enhanced radiographic image with flaw automatically located (from raw image 1)

d) Enhanced radiographic image with flaw automatically located (from raw image 2)

Figure 7. Sintered component samples with automatically detected crack regions



a) Digitally zoomed crack detail for enhanced image 1



b) Digitally zoomed crack detail for enhanced image 2

Figure 8. Sintered component samples with detected crack details, derived from Figure 7.

Figure 7 clearly shows that the AutoInspect system has been able to automatically detect very small crack flaws in the sintered PM components and sentence these as defective. The resolution and level of unsharpness was more than sufficient to detect these 80µm wide cracks within the neck of the component. It can be seen that because of the angle of the detectors the X-ray image shows the component with a shadow. However, this does not matter for the automated defect detection, as the shadow is constant for good and bad components and the final sentencing is carried out by subtracting from a reference image of a known good component.

5. Conclusion

A selection of acquired X-ray images have been presented and demonstrate the capability of the ChipCheck and AutoInspect X-ray inspection systems. This investigation has shown that TDI X-ray detectors have offered an effective, robust system and contributed to a cost-effective solution to inline inspections across two widely differing fields of application where the problems and requirements vary significantly.

The use of TDI linear detectors can significantly reduce the cost of the system. However, the X-ray source is the biggest contributor to the cost of the solution. Selecting between a mini or microfocus source is critical and depends on the industrial detection requirement. For ChipCheck, using the TDI linear array X-ray approach together with mini focus X-ray source, an image pixel size equivalent to 18µm was achieved. A microfocus X-ray source was selected for the AutoInspect system and in conjunction with maximum magnification and detector position offers a potential image pixel size of 13.5µm. Using only a single X-ray source in the implementation meant that doubling the imaging views did not double the cost of the radiographic system.

The wire bond reference investigations show the ChipCheck setup to be highly appropriate for inspection of electronic components now and in the future when Cu bond wires and smaller wire diameters become more prevalent.

The finalised AutoInspect prototype was capable of automatically detecting small cracks within sintered PM components and sentence them as being defective, ensuring that they would not enter the supply chain. The TDI detectors were capable of sufficient sensitivity to allow the developed defect recognition algorithms to operate effectively on the acquired images to carry out automatic sentencing of the components under inspection.

6. Acknowledgements

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